Natural Ventilation of Buildings: From Fluid Mechanics to Architectural Design Guidance

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Declaration

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This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. I further state that no substantial part of my thesis has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee.

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Abstract

Over the last two decades, natural ventilation of buildings has rapidly established itself as a viable low-energy alternative to air-conditioning and mechanical ventilation systems. With careful design, natural ventilation has the capacity to reduce the energy expenditure of buildings and can provide a comfortable indoor environment for occupants.

Undeniably, a successful natural ventilation design calls for an integrated approach, ideally involving *architects* and *ventilation engineers* working closely together through all stages of a building design process. However, establishing an environment conducive to open communication and shared knowledge exchange between both camps may be difficult in a practical setting, given that both have developed their own unique set of language conventions, philosophies, methods of thinking and problem-solving. Further to this, there is an apparent delay in the time taken for information on natural ventilation to be transferred from the fluid mechanics literature (where fundamental developments in the science underlying and explaining natural ventilation flows tend to be made) into architectural design guidance, which further exacerbates the barriers to knowledge exchange in practice.

This research endeavours to serve as a springboard for fostering the transfer and delivery of information on natural ventilation from the fluid mechanics literature to an architectural audience. Focus is on the intuitive value of a simplified mathematical approach as a vehicle with which to model and explain natural ventilation flows. Based on this approach, rapid and intuitive guidance for use in preliminary design is developed and proposed to inform the suitable sizing of façade openings to meet specific ventilation targets. Our proposed guidance, which centres around hand calculations and the use of visual charts, is anticipated to be readily usable by architects and engineers, thereby facilitating two-way communication and dialogue between both members in a design process. Moreover, attempts are made to gain direct insight into the information needs of young architects in the context of a natural ventilation design with a view to improving our current understanding and means of conveying technical information to architects.

It is hoped that this research will prove of interest to those engaged in low-energy building design, whether as practitioners or academics, from architectural, building services or wider engineering backgrounds.

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Undertaking this Ph.D. has been a truly life changing experience for me and it would not have been possible without the sheer amount of support and guidance I received, both emotionally and intellectually, along the journey. It is the best opportunity here to thank everyone who has helped throughout my graduate career and probably the last opportunity to express my gratitude.

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Contents

Nomenclature

Tables I, II and III provide an overview of the general notation and terminology used in this thesis, with the exception of the few that appear once or twice in isolation. Note that Chapter 5 (Part I) has its own specific set of notation and terminology, which is independent from the rest of the thesis, and therefore is not included in the list below. The nomenclature that is specific to Chapter 5 (Part I) is instead shown separately in Table 5.1 of §5.1.

Symbol	**Description**	**Units**
a	Actual (or physical) opening area	$\mathrm{m^2}$
A^*	Total effective opening area	$\mathrm{m^2}$
B	Heat flux	$\mathrm{m^4\,s^{-3}}$
D	Opening diameter	m
$\mathscr{D}ir$	Direction number	-
$\mathscr{D}ra$	Draught number	-
DR	Draught Rating	%
c	Discharge (or loss) coefficient	-
$\mathrm{c_p}$	Specific heat capacity of ambient air	$\mathrm{J\,kg^{-1}\,K^{-1}}$
C	Constant related to the plume entrainment coefficient	-
C_{pl}, C_{pw}	Wind pressure coefficients at the leeward and windward façades, respectively	-
Fr	Froude number	-
g	Gravitational acceleration	$\mathrm{m\,s^{-2}}$
g'	Reduced gravity	$\mathrm{m\,s^{-2}}$
h	Interface height	m
H	Vertical distance between (midpoints of) openings	m
k_1, k_2	Constants	-
l	Depth of opening in flow direction	m
L	Characteristic length of line source	m
p	Pressure	$\mathrm{kg\,m^{-1}\,s^{-2}}$ (or Pa)
Q	Ventilation flow rate	$\mathrm{m^3\,s^{-1}}$
R	Vent area ratio	-
R^*	Ratio of effective vent areas	-

Table I: List of general symbols used in this thesis (continued on next page).

Symbol	Description	Units
Ra	Rayleigh number	-
Re	Reynolds number	-
T	Air temperature	°C
U_{w}	Wind speed	$\mathrm{m\,s^{-1}}$
W	Heating power	Watts
z	Vertical coordinate (with origin at floor level)	m

Table I: List of general symbols used in this thesis (continued).

Greek symbols	Description	Units
α	Plume entrainment coefficient	-
γ, λ	Empirical constants	-
ρ	Air density	$\mathrm{kg\,m^{-3}}$
$\Delta\rho$	Density difference	$\mathrm{kg\,m^{-3}}$
ΔT	Temperature difference	°C
Δp_{w}	Wind pressure drop	$\mathrm{kg\,m^{-1}\,s^{-2}}$ (or Pa)

Table II: List of Greek symbols.

Subscripts	Description
b	bottom (or lower)
c	critical
ext	external
int	internal
LP	line plume
P	plume
max	maximum
min	minimum
req	required
s	stack
t	top (or upper)
occ	occupied
w	wind

Table III: List of subscripts.

Glossary of terms

Table IV is a list of terms and corresponding definitions referring to specific aspects of natural ventilation. The purpose of this glossary is to provide an accessible 'dictionary' of the terms used extensively throughout this thesis and to assist the reader in understanding key concepts. Terms appearing once or twice in isolation are not listed in Table IV, but instead are defined in the footnotes at the bottom of the main text in which they are cited.

Term	Description
Buoyancy-driven flow	The ventilation driven by the buoyancy force arising from differences in air density between the internal and external environments, which in turn are generated by differences in temperature between the internal and external air
Direction number	A dimensionless number which sets the direction of airflow at the upper opening. It is a measure of the strength of the outflowing warm air at the upper opening in resisting the downward flow of cool, denser air from the exterior through the same opening (*cf. Froude number*)
Discharge coefficient (or loss coefficient)	A dimensionless number which captures all of the effects (such as flow contraction and frictional effects) that cause a loss in total pressure as flow passes through an opening. The discharge coefficient represents the ratio of the actual airflow rate (found by measurement in a real flow) through an opening to the flow rate predicted by idealised theory of an inviscid fluid
Displacement flow	A mode of ventilation in which cool air is introduced to a space through low-level openings and 'displaces', but does not mix with, the warmer internal air, which escapes out through openings made at upper levels in the façade (see also *Unidirectional flow*)
Draught	Unwanted air movements within a space associated with rapidly fluctuating airflows
Draught number	A dimensionless number which characterises the 'vigour' of mixing by the inflowing cool air through the lower opening with the warmer indoor air. It is a measure of the relative strengths of the destabilising effect of inertia that drives mixing and the effect of buoyancy that acts to suppress mixing (*cf. Froude number*)
Effective opening area	An area which characterises the resistance an opening poses to the flow (*i.e.* the reduction in the area of the flow path that the airflow takes as it passes through an opening). The effective opening area is dependent on the value of the *discharge coefficient* and the *physical area* of the opening

TABLE IV: List of commonly used terminologies (continued on next page).

Term	Description
Exchange flow (or bidirectional flow)	A term used to describe the simultaneous outflow and inflow of air through the upper opening, whereby warm air from the interior exits the opening and cool air from the exterior enters through the same opening
Froude number	A dimensionless number used in fluid mechanics to characterise the relative importance of inertia and buoyancy in a given flow. The Froude number can also be represented in different forms (see also *Direction number* and *Draught number*)
Heat flux	The rate at which heat is supplied to the interior by sources of heat
Neutral pressure level	The level at which the air pressure inside and outside the enclosure are equal
Rayleigh number	A dimensionless measure of the relative importance of the destabilising effects of buoyancy, which promote convective motion, and the stabilising processes of diffusion and viscosity, which tend to inhibit motion
Reduced gravity	A measure of the density difference between the internal and external air relative to a reference air density (usually taken as the density of the outdoor air). It is used to quantify how buoyant the air inside a space is relative to the outdoor air
Reynolds number	A dimensionless number used in fluid mechanics to describe the nature of fluid flows (*i.e.* laminar or turbulent). It is a measure of the relative magnitudes of the fluid's inertia and viscosity
Stack effect	See *Buoyancy-driven flow*
Stack pressure	The difference in air pressure between the internal and external environments, which provides the primary mechanism for driving airflow through a building. The stack pressure depends mainly upon the temperature difference between the internal and external air and the vertical distance separating the upper and lower openings
Steady state	The condition in which the inward and outward fluxes of volume and heat through an enclosure are in balance. At steady state, there is no change in both the volume flow rate through the openings and the net buoyancy in the enclosure with time
Thermal interface	A 'horizontal plane' separating two air layers comprised of different temperatures (*i.e.* warmer upper layer and cooler lower layer)

TABLE IV: List of commonly used terminologies (continued on next page).

Term	Description
Thermal stratification	The layering of air of different temperatures from the floor to the ceiling, with relatively cooler (denser) air near the floor and warmer (buoyant) air towards the upper region of the space. These air layers of different temperature are separated by interface(s), see *Thermal interface*
Turbulent flow	The motion of a fluid (*e.g.* air) in which the fluid's inertia overcomes the damping effect of the fluid's viscosity, resulting in rapid and irregular fluctuations in velocities and pressures, see *Reynolds number*
Unidirectional flow	A term used to describe the flow of air (and heat) in a single direction through openings, whereby outdoor air is drawn in through lower openings and warm air is expelled out of the interior through upper openings in one sense
Vent apportion	The way in which the total (effective) area of the openings is split between the upper and lower levels in the façade
Vent area ratio	The ratio of the area of the upper opening to the area of the lower opening
Vent location	The position of the openings with respect to the *neutral pressure level* and/or the direction of the prevailing wind (*e.g.* windward or leeward façades)
Ventilation performance	The ability of a natural ventilation system in enhancing the ventilating flow through a given space and/or in satisfying the design requirements for fresh air supply rate and indoor air temperature
Ventilation strategy	A plan by which fresh air is supplied purposefully to the interior for ventilation and cooling (or heating)
Viscosity (of a fluid)	The 'stickiness' of the fluid characterising the resistance of the fluid to flow
Well-mixed interior	The condition in which the heat contained within a space is distributed uniformly throughout so that the temperature is the same everywhere in the space
Wind pressure coefficient	A dimensionless number which reflects how the wind direction, the geometry of the building and its orientation affect the air pressure exerted by the wind on the façade

TABLE IV: List of commonly used terminologies (continued).

Chapter 1

Introduction

Preamble

Concerns about the rise in anthropogenic carbon emissions and the basic desire to conserve the world's resources have contributed to a reawakened interest in, and demand for, naturally ventilated buildings. The challenge from a design perspective centres around harnessing the naturally occurring pressure differences caused by the wind and differences in temperature between the interior and exterior environments to drive a flow of air through a building. A natural ventilation strategy, when suitably designed for and implemented, can lead to significant reductions in energy consumption relative to mechanical ventilation systems (Short & Woods, 2004; Krausse *et al.*, 2007) and can provide tangible improvements to occupant comfort (de Dear & Brager, 2002).

In order to design well-performing and energy efficient naturally ventilated buildings, architects and engineers should work closely together through all stages of a design process. Through collaborative efforts, creative and novel solutions can emerge as both members are actively engaged in relaying knowledge, design ideas and in addressing key problems. Engineers have the expertise to design the structural and ventilation components, while architects have the artistic and utilitarian flair to achieve harmony between the building and its inhabitants.

The key ingredient for successful interdisciplinary collaboration lies in communication. Ideally, each stage of the design process should involve active communication and a systemic understanding between both architects and engineers so that collective decisions can be made at each stage. However, challenges in architect-engineer collaboration may arise – amongst myriad other challenges – due to the contrasting design philosophies, value systems, language conventions, methods of thinking and problem-solving. These differences, inculcated by their prior academic and professional training, may hinder or even restrict cross-disciplinary communication and knowledge exchange in practice.

Whilst tremendous advances have been made over the past two to three decades in the science underlying and explaining the physics of natural ventilation, advances that have strong implications for effective design, the bulk of this material is published in the engineering/scientific journals rather than in the literature more familiar to, and accessible by, the architectural community. Ironically, even the most recent advances may require many years to filter through to the architectural community who, arguably, stand to benefit most directly from them. At best then, a delay is to be expected between a given advancement and its practical uptake and, at worst, the technical nature and terminology used in the scientific literature that conveys these advancements may present an impasse to knowledge transfer between scientific and architectural communities.

As yet, a framework for conveying the essential physics of natural ventilation into formats suitable for an architectural audience has not been proposed explicitly in the open literature and the research dedicated to this interdisciplinary field is thus far, to our knowledge, lacking.

The dearth of this form of research has resulted in an extensive but fragmented and widely dispersed 'extremes' of information on natural ventilation. At one extreme is the specialist literature which explains key developments made in the physics underlying airflows through buildings in great mathematical detail. In sharp contrast is the design-based literature which gives considerable emphasis to the design features/elements of the building. Often only scant information is provided on aspects affecting the physics of ventilation, such as the size and location of openings, which ultimately dictate ventilation flow rates and air temperatures achieved in a building. Thus the need to merge the seemingly disparate streams of information on natural ventilation to suit the needs of architects and the wider building design community is evidently deserving of further study.

The philosophy which underpins this thesis is to bridge what Hawkes (1996) referred to as the "crippling communication barrier between the arts and sciences...". On the basis of 'bridging barriers', however, inevitably leads to certain conflicting pressures on the language and presentation styles, which will impact how information on natural ventilation can be successfully conveyed. On the one hand, the prevalent use of complex mathematical methods and technical notation would likely render the results of any scientific work of limited value to architects, as the relevance of the information to architects' design decision-making is not made evident to them. On the other hand, the over-simplification of mathematical methods would likely jeopardise the credibility of the work, as the essential physics governing natural ventilation flows is 'lost' in the process of simplification. This then raises the question of how can we, as academic researchers in the field of low-energy building ventilation, communicate the key physics of natural ventilation in a viable format that enables architects to understand and apply them without compromising or undervaluing the well-established technical research base?

In order to meet the interests of a broad range of professions, whether this be from architectural or engineering backgrounds, we have strived to communicate the work in this thesis as plainly and straightforwardly as possible using simple terminologies, schematics and simplified mathematical formulae that have the potential for wide acceptance. Whilst we have made the greatest effort in achieving the appropriate tone, there may be certain aspects of the work where, in trying to make the physics more generally comprehensible, our standards fall short of the scholarly researcher, engineer or architect.

At this point, the reader may recognise the inherent irony of this thesis. Conventional technical theses are generally written in a style that is catered to a scientific audience who has already acquired expertise in the specific field of interest. Hence, the authors of such theses are likely to employ an analytical and quantitative mindset to communicate to a technical audience who is expected to share similar frames of mind. The irony of this research lies in the fact that it seeks to explore methods to inform technical researchers and practitioners *how* to communicate the physics of natural ventilation to architects; an audience who not only adopts a completely different set of conventions in which to express themselves, but is also trained to think and solve problems in ways that are unconventional to an engineer. Thus, we have attempted to stand back from the mindset of a 'technical researcher' and have instead sought to convey the work in a way that a 'novice' might wish to read. This places the thesis in a unique position as the style is unconventional to typical scientific writing.

On a final note, this thesis aspires to redress the imbalance in the information transfer on natural ventilation from the engineering/scientific literature to the architectural community and to culminate new insights into ways in which communication barriers can be bridged. Salvadori (1991) epitomises the ethos of the work herein in his eloquent statement:

> *"Let us help architects in their demanding, fascinating, and most needed work by surrounding them with technicians who understand them, but let us also ask them to understand, in their own physical way, their technicians. There is no other way to close the gap."*

1.1 Emergence of schism

Essentially, buildings provide shelter and allow for living in various climates. Before the development of mechanical HVAC (heating, ventilating and air-conditioning) systems, all buildings were naturally ventilated. For example, the hemispherical Arctic igloo, the traditional Yurts of Mongolia and the windcatcher towers of the Middle East (Figure 1.1(a)) all bear witness to man's response to the region's climate.

(a)

(b)

FIGURE 1.1: Examples of the different methods of ventilation employed in traditional domestic and modern commercial buildings: (a) traditional Middle Eastern windcatcher towers ('Badgirs') in Iran designed to channel the wind to ventilate and cool indoor spaces, naturally (photograph taken from Flickr); (b) mechanically ventilated and fully-sealed commercial offices of the Marsham Towers in London, UK (photograph by Malcolm Campbell). The Marsham Towers were completed in 1971 and later demolished in 2003.

Historically, the sciences and the arts have enjoyed a symbiotic relationship in traditional architecture and the roles of what we now regard as the 'architect' and 'engineer' were fused as one. The historic position of the architect-engineer in the Vitruvian sense is one who "seamlessly and simultaneously pursues the goals of function, structure and beauty" (*Utilitas, Firmitas* and *Venustas* in the original Latin). However, with the dawn of the first Industrial Revolution (*circa* 1760 to 1840), engineering emerged as a distinct discipline and separated itself from architecture, the two which historically coexisted together (Billington, 1991; Hawkes, 1996). To cope with the rapid growth in population and the need for higher standards of living, engineers devised new ways of constructing and ventilating buildings. Armed with new systematic methods that could improve building performance, engineers begun to identify architecture as a pure 'art form', which was solely concerned with the aesthetic value of a building (Todesco, 1998). At the same time, architects continued to profess the importance of art in design and tended to view engineers, in Banham's (1960) words, as "noble savages". Indeed, this apparent dichotomy between architects and engineers is also discernible today. For example, at a joint engineering/architectural seminar held in

Paris on the design of bridges on the LGV Méditerranée, Benaim (2002) commented that there was an overall consensus that engineers should "abdicate their aesthetic role; they should practice as technicians, leaving aesthetics to architects".

Owing to the separation of the roles of architects and engineers, however, has meant that academic curricula were required to train both disciplines as specialists to suit their new roles (Scott, 1967; Salvadori, 1991; Benaim, 2002). While engineering education became increasingly technical, architecture drifted further away from the building sciences towards the fine arts (Szokolay, 1994). This has led to an eventual bifurcation in knowledge, in part promoted by the exclusive techniques of teaching. The distinct methods of teaching, housed by the architectural and engineering institutions, have inevitably contributed to the moulding of architects' and engineers' attitudes to knowledge exchange and instilled work habits that are consistent with them. For example, Gann & Salter (2001) commented that:

> *"As each field has become more specialised, they have developed their own language and understanding. They have also guarded entry against what they perceive to be 'external' interests. Demarcation lines have therefore been maintained. This has hindered communication and the transfer of knowledge across disciplinary boundaries."*

It was also during the first Industrial Revolution which saw the founding of many learned societies and professional bodies, such as the Institution of Civil Engineers (ICE) in 1818 and the Royal Institute of British Architects (RIBA) in 1834. These professional bodies provided separate platforms for disseminating information and knowledge primarily for the benefits of their members. Indeed, whilst the emergence of these professional societies have contributed to the enhanced flow of information through organised meetings and journal publications, they may have also furthered the bifurcation of knowledge between engineering and architectural communities.

Concurrently with the growth of professional societies, building regulations emerged to ensure that the relevant legislative policies were carried out. For example, the first Public Health Act in the United Kingdom (UK) was passed in 1848, and has had two major revisions in 1936 and 1961, leading to the first set of national building standards, The Building Regulations in 1965.[1] The key emphasis of the regulations over the major half of the 20th Century was on the provision of ventilation control mechanisms that could guarantee a comfortable, uniform indoor climate.

[1] Over the years, The Building Regulations (such as 'Approved Document F: Ventilation') have had almost yearly amendments and are the principle core of legislation today for buildings in the UK.

Consequently, to satisfy the constraints set out by the regulations, buildings (notably commercial) resorted to standardisation. Mechanical HVAC systems were designed to provide a constant indoor temperature and air quality, regardless of the outdoor conditions. The rejection of the traditional symbiosis between the indoor and outdoor environments was fundamentally challenged: the strive for buildings to connect the interior habitable space to the outside has been superseded with the creation of artificial indoor environments that could be achieved with the ease of a push of a button. The Marsham Towers in London, UK (Figure 1.1(b)), for example, was heralded as a 'modern' and 'state-of-the-art' commercial building for the early 1970s, boasting glass façades, centralised air-conditioning, marble entrances, express lifts and escalators.

Perhaps due to the specialist knowledge required to design mechanical HVAC systems, architects began to abdicate much of the responsibility for the design of building ventilation systems to engineers in exchange for architectural freedom. Since HVAC systems were purposefully designed to deliver a 'guaranteed' air supply rate and indoor temperature for buildings occupants, Todesco (1998) commented that "architects were no longer constrained by the need to ensure that buildings had ample daylighting, remained airy and cool in the summer and warm in the winter" and had the "freedom to pursue unrestricted building designs".

Consequently, the design of buildings that at one time fused both architectural and engineering disciplines evolved into a segregated process. It became customary to regard the building design process as a 'linear' or 'top-down' process (Cooper, 1982*a*; Holm, 1993; Manning, 1995; Ellis & Mathews, 2001), in which architects alone develop the overall design concept, which is then 'fed' to the engineers at the succeeding stages to 'size' the ventilation system. However, Holm (1993) notes that by the time 'calculations' are performed by the engineer, most of the major design decisions made at the earlier stages by the architect have already been 'nailed down', thereby making it difficult for the engineer to modify, or even contribute to, the overall design concept. The separation of the tasks and responsibilities of architects and engineers in a design process, tied in with the differences in their methods of thinking and problem-solving instilled by their prior training and experience, are factors that are all likely to impact architect-engineer communication in practice.

The intention of this introductory section was to provide a general awareness and appreciation of the historical relationship between architects and engineers, and to highlight some of the key events in history that have shaped their current dichotomy. The interdependency of the events discussed also sheds light on the sheer complexity of the 'communication problem' that exists today between the architectural and engineering design communities.

1.2 Motivation

The context and motivation for the work in this thesis – which is expanded upon further in this chapter – can be summarised as follows.

To promote the benefits of natural ventilation: Natural ventilation is a low-energy strategy that has the potential to reduce the energy consumption of a building whilst providing perceptible improvements to the comfort of occupants. We discuss these benefits in greater detail in §1.2.1.

To overcome communication barriers: The design of naturally ventilated buildings should ideally involve the collaborative input of both architects and engineers through all stages of a building design process. However, cultivating an environment of mutual understanding, open communication and a commitment to shared goals between both professions may prove challenging. In §1.2.2 we discuss some of the barriers to communication between architects and engineers, and the possible implications of these in a design process.

To address the technical challenge: A fundamental challenge faced by architects and engineers in the design of naturally ventilated buildings is to determine the suitable size and location of openings that will provide the necessary ventilation. This task is further complicated as the comfort of occupants must also be considered. Confident and well-informed decisions in a design process therefore calls for an understanding of the underlying physics that control rates of airflow and indoor temperatures to ensure that adequate ventilation is delivered to all parts of the building. Simplified mathematical models – based on the fundamental physics governing air and heat flows through buildings – have been proven particularly useful not only for identifying key variables that affect ventilating flows, but also for informing early stage design decisions, such as the size and location of ventilation openings. We highlight some of the key benefits of simplified mathematical models in §1.2.3.

To bridge the literature gap: Particularly in the early design stages, architects need to acquire accurate information on natural ventilation as decisions made in these stages often determine the major thermal and ventilation characteristics of a building. However, current advancements in the understanding of numerous fundamental aspects of natural ventilation, essential information for design, are published in the engineering/scientific literature rather than in the literature more directly accessible to architects. We discuss the need to improve the transfer of information from the technical literature to practising architects in §1.2.4.

1.2.1 To promote the benefits of natural ventilation

Building energy consumption

Currently, the bulk of the cooling and heating demands are met by mechanical HVAC systems, which require an input of energy (*e.g.* electricity) in order to operate heat pumps, compressors and fans. In the European Union (EU), buildings alone (commercial and residential) account for approximately 40% of the total primary energy consumption per year, more than half of which is expended on the heating and cooling of buildings (Pérez-Lombard *et al.*, 2008; European Commission, 2015). The reliance on HVAC systems not only has undesirable implications in terms of building energy consumption, but also contributes to greenhouse gas emissions and is therefore seen as a significant contributor to global warming. According to the Committee on Climate Change (2013), buildings in the UK contribute to approximately 43% of the total primary energy consumption across all sectors, accounting for an estimated 37% of greenhouse gas emissions in 2012.

With the expected rise in global temperatures associated with climate change could mean that, even in relatively mild climate, modern buildings are likely to require additional cooling more often than heating. In Switzerland, for example, where the climate is broadly similar to that in the UK, Christenson *et al.* (2006) predict over a ten-fold increase in the energy demand for cooling of buildings in the coming decades.

In response to the growing concerns over the energy consumption of buildings and the associated greenhouse gas emissions, there has been an intense focus on developing low-energy strategies for ventilating buildings. This has been given further momentum by the various environmental treaties being ratified internationally, such as the United Nations Framework Convention on Climate Change which established the Kyoto Protocol in 1997 and the Paris Agreement in 2015. Following the Paris Agreement, current energy policy and legislation in the UK is committed to reducing greenhouse gas emissions by 80% relative to 1990 baseline levels by 2050.

Natural ventilation offers a potential solution for reducing greenhouse gas emissions from buildings and can be an important plank of the UK's carbon reduction strategy. Used as part of a low-energy design and operating strategy, natural ventilation has already been proven to be an effective approach for reducing building energy expenditure whilst providing measurable comfort improvements for occupants. The Frederick Lanchester Library in Coventry, UK, is an example of a naturally ventilated building that has been reported by Krausse *et al.* (2007) to consume less than half the energy of an equivalent mechanically ventilated building. The CH2 Building in Melbourne, Australia – which exploits a mixed-mode ventilation system – has been awarded with a six Green Star rating and is in the top 20% of buildings for occupant satisfaction in Australia (Birt & Newsham, 2009). It is also of note that this building benefitted from the collaborative teamwork of both architects (*e.g.* Koen Steemers and Mick Pearce) and engineers (*e.g.* Gary R. Hunt) on the ventilation and lighting control at the key early stages in design (personal communication, Gary R. Hunt); this, in turn, reinforces the importance of architect-engineer collaboration in a design process.

Comfort, well-being and productivity

Rather than recirculating the air within a building, natural ventilation systems necessarily supply occupants directly with fresh air from the outdoors and have been shown to offer benefits for perceived productivity and overall well-being. In a review of Post Occupancy Evaluations, Seppänen & Fisk (2001) estimated that, compared to air-conditioned buildings, occupants in naturally ventilated buildings are approximately 80% less likely to suffer from 'Sick Building Syndrome' (SBS) – a condition typically marked by headaches, fatigue, irritation to the eyes and throat and other respiratory problems (World Health Organization, 1983). Robertson *et al.* (1990) and Burge (2004) reported that SBS-related symptoms can lead to reduced productivity levels and increased absenteeism in the workplace.

The direct link to the outdoor environment afforded by naturally ventilated buildings also offers additional benefits that may extend to occupants' perception of comfort. In a review of thermal comfort field studies, de Dear & Brager (2002) note that occupants in naturally ventilated buildings are more likely to adapt to, and thereby tolerate, a wider range of indoor temperatures compared to occupants in centrally-controlled air-conditioned buildings. This may be partly attributed to the expectation of a wider variability in temperatures within naturally ventilated buildings, but may also be linked to higher levels of perceived control. Results of Post Occupancy Evaluation surveys (Leaman & Bordass, 2007; Deuble & de Dear, 2012) indicate that occupants of naturally ventilated buildings are able forgive minor discomforts more readily, provided they can exercise a modicum of personal control over their thermal environment.

1.2.2 To overcome communication barriers

In order to design well-performing naturally ventilated buildings, it is imperative for architects and engineers to collaborate and work closely together through all stages of a design process. This is particularly important for meeting functional, structural and aesthetic goals, for ensuring the relevant Building Regulations or codes of practice are adhered to, and for achieving overall design coherence. Despite the importance of interdisciplinary collaboration, working together and sharing knowledge with experts outside one's own discipline may not always be natural, or straightforward, in a practical setting. Differences in personalities as well as pedagogical and professional upbringing all influence how architects and engineers think and approach their work; these ingrained differences in turn drive, dictate and ultimately determine the success of collaboration. In this section we describe some of the key differences in the way architects and engineers think and solve design problems, and how these differences affect collaboration in a building design process.

Contrasting thought processes and methods of problem-solving

As mentioned earlier, the separation of engineering and architecture as distinct disciplines emerged during the first Industrial Revolution. Concurrently, academic curricula and methods of their delivery in engineering and architectural institutions also diverged over time. While engineering curricula drifted towards a more technically-focussed nature, Peters (1991), Szokolay (1994) and Olsen & Mac Namara (2014)[2] point out that most architectural programmes, most notably in the UK and the United States, often shy away from the formal mathematics and buildings physics, giving greater priority to design studios and 'soft' subjects, such as psychology, art and history, which are considered to support 'creative thinking'. This aspect is also highlighted by Salingaros & Masden II (2008) who commented that architectural education focusses predominately on teaching students to break out of any evidence-based knowledge that would "prevent them from freely exploring the supposed boundless intellectualised expression of contemporary architecture". The role of science in architecture is evidently fading and is even reflected in changes of its definition in the English language: the 1951 edition of the Concise Oxford Dictionary defined architecture as the "science of building", and the current (2011) definition is modified to "the art or practice of designing and constructing buildings".

There is little doubt that the training engineering and architectural students receive early in their academic career has instilled distinct ways of thinking and problem-solving that are carried forward and applied in design. Peters (1991) generalises how engineers use abstract models to quantify characteristics of physical phenomena in mathematical form, while architects employ visual language to translate their conceptual ideas into graphical notation. Raisbeck & Tang (2009, cited in Collins 2014, p. 10) continues this theme, suggesting that architects tend to organise their knowledge through visually-dominated means such as sketches and drawings. This dominance of visual values is unsurprising given the nature of architectural work is firmly rooted in the visual arena of perception and imagery.

[2] Olsen & Mac Namara (2014) note that schools of architecture in Europe, particularly German and Swiss schools, have "more significant mathematics requirements for entry and focus on more technical courses within the programmes" compared to the United States. They also argue that the 'informal' approaches to education in the US have contributed to the "European dominance in technologically innovative architecture."

In a study investigating the different problem-solving processes of architecture and engineering students, Lawson (2005) reported that architectural students approached the task by a willingness to propose solutions, and only after deciding on a solution did they analyse it for underlying principles; the emphasis was on the achievement of a desired result or the final 'product', as opposed to a critical investigation of the complexity of the problem they faced.[3] In contrast, engineering students proceeded in a systematic manner when analysing the problem and sought to understand the underlying principles prior to offering a solution.

In this sense, the way architects and engineers approach design problems can be viewed in the light of Hudson's (1968) systems of 'divergent' and 'convergent' thinking. Architects are inherently 'divergent' thinkers whose thinking processes are inextricably bound to intuition, whereby creative ideas are generated by exploring many possible solutions. Engineers on the other hand are 'convergent' thinkers whose thinking processes are characterised by a logical, analytical approach to problem-solving, which allows for a systematic derivation to an answer (Peters, 1991). Although answers to specific design questions may be provided to the architect eventually by the engineer, the route to which the solution is approached may prove to be unattractive and time-consuming for the architect.

Segregated design process

The contrasting systems of thinking and approaches to problem-solving employed by architects and engineers may offer a possible explanation as to why a building design process has oftentimes been referred to as a 'top-down' process, as mentioned in §1.1. In such a process, the involvement of the architect and engineer occurs in a sequential manner at different stages in the process. Figure 1.2 shows a top-down design process for natural ventilation grouped into four key stages: Conceptual design (Stage 1), Basic design (Stage 2), Detailed design (Stage 3) and Design evaluation (Stage 4). A detailed overview of the key stages of a natural ventilation design process, including a description of the experimental, theoretical and numerical techniques available to tackle issues arising in each stage, is given in Heiselberg (2004) and Etheridge (2011). The key stages shown in Figure 1.2 also broadly align with the stages described in RIBA Plan of Work (2020), which provides a roadmap for architects, engineers and consultants to use on building projects.

The design process begins with Conceptual design (Stage 1). This stage typically involves identifying clients' requirements, developing an overall building concept and generic appearance (such as building form, size and shape), and exploring the type of ventilation strategy

[3]This cognitive style most likely stems from the teaching practices in architectural schools, whereby students learn through a series of design studios in which the critiques they receive are mostly based on 'solution-focussed' criticisms rather than on the methodology they have used (Altomonte, 2009). Altomonte (2009) commented that this approach to teaching hinders the development of critical thinking amongst architectural students and favours the "mere, albeit often short-lived, acquirement of information."

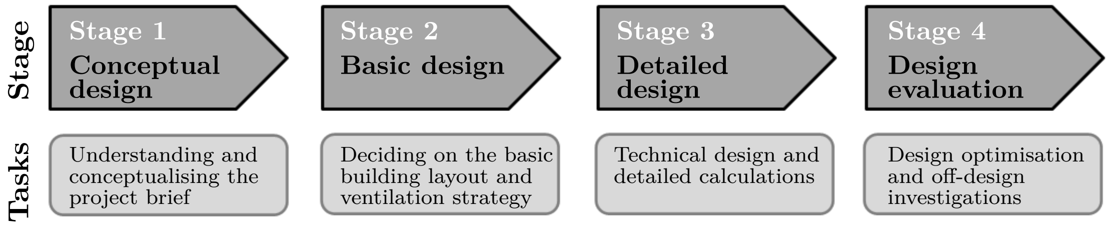


FIGURE 1.2: Natural ventilation design process showing the key stages and tasks carried out at each successive stage.

to employ. Conceptual design is an iterative process, whereby an assemblage of various ideas regarding the overall concept are explored and modified several times before narrowing down towards a more well-defined concept that fulfils the project's criteria (*i.e.* involves a divergent thought process). The next stage is Basic design (Stage 2). At this stage, key variables influencing the ventilation (such as internal heat gains and wind loads on the building, see Figure 1.3) are identified and the overall design concept and ventilation strategy are developed further. It is also the stage where the required vent sizes need to be determined in order to ensure the intended ventilation is achieved (*i.e.* involves a convergent thought process).

In a top-down design process, the early design stages (Stages 1 and 2) are typically dominated by the architect and input from the engineer is often limited (Torcellini *et al.*, 1999; Herbert, 1999; Hayter *et al.*, 2000; Ellis & Mathews, 2001; Charleson & Pirie, 2009). In these early stages, the architect liaises directly with the client and prepares sketches of the envisaged building layout and ventilation strategy that fulfils the project brief. Ellis & Mathews (2001) emphasise that the decisions made at the early stages lay the foundation of the overall building design and that all subsequent design calculations are based on these decisions. However, Charleson & Pirie (2009) note that, particularly at the early stages, architects require design flexibility and freedom, and that early involvement of the engineer could prematurely stifle architects' creative explorations. The activities performed by the architect have been likened to a "black box", in which courses of action – clear of disruption by potentially overbearing engineering advice – are driven largely by intuition, as it is often perceived as a creative way of seeking 'original' and 'unique' building designs (Manning, 1995).

Once the architect and client have settled on a building design concept, the engineer is then asked to provide the necessary 'inputs' according to the agreed concept. Consequently, the involvement of the engineer takes place in the later stages (Stages 3 and 4), or at best, the latter part of Stage 2. In these later stages, the proposed building design is analysed by employing modelling/simulation tools to predict and evaluate the performance of the ventilation system. However, by the time calculations/simulations are performed, the engineer is already tightly bounded by the earlier agreed upon choices made by the architect. As a consequence, any potential modifications or attempts to rectify choices made at the early stages are subsequently 'added on'. Hardy (1971, cited in Cooper 1982*b*, p. 273) elaborates:

> *"The traditional design process was such that the architect produced a basic design scheme, which was then handed over to a structural engineer who designed a suitable structure. A heating and ventilating engineer then designed the thermal plant... In all these stages the design decisions made by the specialists had already been severely restricted by the [architect's] original design."*

Evidently, architects are an essential link in the design of efficient naturally ventilated buildings. Specifically at the early design stage, architects require accurate and accessible information on ventilation principles so that informed decisions can be made before important building characteristics are frozen. Ideally, the information needs to be coupled with guidance for ventilation in a form that enables a rapid and straightforward predictive capability so that vent areas, airflow rates and indoor temperatures can be estimated to ensure that ventilation and comfort targets are met. This form of guidance is crucial, as early stage decisions made by the architect are often carried through the design process, which can potentially impact the overall building design and its performance.

1.2.3 To address the technical challenge: an engineer's approach

One of the key challenges in the early stages of a natural ventilation design process is to determine the size and location of the openings that will provide the necessary airflow rate and indoor temperature. This is indeed challenging, as the factors affecting air and heat flows through buildings are complex, highly variable and often difficult to predict and control. Wind speed and direction can vary extensively and outdoor air temperatures can change both on diurnal and seasonal scales. Internal heat gains may vary by orders of magnitude depending on the occupant density and activity, the material composition of the building fabric, and incidental gains from electrical equipment, solar radiation and so on. Moreover, sources of heat often have different geometries, strengths and locations within a space, leading to complex airflow patterns and thermal stratification. Figure 1.3 shows some of the variables that affect indoor air temperatures and rates of air exchange with the outdoor environment.

Whilst the set of 'variables' shown in Figure 1.3 is by no means exhaustive, Figure 1.3 clearly depicts the inherent complexity of a natural ventilation system and the challenge for

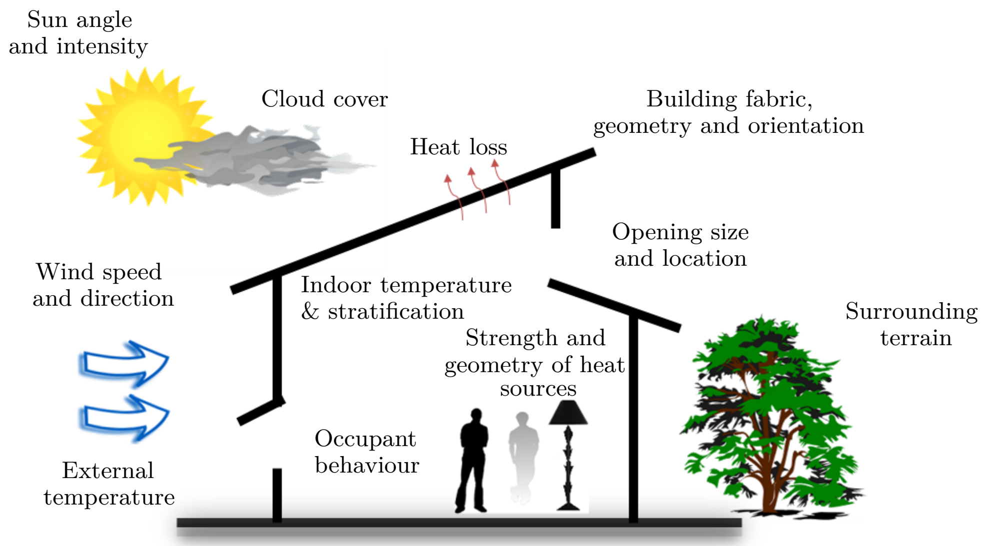


FIGURE 1.3: Simplified illustration of an example naturally ventilated building showing some of the variables which play a role in the design and performance of a natural ventilation system. Illustration inspired by Ward (2004) and Acred (2014).

architects and engineers when devising a natural ventilation strategy. There is a spectrum of theoretical, experimental and numerical modelling tools that are available to tackle this challenge. These tools range from the 'simplified' mathematical models to the highly 'detailed' using computational fluid dynamics (CFD). Although each type of modelling tool can provide valuable insight into the behaviour of ventilation flows in buildings, it is important to note that the results should be interpreted with caution and that their use must come in tandem with an understanding of the inherent limitations of the particular tool being used.

We stress that it is not our intention here to discuss the merits, or otherwise, of the different modelling tools; this has already been discussed elsewhere in the literature, *e.g.* Hitchin & Wilson (1967), Linden (1999), Castro & Graham (1999), Li & Heiselberg (2003), Chen (2009), Omrani *et al.* (2017). Rather, we wish to provide a strong physical basis for the use of a simplified mathematical model as the most promising approach to meet the objectives of this research (§1.3). In the following section, we briefly highlight some of the key attributes of simplified mathematical models that make them an extremely powerful investigative and qualitative tool for informing early stage design.

Benefits of simplified mathematical models

Although not able to capture the same level of detail as CFD[4], simplified mathematical models necessarily translate a physical problem (involving the flow of air and heat in buildings) into a tractable mathematical description of the ventilation flow through a set of appropriate (and justifiable) assumptions, while still retaining the essential physics of the flow. The model is simplified in the sense that it does not provide detailed predictions of the airflow velocities and indoor air temperatures at various locations within the space. Rather, it enables 'bulk' quantities of the ventilation, such as room air temperatures, airflow rates and flow speeds at openings to be predicted. These quantities, typically of primary interest to architects (and ventilation engineers) at the early design stage, can be deduced in terms of the geometry of the room (*e.g.* vent areas and room height) and the strength of the heat source(s), for example. As such, simplified mathematical models are capable of elucidating some of the key relationships between design variables that are not immediately clear from a CFD investigation (Castro & Graham, 1999). Moreover, unlike the results generated from a CFD simulation (which, typically, are specific to a given building design), analytical expressions obtained from simplified mathematical models allow a given ventilation strategy to be applied to a wide range of buildings with a similar generic geometry and relative heat input distribution, thereby broadening their appeal and applicability for use in preliminary design.

The benefits of a simplified mathematical model, therefore, are clear: it provides an extremely powerful tool for gaining an intuitive understanding of the behaviour of airflows in buildings and can be seen as an important vehicle for supporting communication between architects and engineers in design; this, in turn, provides the rationale for our simple mathematical approach herein, which we return to discuss in more detail in §1.3.2.

1.2.4 To bridge the literature gap

Undeniably, the challenges faced by architects and engineers in a building design process are complex and require an understanding of the physics that underlie ventilating flows, as well as other skills and expertise related to building design. As reasoned in §1.2.2, it is essential for architects to acquire accurate and intuitive information on ventilation

[4]One of the major advantages of CFD over simplified mathematical models is the ability to provide high-resolution predictions of indoor flow patterns, such as time-varying airflow velocities and temperature distributions at different locations of interest. This information, typically stored as data files, can be transformed into graphical formats, which can provide a visually straightforward way of illustrating airflow patterns within a room. For example, colour maps showing the spatial variation of room air temperatures, and arrows depicting the direction and speed of the airflow are typical outputs from a CFD simulation (see, for example, Assimakopoulos *et al.* (2008)). Due to the inherent flexibility of CFD, however, the use of such a tool requires a clear understanding of the fluid mechanics appropriate to the flow under consideration to ensure reliability of results. Castro & Graham (1999) discussed the main limitations of CFD in a wind engineering context and reported that the results from CFD vary considerably with the choice of turbulence closure model, domain size, boundary conditions and meshing details.

principles early on in a design process when critical project-shaping decisions are being made. Well-balanced and informed professional judgement in the early stages is dependent upon the direct access to disciplinary information, whether this be through the knowledge exchange between architects and engineers in a design process or the use of scholarly research publications.

Over recent decades, demand has outstripped our understanding of how naturally ventilated buildings truly operate and a number of open questions regarding establishing and controlling airflows in these spaces have motivated considerable, and indeed ongoing, research. Certainly within the academic research community, the growth of interest in natural ventilation is strikingly evident. Over the past thirty years, for example, there has been in excess of a five-fold increase in the annual number of peer-reviewed documents published on the topic. A clear indication of this trend is evident in Figure 1.4, which plots the number of documents (including articles, conference papers, books and annual reviews with citations registered in bibliometric indexing databases) published worldwide between 1986 and 2016, with both "natural ventilation" and "building" appearing in the title, abstract, or keywords. To generate the plot in Figure 1.4, we have opted for *Scopus* since, at the time of writing, it is claimed to be the largest abstract and citation database of peer-reviewed literature.

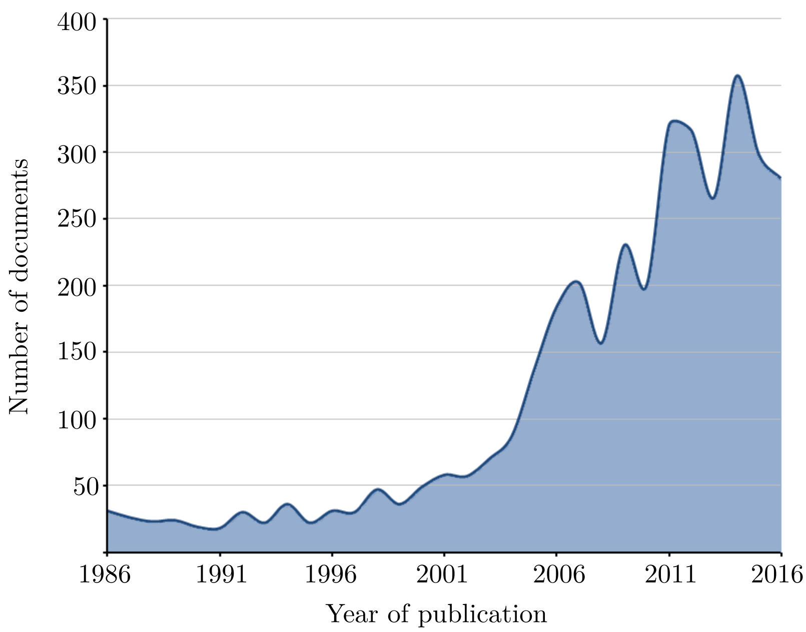


FIGURE 1.4: The number of documents published on the topic of natural ventilation between 1986 and 2016. Documents include articles, conference papers and books (Graph credit: Scopus (2017)).

The pie chart in Figure 1.5 shows the percentage of published documents on the topic of natural ventilation (from 1986 to 2016) based on the subject area of a particular journal (for example, the subject area of the journal titled 'Journal of Fluid Mechanics' is 'Engineering'). Although the subject area 'Architecture' cannot be singled out exclusively in *Scopus*, as evidenced in Figure 1.5, there is a noticeable difference in the percentage of publications between 'Engineering' and other subject areas.

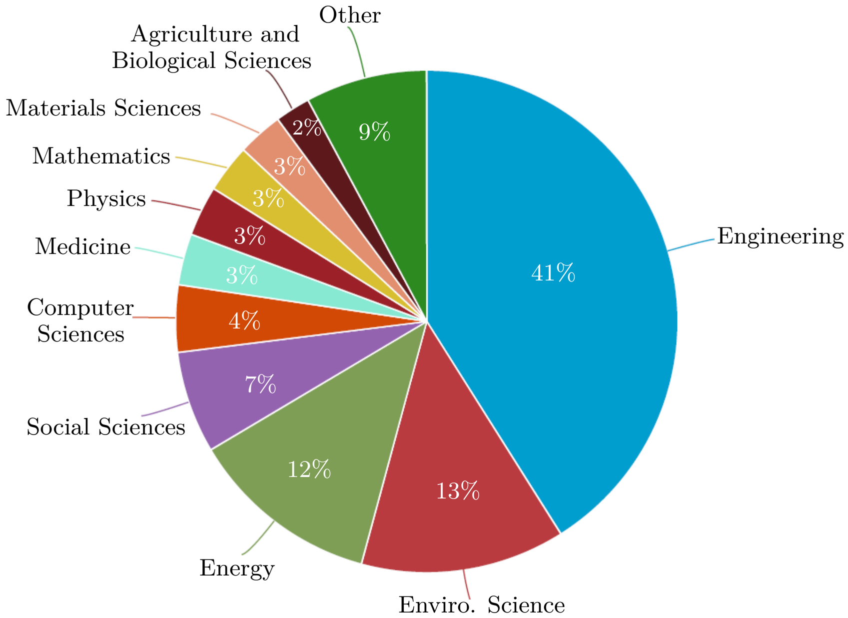


FIGURE 1.5: Pie chart showing the percentage of publications on the topic of natural ventilation (between 1986 and 2016) based on the subject area of the publication's title (Graph credit: Scopus (2017)).

On closer inspection of the individual segments of the pie chart, it appears that there is also a mismatch in the number of articles on natural ventilation published in the 'technical-based' journals and those journals that focus primarily on topics related to aspects of architecture/building design. The *Analyse Search Results* tool in *Scopus* indicates that approximately 1500 articles are published in the technical-based journals, with the most popular being: 'Building and Environment', 'Energy and Buildings' and 'International Journal of Ventilation'.[5] In contrast, approximately 500 articles are published in the 'design-based' journals, with the most popular being: 'ASHRAE Journal', 'Architecture Science Review' and 'Building Research and Information'. This apparent mismatch in the number of articles may have been the result of a delay in the translation and dissemination of research findings from the technical journals to journals that are more directly accessible to an architectural audience. Whilst technical publications in academic journals have an important role in

[5]We note that 'Building and Environment', 'Energy and Buildings' and 'International Journal of Ventilation' are interdisciplinary journals which cover a broad spectrum of research topics, ranging from the complex fluid dynamics of building ventilation to case studies on human comfort, for example.

enhancing the understanding of building ventilation flows, the amount of time spent by academics on research (*e.g.* developing novel experimental and mathematical models) and the exclusive focus on publishing in 'recognised' journals affiliated with their specialism may, perhaps, be disproportionately greater than the time spent on conveying their findings to practitioners outside their professional field. Moreover, the length of the peer-review process (*i.e.* from submission to publication) exacerbates this issue further, as the delay slows the dissemination of scholarly research.

Examples of technical- and design-based literature

The following example excerpts have been deliberately chosen to contrast some of the typical presentation styles commonly found in the 'technical-based' and 'design-based' literature. Figures 1.6 and 1.7 are excerpts taken directly from Hunt & Linden (2001) and Thomas (2006), respectively; the former is from an article published in an engineering/scientific journal (Journal of Fluid Mechanics), while the latter is from a book targeted specifically for practitioners with interest in low-energy building design. Whilst these excerpts are isolated examples, they are broadly representative of the presentation styles (*e.g.* the terminologies and graphical notation employed) of information on natural ventilation that are commonplace in the technical- and design-based literature.

Figure 1.6 exemplifies the typical presentation style of articles published in the engineering/scientific journals. The content of the work necessarily involves a detailed description of 'technical-based' research breakthroughs, specifically the development of novel theoretical and experimental models for examining and predicting ventilation flow behaviour in buildings. The use of small-scale laboratory experiments, in particular those involving salt-in-water (also known as the "salt-bath technique"), to complement and validate the predictions from theoretical models, are also common and have a long-standing pedigree in fluid mechanics (*e.g.* Baines & Turner (1969), Baines (1975), Epstein (1988), Linden *et al.* (1990), Cooper & Linden (1996), Hunt & Linden (2001), Hunt & Coffey (2010)).

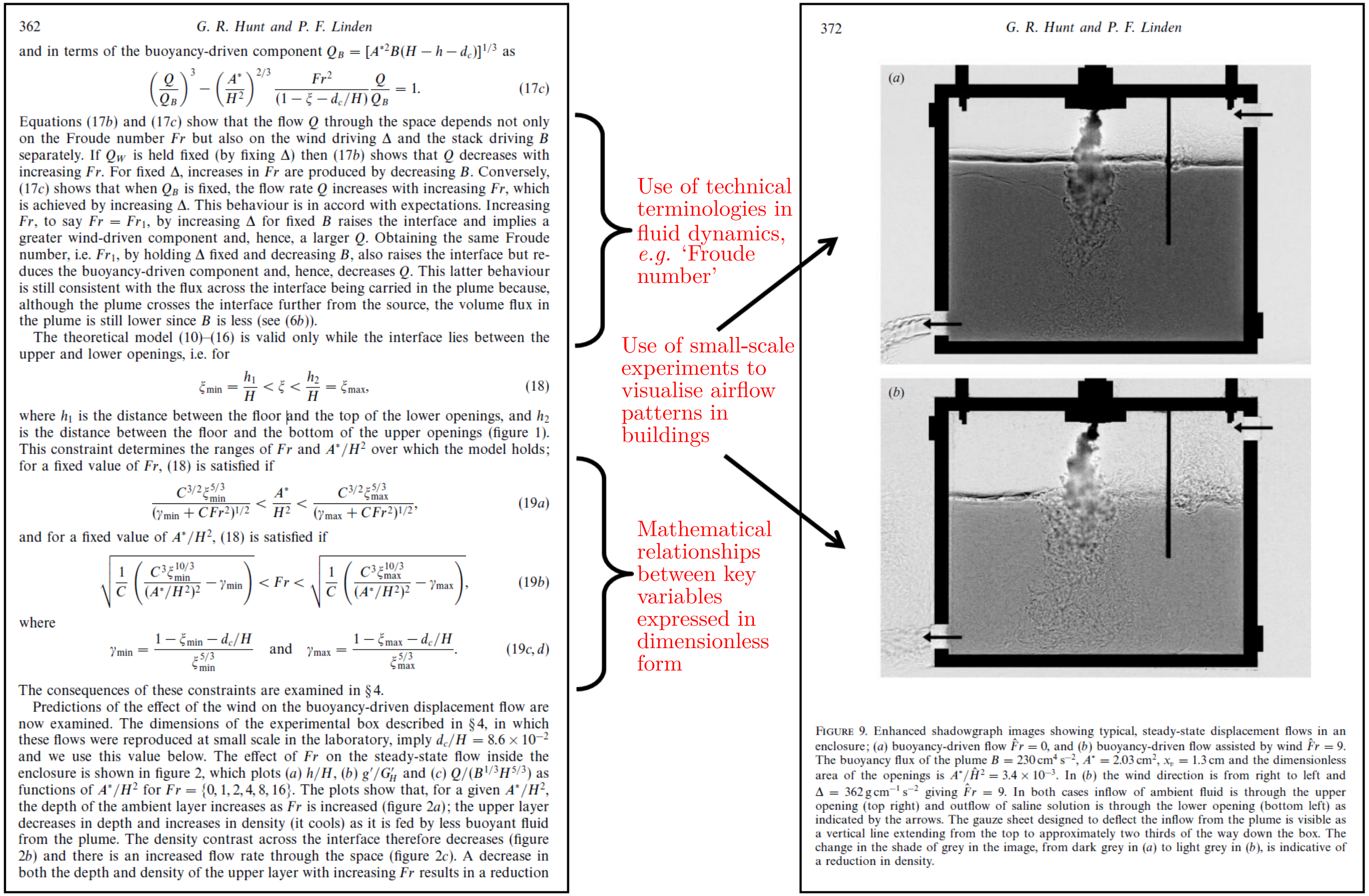
The excerpt in Figure 1.6 shows 'snapshots' of the small-scale experiments of Hunt & Linden (2001) who used the salt-bath technique to simulate the flow of air and heat in a room in the presence of an assisting wind. They used a transparent (impervious) Perspex box, with fixed internal dimensions, to represent the room, and a number of circular holes were made in the 'roof' and 'floor' of the box to represent ventilation openings. The box was suspended in a large visual flume, which recirculated freshwater to represent the flow of wind around the building. In order to simulate heat inputs (arising from localised sources, such as occupants), salt solution was injected at a constant rate through a circular nozzle positioned at the top of the box. The resulting flow within the model building was then visualised by adding coloured dye to the salt solution, and by using a shadowgraph to enhance the visualisation of density variations and airflow patterns as well as fine-scale structures in the flow. This technique, using salt-in-water to simulate natural ventilation flows at small-scale, is described in greater detail in Baker & Linden (1991) and Partridge & Linden (2013), both of whom demonstrate that the ventilation flows developed using the aforementioned technique are dynamically similar to those in real buildings. In addition to isolating and detecting specific airflow phenomena, visualisation of the (otherwise invisible) motion of ventilation flows through buildings can provide a highly powerful way of illustrating flow patterns to designers. Moreover, as dynamical similarity is achieved, this small-scale modelling technique enables airflow behaviour to be predicted at full-scale (*e.g.* by measuring the height of the interface and the difference in density between the ambient fluid and the salt layer within the box, quantitative predictions of ventilation flow rates and equivalent temperature differences can be deduced).

However, despite the potential for enabling and guiding effective ventilation designs, the information contained in technical publications is necessarily couched in scientific terminology and mathematical notation as specialist engineers and fluid dynamicists are the target audience. Thus, isolated from an architectural context, most technical-based publications are likely to be of interest to, and read predominantly by, individuals with expertise in the sciences/engineering rather than architects.

The presentation style of 'design-based' information is typified by the excerpt in Figure 1.7. Evidently, this style is in marked contrast to the style shown in Figure 1.6. Rather than of a technically-orientated nature, ventilation 'principles' are conveyed using relatively simple terminologies and visual illustrations.[6] The emphasis is placed on providing general guidance and 'rules-of-thumb' for tackling problems commonly encountered in design, as opposed to a detailed investigation of the fluid mechanics underlying the ventilation. For example, the excerpt of Thomas (2006) in Figure 1.7 illustrates the necessary formulae for calculating the ventilation flow rate through a simple room depending on whether the flow is buoyancy-driven or wind-driven, albeit the interpretation or derivation of the formulae and their origin are not explicitly shown.

Indeed, most (if not all) design guidance stems directly from the technical research base. The excerpt of Thomas (2006) in Figure 1.7 may, for example, be regarded as a 'translation' of the original work by Hunt & Linden (2001) on wind-assisted natural ventilation flows, albeit presented in a predominantly visual form. This particular style of presentation, a familiar

[6] One may find pages in technical-based articles similar to Figure 1.7, particularly the aspect of the article that makes reference to real world applications of a new theory. For example, a single storey building (or room) is often represented as a 'box-like' enclosure, which is widely used in the mathematical analyses of room airflows, *e.g.* Linden *et al.* (1990), Hunt & Linden (2001), Hunt & Coffey (2010).


362 G. R. Hunt and P. F. Linden

and in terms of the buoyancy-driven component $Q_B = [A^{*2}B(H-h-d_c)]^{1/3}$ as

$$\left(\frac{Q}{Q_B}\right)^3 - \left(\frac{A^*}{H^2}\right)^{2/3} \frac{Fr^2}{(1-\xi-d_c/H)}\frac{Q}{Q_B} = 1. \qquad (17c)$$

Equations (17*b*) and (17*c*) show that the flow Q through the space depends not only on the Froude number Fr but also on the wind driving Δ and the stack driving B separately. If Q_W is held fixed (by fixing Δ) then (17*b*) shows that Q decreases with increasing Fr. For fixed Δ, increases in Fr are produced by decreasing B. Conversely, (17*c*) shows that when Q_B is fixed, the flow rate Q increases with increasing Fr, which is achieved by increasing Δ. This behaviour is in accord with expectations. Increasing Fr, to say $Fr = Fr_1$, by increasing Δ for fixed B raises the interface and implies a greater wind-driven component and, hence, a larger Q. Obtaining the same Froude number, i.e. Fr_1, by holding Δ fixed and decreasing B, also raises the interface but reduces the buoyancy-driven component and, hence, decreases Q. This latter behaviour is still consistent with the flux across the interface being carried in the plume because, although the plume crosses the interface further from the source, the volume flux in the plume is still lower since B is less (see (6*b*)).

The theoretical model (10)–(16) is valid only while the interface lies between the upper and lower openings, i.e. for

$$\xi_{min} = \frac{h_1}{H} < \xi < \frac{h_2}{H} = \xi_{max}, \qquad (18)$$

where h_1 is the distance between the floor and the top of the lower openings, and h_2 is the distance between the floor and the bottom of the upper openings (figure 1). This constraint determines the ranges of Fr and A^*/H^2 over which the model holds; for a fixed value of Fr, (18) is satisfied if

$$\frac{C^{3/2}\xi_{min}^{5/3}}{(\gamma_{min}+CFr^2)^{1/2}} < \frac{A^*}{H^2} < \frac{C^{3/2}\xi_{max}^{5/3}}{(\gamma_{max}+CFr^2)^{1/2}}, \qquad (19a)$$

and for a fixed value of A^*/H^2, (18) is satisfied if

$$\sqrt{\frac{1}{C}\left(\frac{C^3\xi_{min}^{10/3}}{(A^*/H^2)^2}-\gamma_{min}\right)} < Fr < \sqrt{\frac{1}{C}\left(\frac{C^3\xi_{max}^{10/3}}{(A^*/H^2)^2}-\gamma_{max}\right)}, \qquad (19b)$$

where

$$\gamma_{min} = \frac{1-\xi_{min}-d_c/H}{\xi_{min}^{5/3}} \quad \text{and} \quad \gamma_{max} = \frac{1-\xi_{max}-d_c/H}{\xi_{max}^{5/3}}. \qquad (19c,d)$$

The consequences of these constraints are examined in §4.

Predictions of the effect of the wind on the buoyancy-driven displacement flow are now examined. The dimensions of the experimental box described in §4, in which these flows were reproduced at small scale in the laboratory, imply $d_c/H = 8.6\times10^{-2}$ and we use this value below. The effect of Fr on the steady-state flow inside the enclosure is shown in figure 2, which plots (*a*) h/H, (*b*) g'/G'_H and (*c*) $Q/(B^{1/3}H^{5/3})$ as functions of A^*/H^2 for $Fr = \{0, 1, 2, 4, 8, 16\}$. The plots show that, for a given A^*/H^2, the depth of the ambient layer increases as Fr is increased (figure 2*a*); the upper layer decreases in depth and increases in density (it cools) as it is fed by less buoyant fluid from the plume. The density contrast across the interface therefore decreases (figure 2*b*) and there is an increased flow rate through the space (figure 2*c*). A decrease in both the depth and density of the upper layer with increasing Fr results in a reduction

372 G. R. Hunt and P. F. Linden

(*a*)

(*b*)

FIGURE 9. Enhanced shadowgraph images showing typical, steady-state displacement flows in an enclosure; (*a*) buoyancy-driven flow $\hat{F}r = 0$, and (*b*) buoyancy-driven flow assisted by wind $\hat{F}r = 9$. The buoyancy flux of the plume $B = 230\,\mathrm{cm^4\,s^{-2}}$, $A^* = 2.03\,\mathrm{cm^2}$, $x_v = 1.3$ cm and the dimensionless area of the openings is $A^*/\hat{H}^2 = 3.4\times10^{-3}$. In (*b*) the wind direction is from right to left and $\Delta = 362\,\mathrm{g\,cm^{-1}\,s^{-2}}$ giving $\hat{F}r = 9$. In both cases inflow of ambient fluid is through the upper opening (top right) and outflow of saline solution is through the lower opening (bottom left) as indicated by the arrows. The gauze sheet designed to deflect the inflow from the plume is visible as a vertical line extending from the top to approximately two thirds of the way down the box. The change in the shade of grey in the image, from dark grey in (*a*) to light grey in (*b*), is indicative of a reduction in density.

FIGURE 1.6: Excerpts taken from the journal article by Hunt & Linden (2001), highlighting the style and format typically found in the technical-based literature.

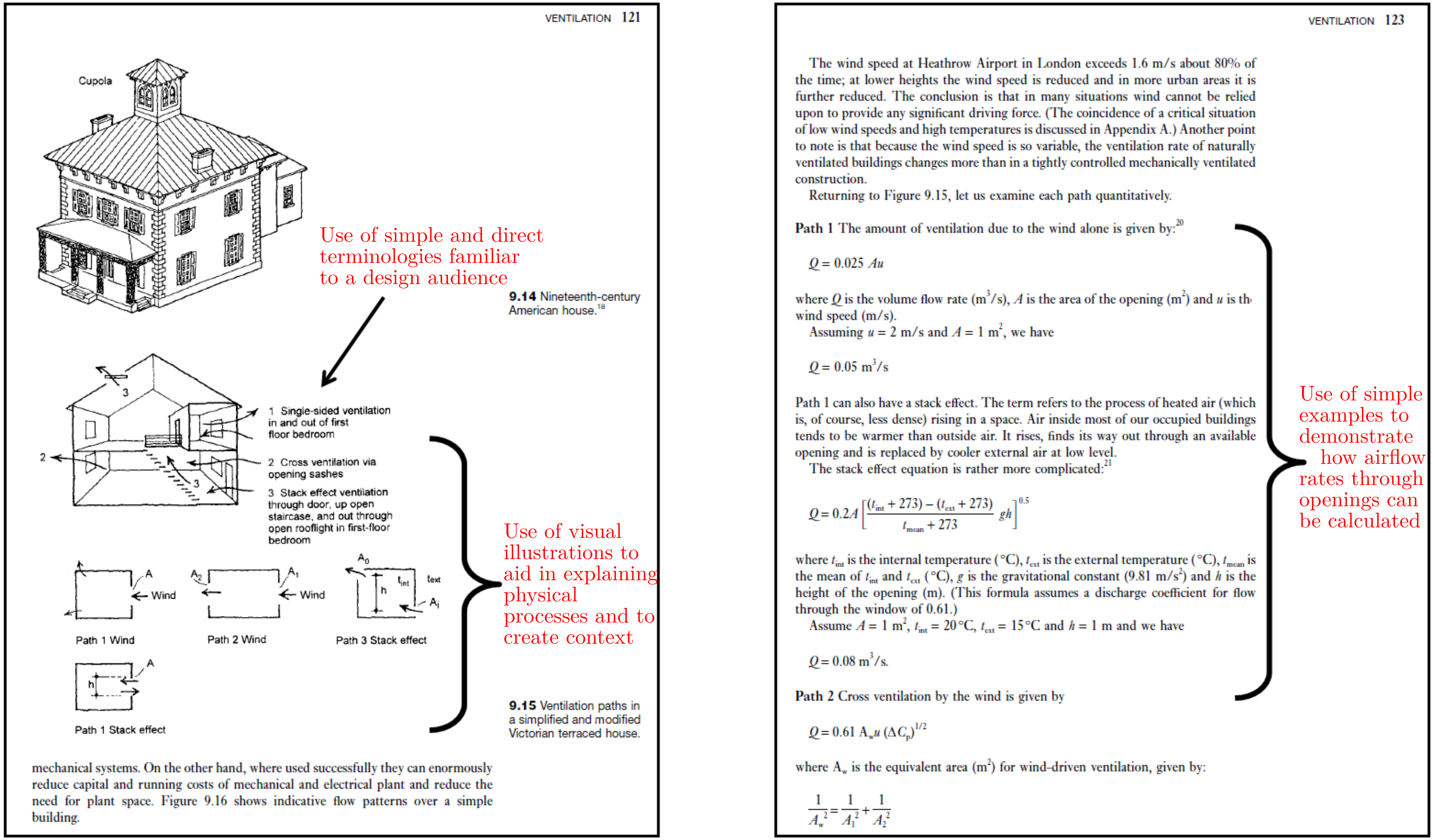


FIGURE 1.7: Excerpts taken from the book by Thomas (2006), exemplifying the style and format typically found in the design-based literature.

'language' to architects, allows for a straightforward interpretation and rapid uptake of information without requiring the necessary background or expertise in fluid mechanics to understand.

However, since technical research relies heavily on the precise and accurate use of terminology and notation, simplifying certain terminologies and styles of presentation to suit a particular context can alter meaning and misconstrue key concepts. As discussed later in Chapter 3, in some cases, the essential core understanding of ventilating flows – key to establishing the desired airflow rate and indoor temperature – may be 'lost in translation' when interpreting/simplifying/conveying the original source text to suit a design context. Needless to say, an incorrect translation and/or misinterpretation of the original source information can lead to unintended errors in design specifications, which can have potentially detrimental implications to the overall performance of a ventilation system.

The overall picture is therefore one of an extensive, but fragmented, information base on natural ventilation flows. The above example excerpts highlight the disparate nature of 'technical-based' and 'design-based' literature on the topic of natural ventilation. The distinction seen, between the styles of presentation, also mirrors the contrasting methods of thinking and problem-solving employed by architects and engineers: architects prefer to communicate visually, while engineers/scientists tend to codify their knowledge through mathematics. Whilst technical publications arguably provide in-depth knowledge and information on natural ventilation that may stand to benefit architects in design, they are generally not catered for them nor fit their design process. Further to this, there is currently a scarcity of research on the information needs of architects with regards to the design of naturally ventilated buildings. There is, thus, a clear need to improve the transfer and delivery of technical information on natural ventilation to the architectural community and to formulate a framework upon which information on natural ventilation and design can be better communicated across disciplinary boundaries.

1.3 Aim and objectives

The overarching aim of this research is to offer insight into ways of improving the transfer of the existing body of technical information on natural ventilation to the architectural community. The research focusses on developing robust approaches to convey specifically chosen topics of natural ventilation from the fluid mechanics literature into rapid and intuitive design guidance for architects. The following six objectives, as illustrated by the flow chart in Figure 1.8, were identified to meet the aim:

Objective 1: To conduct a survey/questionnaire on a group of architects to gain a first-hand perspective into architects' views, opinions and information requirements for natural ventilation;

Objective 2: To identify some of the pertinent information gaps on natural ventilation between the technical- and design-based literature. The key design questions – associated with the design of efficient and comfortable naturally ventilated spaces – informed by these gaps are presented in §1.3.1;

Objective 3: To answer the design questions in §1.3.1 by drawing from the existing body of knowledge in the fluid mechanics literature to construct simplified mathematical models that capture the key physics of natural ventilation flows;

Objective 4: To translate the results of the models into rapid and easy-to-apply formats for guiding early stage design;

Objective 5: To formulate a 'dissemination framework' to facilitate technical researchers and practitioners when communicating with, and/or tailoring their work for, an architectural audience;

Objective 6: To 'test' our dissemination framework on a previously unexplored area of natural ventilation flows by developing a brand new mathematical model (made as part of this thesis), and by conveying the key results of the model into an appropriate format suited for an architectural audience.

1.3.1 Key design questions

To be effective, a natural ventilation system must meet specific requirements for the supply of fresh air (for respiration and the removal of excess heat, body odours and carbon dioxide) and to ensure indoor air temperatures are comfortable. The key to achieving the specific (or desired) ventilation is by the correct sizing and positioning of openings in the façade. While architects may have an idea of the required ventilation flow rate they wish to achieve in a given space, the challenge is to determine the size and location of the individual openings that will ensure the desired ventilation.

We establish the three key questions which specifically target the sizing and positioning of openings and are identified to arise in the early stages of a natural ventilation design process. Crucially, these questions stem from the fluid mechanics literature, but the answers to these questions have not yet been communicated in a specific format for the immediate application by architects. The key questions, listed below, are addressed in this thesis. We note that, whilst the existing design guides on natural ventilation do attempt to provide relatively straightforward solutions to some of these questions, we will later show that these are indeed erroneous and misguided.

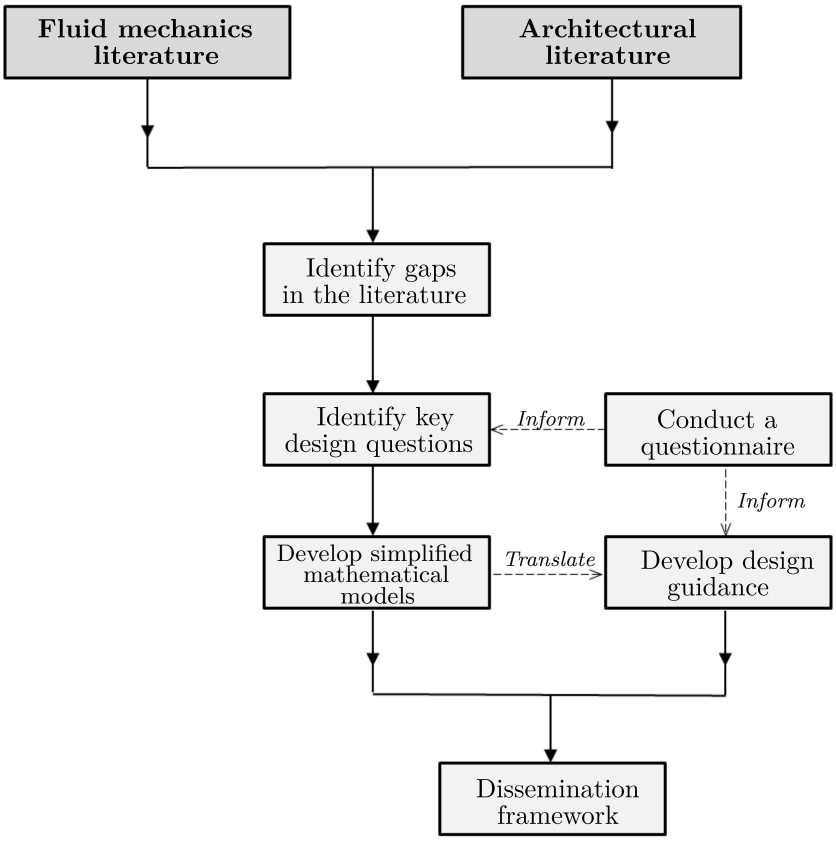


FIGURE 1.8: Flow chart illustrating the general rationale and objectives of this research.

Q: How does one size and locate individual openings in the building façade so that...

(a) air flows in the intended direction through all openings?

(b) the requirements for ventilation flow rate and indoor air temperature are satisfied simultaneously in the occupied region of the building?

(c) the desired ventilation is achieved without creating uncomfortable draughts?

1.3.2 Focus and approach

In order to tackle the design questions identified in §1.3.1, we focus on early stage design approaches for natural ventilation. Specifically, we home in on the intuitive value of a simplified mathematical approach as a vehicle with which to model and explain the physics of natural ventilation. The rationale of this approach is mainly three-fold. Firstly, simplified mathematical models have been proven to be robust in numerous small-scale laboratory experiments (*e.g.* Linden *et al.* (1990), Hunt & Linden (2001), Hunt & Coffey (2010), Partridge & Linden (2013)) and full-scale measurements (*e.g.* Kenton *et al.* (2004)) of natural ventilation. Secondly, owing to their relative simplicity, they have the capacity to impart both quantitative and qualitative information regarding the behaviour of a ventilation system. Even without explicitly solving the model, the form of the equations can provide an indication of how key design variables are interrelated to one another. Thirdly, simplified mathematical models can lend themselves to providing rapid and intuitive design guidance through simple hand calculations. Design guidance, in particular those centred around hand calculations and visual charts, can be used readily by both architects and engineers, thereby providing a common platform for communication and dialogue between both members in a design process.

To ensure that our mathematical model is tractable and easy-to-apply, we focus on a room (or a single storey building) ventilated by buoyancy (stack effect) only. Specifically, we focus on a subset of variables shown in Figure 1.3, namely ventilation flow rates, air temperatures, heat inputs, building geometry, vent sizes and vent location. We refer to these as 'primary variables'. The flow chart in Figure 1.9 shows the interdependency between the primary variables. Whilst numerous other variables can influence the design and performance of a natural ventilation system (*e.g.* heat loss through the building fabric, occupant vent-opening behaviour, *etc.*), in the subsequent chapters we demonstrate that the primary variables chosen herein are capable of capturing the essential physics of stack ventilation to a sufficient extent to inform early stage design.

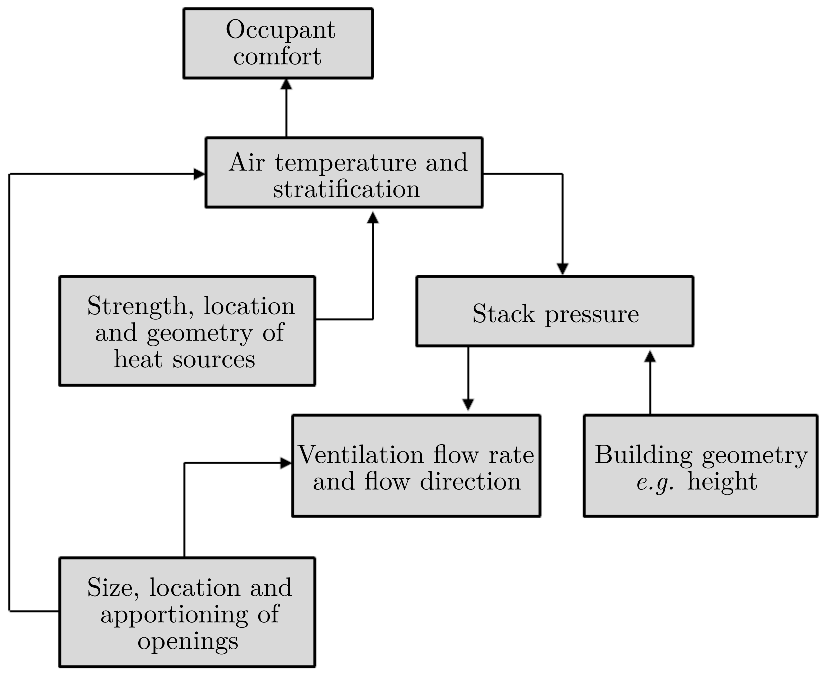


FIGURE 1.9: Flow chart summarising the interaction of the primary variables. An arrow pointing from variable X to variable Y should be read as 'X affects Y'.

Since the core ethos of this thesis is on promoting the transfer and uptake of technical information on natural ventilation by architects, it is therefore imperative to acquire a deeper understanding of the architectural audience with whom we wish to better convey technical information to. As a step towards achieving this goal, we focus on the qualitative value of a questionnaire as an instrument to gain direct insight into architects' current information requirements with respect to their designing naturally ventilated buildings. The feedback gathered from the questionnaire is anticipated to provide valuable information towards improving our current understanding of the needs of architects, and more importantly, towards improving our existing means of communicating technical information to the architectural community.

1.4 Thesis layout

The general layout of the thesis is described below. Each chapter addresses a key design question from §1.3.1 and is presented in a format designed specifically to enable architects, rather than solely expert fluid dynamicists, to understand the results and apply them. To accommodate the intended readership, we attempt to communicate the work as plainly and straightforwardly as possible using clear, simple terminologies. A glossary of ventilation-specific terminologies in Table IV (see Glossary, pp. ix–xi) provides a brief definition and explanation of the terms used frequently in this thesis and can be accessed easily by the reader at any point.

In Chapter 2 we identify the information needs of modern-day architects who seek to design low-energy, and specifically naturally ventilated, buildings. We present the results of a survey representing a snapshot of the personal views and opinions of a group of student architects. The aim of this focussed study was to gain insight into and raise awareness of architects' current information requirements (**Objective 1**). Aspects concerning architects' perceived knowledge of natural ventilation, the resources they most frequently use/refer to (and prefer to use) for design guidance, their perceived barriers when designing for natural ventilation, and their preference for the style and format for future natural ventilation design guides are covered. Based on our findings, recommendations on the writing/presentation styles for technical researchers and practitioners are offered (**Objective 5**).

In Chapter 3 we introduce the fundamental concepts and literature on natural ventilation relevant to the work covered in Chapters 4 and 5. We describe a number of simplified mathematical models which capture the key physics underlying natural ventilation flows, and show how they enable a range of rich behaviours, including airflow patterns, rates of ventilation and indoor temperatures, to be predicted. The purpose of this chapter was to review the core components that underpin the modelling of room airflows, which we use and build upon in the subsequent chapters to address the key design questions. A further intention of this chapter was to identify some of the recurring information gaps (and misconceptions) on natural ventilation (**Objective 2**). In order to identify these gaps, we compare and contrast the findings from a number of key studies seminal in the area of building ventilation with the recommendations from the existing (and notably accepted) design guides.

In Chapter 4 we present a simplified mathematical approach for the sizing of individual ventilation openings. We build our approach based on two well-established, experimentally validated mathematical models of stack ventilation in rooms, and show how opening areas can be determined at which transitions between the desirable and undesirable airflow patterns occur. Based on our approach, we propose a step-by-step methodology for calculating the physical opening areas required to deliver the desired airflow rate and indoor temperature, and crucially, to ensure that the air flows in the intended direction through all openings (**Objectives 3 and 4**).

In Chapter 5 we present a simplified mathematical model to investigate some of the effects of thermal stratification and draughts in a room. The intention for examining these effects was two-fold. Firstly, the stratification affects not only the stack pressure that drives the ventilating flow, but also influences the indoor temperature distribution and therefore the comfort of occupants. Secondly, the inflow of cool air through openings may lead to strong draughts, which can result in significant mixing of the internal air; this, in turn, will affect the apportioning of the accumulated heat within the room and hence the comfort of occupants (Hunt & Coffey, 2010; Coffey & Hunt, 2010).

We present the work of Chapter 5 in two distinct parts and in different styles. This was done intentionally so as to 'test' the general application of our proposed dissemination framework. In **Part I**, which mimics the typical style of a engineering/scientific research paper, we develop a simplified mathematical model to predict the effect of draught (internal mixing) on the ventilation flow rate and stratification in a room with a particular opening arrangement and indoor heat input distribution. The aim of Part I was to provide new quantitative and qualitative insights into the fluid mechanics that control rates of airflow and indoor temperatures (**Objective 3**). By incorporating the dissemination framework, in **Part II** we convey the key results from our predictive model in a tailored format to assist architects (and engineers) in the rapid sizing and positioning of ventilation openings (**Objective 6**).

Finally, we summarise the major outcomes of the research and draw our conclusions **in Chapter 6**. We also propose avenues that may potentially be considered for future work.

Chapter 2

Capturing the needs of architects: a survey

The work of this chapter is based on the following publication:

> R. BAEUMLE & G.R. HUNT (2018) Capturing the needs of architects: A survey of their current information requirements for natural ventilation design. *International Journal of Ventilation*, **17** (2), 120–147.

* * *

2.1 Introduction

This chapter focusses on identifying the information needs of modern-day architects seeking to design low-energy naturally ventilated buildings. The primary driver for this work stemmed from the need to improve the transfer of information from the technical literature to practising architects. Moreover, there is currently a gap in the knowledge available to academic researchers and technical practitioners regarding architects' current means of obtaining and using information with respect to their designing naturally ventilated buildings.

Prompted by both a need to encourage architect-engineer communication and the uptake of technical information on natural ventilation, we conducted a survey on a group of 33 MA/MSc/MArch student architects at the Architectural Association (AA) in London. Their personal views and experiences were collected via a bespoke questionnaire that we designed specifically to gain direct insight into the needs of young architects. Rather than attempting to make any preconceived assumptions regarding what architects 'should need to know', we designed the survey to be a 'sounding board' for architects' opinions; their opinions were sought on a range of natural ventilation design specific matters, including on their vision for the types and styles of information they would like to have at their fingertips.

This chapter presents the results of our questionnaire. The collated views and needs of young architects are highlighted using visual charts and tables. Our findings are potentially of interest to those engaged in sustainable building design, whether as practitioners or academics, from architectural, building services or wider engineering or scientific backgrounds. Moreover, we anticipate that our findings may prove of interest to those aiming to promote a wider uptake of technical information on natural ventilation by architects.

2.1.1 Chapter structure

This chapter is laid out as follows. In §2.2 we briefly review a number of published studies that have focussed on examining how architects obtain and use information in a building design process. Our questionnaire has been inspired by these, and for this reason we regard them as noteworthy. In §2.3 we introduce our questionnaire by describing the methodology we chose and the rationale for the line of enquiry (and grouping of questions into distinct themes) that underpinned our questionnaire. We overview the key findings from our survey in §2.4 using visual charts and tables, and based on these, we offer recommendations for the writing/presentation styles for technical researchers and practitioners (§2.5) that potentially better engage architects with scientific information. Finally, we draw our conclusions in §2.6 and discuss the limitations of our survey.

2.2 Communicating technical information to architects: a brief overview of previous studies

Today the challenges associated with the design of low-energy buildings demand for more information, knowledge and expertise than a single individual can possess. However, despite the importance and potential of technical information for guiding effective ventilation designs, as noted in §1.2.4, much of this well-established technical resource base still remains largely untapped by architects. Although the growing need for improved interdisciplinary collaboration in design (as well as in research) has motivated considerable efforts over the recent decade to raising awareness of the importance of technical communication (Hargis *et al.*, 2004; Oke, 2006; Cunningham & Stewart, 2012; Norouzi *et al.*, 2015; Passe & Battaglia, 2015), the recognition of the 'communication problem' is, in fact, not new and has been discussed in the open literature since the 1960s.

One of the first of such studies in the UK was carried out in 1968 by the British Building Research Establishment (BRE) at the York Institute of Advanced Architectural Studies (IAAS). The aim of the study was to identify ways of improving the communication of technical information to architects, as the BRE recognised that their in-house technical literature was making limited impact within the architectural community. Several hundred architects' offices throughout the UK took part, either by giving interviews or completing a postal questionnaire. The study highlighted that the style of presentation is a key factor in the information transfer process (Goodey & Matthew, 1971). In particular, the study made over 20 recommendations for the 'ideal' presentation of information to architects, emphasising aspects of brevity, clarity, visual illustration and the need for architectural vocabulary.

A follow-up study, completed by Mackinder & Marvin (1982), was later commissioned by the BRE at the IAAS. In contrast to the previous study, this later study stepped back from concentrating merely on presentation styles and instead focussed on how architects use the information and their decision-making in a design process. While the study endorsed the recommendations of Goodey & Matthew (1971), Mackinder & Marvin (1982) reported a remarkable unwillingness on the part of the architect to consult written material even when the information was presented in 'exemplary' formats. They found that there was a strong preference for relying on personal experience due, in part, to the perceived time-consuming and cumbersome nature of consulting written information. Detailed comments made by architects regarding the use/disuse of certain types of information (cited in Newland *et al.* 1987, p. 3) reflected a common consensus, namely that the information from the 'world of academia' was perceived as being ill-suited to architectural needs. Ritter (1981, cited in Newland *et al.* 1987, p. 3) commented that for technical information to be used and successfully applied by architects, in addition to being in an appropriate format, the information should be made relevant to them, tailored for them and should reflect architects' predilections in support of their design goals.

Furthermore, Cooper & Crisp (1984) emphasised the need for different approaches to communication with architects who have different predispositions towards technical-related topics. In their study, 24 British architects and engineers were interviewed regarding the use of natural daylighting when designing office-type accommodation. They reported that the decision on whether daylighting would be exploited was influenced by the personal preferences, prejudices and belief systems held by the architect and engineer. Those who appeared to be more inclined towards the inclusion of daylighting in their building designs perceived the provision of information and design aides to be useful. However, those who rejected daylighting, simple provision of information made limited impact on their design decision-making process. A similar finding was also reported in an earlier study by Asprino *et al.* (1981) where the design process of a team of two architects and a final year architectural student was compared. They argued that if architects are predisposed not to consult information on a certain topic, simply altering the presentation style would make limited impact on the decisions they make in a design process. Russell *et al.* (1997) commented that designers are often suspicious of untried, unfamiliar or distant information from outside their profession which, as they see it, is a straitjacket to their creative process by imposing rules veiled under the pretence of offering design guidance. While necessary, it is evident that 'good' presentation in itself is not sufficient to overcome architects' pre-existing belief systems and their ingrained work habits. As Lera *et al.* (1984) concluded:

> *"...the strong belief systems and predispositions held by the architect may have an overriding effect, and that merely changing the presentation format will not overcome existing barriers to the information transfer process."*

The aforementioned studies provide some valuable insight into the architecture profession, in particular their attitudes and concerns towards the presentation of technical information, and some of the perceived factors that deter or even prevent them from using particular information sources. These studies also demonstrate the potential value of questionnaires and interviews to help enhance understanding and appreciation of architects' information requirements, and to provide a platform on which to base future efforts to improve the communication of technical information. Indeed, the studies have inspired, to a large extent, the survey presented herein. We now present the results of our survey.

2.3 Method of enquiry

We administered our questionnaire to the group of 33 MA/MSc/MArch student architects, aged between 20 and 30 years, in their lecture room on campus during class time in order to ensure a 100% response rate. The questionnaire was completed by all and each questionnaire was collected personally by the authors before the students left. Gathering respondents in a group setting and personally distributing the questionnaire – as opposed to electronic mailing – has already been proven to be a highly effective approach to increase the motivation of participants to respond (Hinrichs & Gatewood, 1967; Wood, 2003; Fraenkel & Wallen, 2011; Adler & Clark, 2014). Moreover, this setting also provided the authors with an opportunity to explain the purpose of the investigation. In our survey, the incentive offered for participating was an opportunity to "influence the future development of natural ventilation design guidance that better addresses the needs of architects."

We conducted our survey on these MA/MSc/MArch students as they were each engaged in their own personal design projects at the time of our study, and hence, were anticipated to provide a realistic snapshot of architects' information needs and requirements in the context of a natural ventilation design. Whilst we did not explicitly question the students regarding their previous professional experience, many we questioned had previous experience working in an architectural practice as this is often a requirement in many architectural schools.[1] In the UK, for example, students take a full year out for practical training as part of their undergraduate course.

The questionnaire, totalling 25 questions, consisted of both closed-ended and open-ended questions (Q1 – Q25, see Appendix). Closed-ended questions invited a response that fits a preordained answer (*e.g.* Q1, Q2, Q6), whereas open-ended questions (*e.g.* Q5, Q10, Q15, Q25) demanded answers in terms of the respondent's own opinion, belief or judgement. The primary objectives of the survey were to:

- determine the students' perceived understanding of natural ventilation;
- detect if there were any recurring gaps in understanding;
- discover whether they intend to use, or have used, natural ventilation strategies in their building design projects;
- discern the common types of resource they exploit for design guidance;
- determine the perceived barriers hindering or preventing them from adopting a natural ventilation strategy in their designs; and
- distinguish ideal (or highly desired) presentation formats of design information for architects.

In the light of these objectives, the questions posed centred around a number of main themes as illustrated by the flow chart in Figure 2.1 and as described below.

Theme 1 opened the questionnaire by asking the academic route the students' took for their secondary and tertiary education;

Theme 2 investigated their preferred types of resource to use at the early stage of a natural ventilation design (in this case, for their studio-based projects), and whether they would consider seeking technical, or other related advice, from different professions (*e.g.* academics involved in low-energy building ventilation research, or engineers and architects working in industry/practices);

Theme 3 covered questions regarding their perceived knowledge of natural ventilation theory;

[1] The Architectural Association (AA) requires students to take their fourth year out for practical training as part of the undergraduate course (Architectural Association Inc., 2017). However, not all students we surveyed did their undergraduate degree at the AA, some having studied abroad prior to starting at the AA.

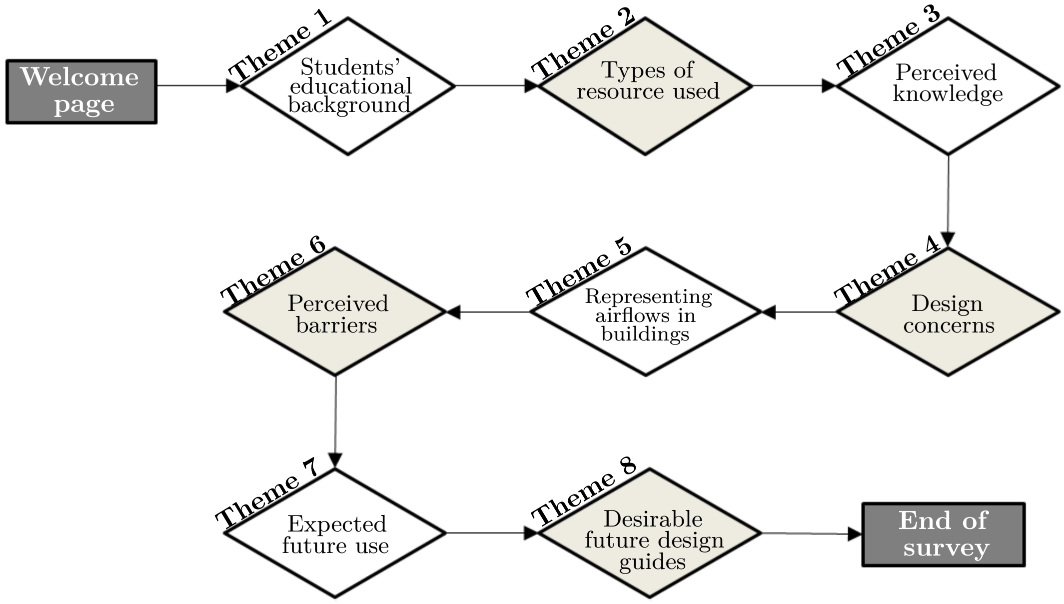


FIGURE 2.1: Flow chart showing the eight themes covered by our questionnaire.

Theme 4 examined their concerns, if any, regarding the application of natural ventilation theory into design practice (*e.g.* the sizing of vents necessary to achieve a desired airflow rate);

Theme 5 investigated how they perceive air to flow through openings made in the façade of a naturally ventilated space by asking them to sketch 'airflow arrows'. This theme also questioned their views on the use of simplified schematics to represent a building or space as commonly used in the mathematical modelling of flows in naturally ventilated spaces;

Theme 6 probed the barriers (perceived or otherwise) to their designing naturally ventilated buildings;

Theme 7 enquired whether an increase in the demand for low-energy buildings in the near future was perceived; and finally,

Theme 8 closed the questionnaire by enquiring as to their preferred format, style and level of detail for future natural ventilation design guidance for architects.

At this stage, it is worth noting that the intention behind our investigation was not to serve as an opinion poll for justifying the use (or otherwise) of natural ventilation in buildings, nor can it be regarded as a representative sample of the viewpoints of all architects – the latter due, for example, to the limited sample size and experience base of those completing the questionnaire. Moreover, the responses of the group surveyed are likely to be influenced by their current course tutors, for example, in terms of their preferences for specific publication sources that are relevant to the topics taught in the syllabus. The data collected and the comments presented herein (*e.g.* those expressing opinions of the respondents) are therefore not meant to be subjected to the rigours and tests of statistical significance, but crucially may be regarded as a snapshot of the views and a window into the needs of future architects.

2.4 Overview of results

The responses to our questionnaire are grouped and summarised below (§2.4.1 – §2.4.6) and some implications of the findings are discussed. We include written responses (in quotation marks) that proved to be particularly pertinent, insightful or informative. The key result which emerged under each subheading below, and that is singled out for attention here, is highlighted in ***italics***.

2.4.1 Educational background

Students had prior training in the sciences and mathematics.

The students were asked to select, amongst the five listed in Table 2.1, the subjects chosen during their secondary education (A-level or equivalent) and their undergraduate degree course. Table 2.1 summarises their responses.

Qualification/degree		**Yes**	**No**
A-level	Mathematics	70%(23)	27%(9)
	Physics	67%(22)	30%(10)
	Science	64%(21)	33%(11)
	General Studies	70%(23)	24%(8)
Higher Degree	Mathematics	0%(0)	82%(27)
	Physics	0%(0)	82%(27)
	Science	3%(1)	79%(26)
	Engineering	18%(6)	64%(21)

Table 2.1: Summary of the types of subjects chosen by the students at secondary and tertiary levels. Percentages represent the total number of votes received divided by the total number (33) of participants. The number of respondents who chose a particular subject is given in parenthesis.

Our findings indicate that over 60% of the students have been exposed to more than one 'technical' subject (such as physics and mathematics) during their secondary education, 21% of whom have chosen (and/or graduated with) an engineering or science degree at university level.[2] Whilst the students' secondary and tertiary educational upbringing may have had some influence on the responses given in the questionnaire, we anticipate that the training they currently receive at the AA will carry the greatest influence in shaping their skills, preferred language conventions, belief systems and predispositions, and thus is likely to have an overriding effect on the responses in the survey.

2.4.2 Resources commonly used for design guidance

The most preferred type of design guidance was case studies of exemplar naturally ventilated buildings.

The participants were asked to select, from a variety of resources, their preferred type of guidance for natural ventilation design. Choices ranged from the traditional print resources, *e.g.* journal papers, to potentially more subjective approaches, *e.g.* relying on experience or the incorporation of a design feature/element/approach that they perceived was expected. The radar chart shown in Figure 2.2 captures their responses.

An overwhelming 97% preferred to use case studies of already built naturally ventilated buildings as a reference point for guidance in design. A possible reason behind this preference may be the fact that case studies provide the evidence-based reassurance which can demonstrate, qualitatively, a specific design strategy is performing effectively.[3] Evidently, reference to design guides/manuals and to building standards (*e.g.* CIBSE AM10 (CIBSE, 2005), ASHRAE Standard 55 (ASHRAE, 2010)), reliance on personal experience and expectation, and the use of architectural journals (*e.g.* Architectural Science Review; ISSN: 0003-8628) are also commonplace when they considered designing naturally ventilated buildings. Almost one third of the students stated that they subscribe to the Architects' Journal (ISSN: 0003-8466), a weekly non-peer reviewed architectural magazine published in London.[4] Somewhat unexpectedly, reference to these sources far exceed those made to scientific articles on natural ventilation flows and airflow control that are widely published in the open literature.

[2] In hindsight, this particular question may be poorly formulated. Ten students noted that, although they graduated with an architectural degree, they have in fact been exposed to more than one science and/or engineering subject during their degree course.

[3] The strong preference for the use of case studies, as indicated in Figure 2.2, somewhat contradicts the comment by Salingaros & Masden II (2008), who pointed out that architects are often hesitant to use evidence-based information as it is seen to hinder architectural design freedom (see §1.2.2). Dr Simos Yannas, Director of environmental design research and teaching at the AA, opposes this statement and commented that a sound theoretical background is imperative to provide students with the ability to translate physical laws into creative architectural forms (Yannas, 2003). He stressed that architectural teaching programmes have to be supported by empirical knowledge and evidence-based information so that students develop an understanding of how different principles can be applied in practice.

[4] The Architects' Journal provides up-to-date architecture news related to building projects within the UK and internationally, and a platform for opinions on design- and construction-related matters.

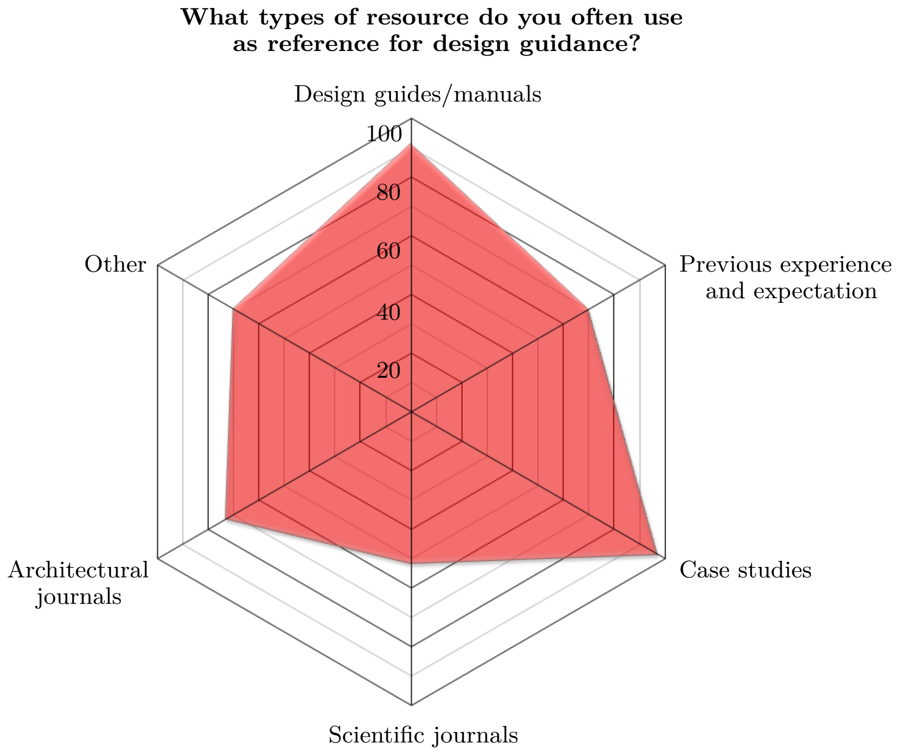


FIGURE 2.2: Radar chart showing the preference for particular types of resource for guidance in a natural ventilation design. Percentages shown against a given resource represent the number of votes received divided by the total number (33) of participants.

Proceedings of PLEA and articles published in the journals 'Building and Environment' and 'Energy and Buildings' were most frequently read and with the greatest interest.

We wanted to discern the types of journal papers and conference proceedings that architectural students are interested in reading. Clearly this information may prove helpful when selecting an avenue for the publication of a particular new finding so as to ensure it hits the target audience. Moreover, this information may also be of use to publishing bodies themselves.

A choice of eight different journals, regarded as either of a technical, an interdisciplinary or a design-related nature, were given in the questionnaire. The radar charts, Figures 2.3(a) and 2.3(b), highlight those journals most frequently read and those which instigated most interest in reading, respectively.

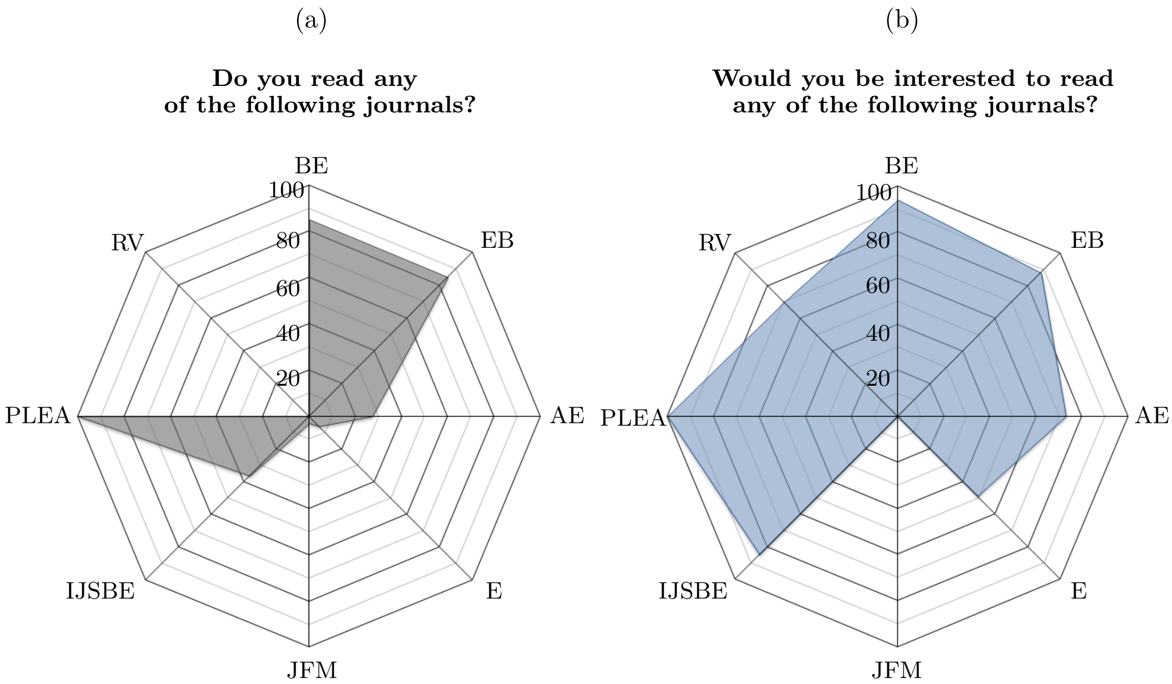


FIGURE 2.3: Radar charts showing the percentage of students who: (a) read a particular journal; (b) are interested in reading a particular journal. Reading in a clockwise direction, the abbreviations labelled on each corner are: Building and Environment (BE), Energy and Building (EB), Applied Energy (AE), Ergonomics (E), Journal of Fluid Mechanics (JFM), International Journal of Sustainable Built Environment (IJSBE), Proceedings of Passive and Low Energy Architecture (PLEA), and Proceedings of Roomvent (RV).

There is a unanimous preference for articles that are published in PLEA[5] conference proceedings – all 33 giving this as their number one choice. This overwhelming preference may be, in part, influenced by the interdisciplinary nature of this particular conference. Other well-established conferences that cover building ventilation (*e.g.* Roomvent, CIBSE or AIVC[6] conferences) are often of a more technical nature and geared towards attracting specialists spanning the building physics, fluid dynamics and wider ventilation communities, rather than solely specialists in one particular field of interest. Interdisciplinary journals, in particular ‘Building and Environment’ and ‘Energy and Buildings’, are also favoured as they span a broad spectrum of applied research topics and, therefore, were deemed by the respondents as being well suited to their changing information requirements at different design stages.

[5]Passive and Low Energy Architecture (PLEA) is an “autonomous, non-profit network of individuals sharing expertise in the arts, sciences, planning and design of the built environment”. Founded in 1981, PLEA holds annual international conferences, workshops and exhibitions, which seek to promote interdisciplinary discussions and debate on the learnings, opportunities and challenges in passive, low-energy architecture (PLEA, 2015).

[6]AIVC is the acronym for Air Infiltration and Ventilation Centre.

Whilst the appearance of the Journal of Fluid Mechanics (JFM) may, at first sight, appear out of place on our list, it was included as this journal now holds an expansive body of information (and guidance) on natural ventilation. Indeed, advancements in our understanding and predictive capability of numerous fundamental aspects of natural ventilation, essential information for design, may be found solely therein: examples include a model for underfloor heating (Gladstone & Woods, 2001), the link between the buoyant plumes that rise above heat sources and the stratification/airflow rates they establish in a room (Linden *et al.*, 1990; Cooper & Linden, 1996; Kaye & Hunt, 2004; Shrinivas & Hunt, 2014*a*), the effects of assisting and opposing winds on room ventilation (Hunt & Linden, 2001, 2005), the role played by thermal mass (Holford & Woods, 2007; Lane-Serff & Sandbach, 2012), the link between the direction of airflow through openings in a façade and opening area configuration/room stratification (Hunt & Coffey, 2010), the effect of draught on the indoor stratification and temperature distribution (Coffey & Hunt, 2010), and numerous others.

Although potentially of direct benefit for both enabling and enhancing ventilation design, the results of our survey reveal that this journal is not consulted, nor is it judged to be of interest to read (Figure 2.3). This finding is not surprising given the title of the journal itself is unlikely to lead an architect to consult it further. Moreover, with this perceived isolation from a design context, it is understandable that no direct association is made by architectural students between JFM and natural ventilation design work. Whilst a keyword search (*e.g.* natural ventilation, building, *etc.*) may retrieve individual articles from JFM, the text therein is necessarily couched in technical terminology and mathematical notation, and thus caters only to a limited readership.

Students were open to seeking guidance from research academics, engineers and fellow architects.

Our survey also explored the respondents' perception of (i) research academics with interest/expertise in low-energy building ventilation, (ii) practising architects and engineers in industry, and specifically whether they are willing to seek advice from them during the course of a natural ventilation design.[7] Despite a few criticisms that emerged, there was, in general, an overall culture of respect towards members of each professional discipline. Their responses are illustrated graphically on a bar chart in Figure 2.4.

Of the three professions, support and advice from engineers was most favoured (receiving 94% of votes for 'yes'). Engineers were perceived as "trustworthy" and with "expertise in dealing with technical issues which architects cannot solve alone", and as being able

[7] We did not ask the students whether they have, in their past and/or current training, consulted any one of the professions listed. Indeed, it may be possible that the responses to this question be based entirely on their personal preconceptions and/or prejudices regarding each professional discipline.

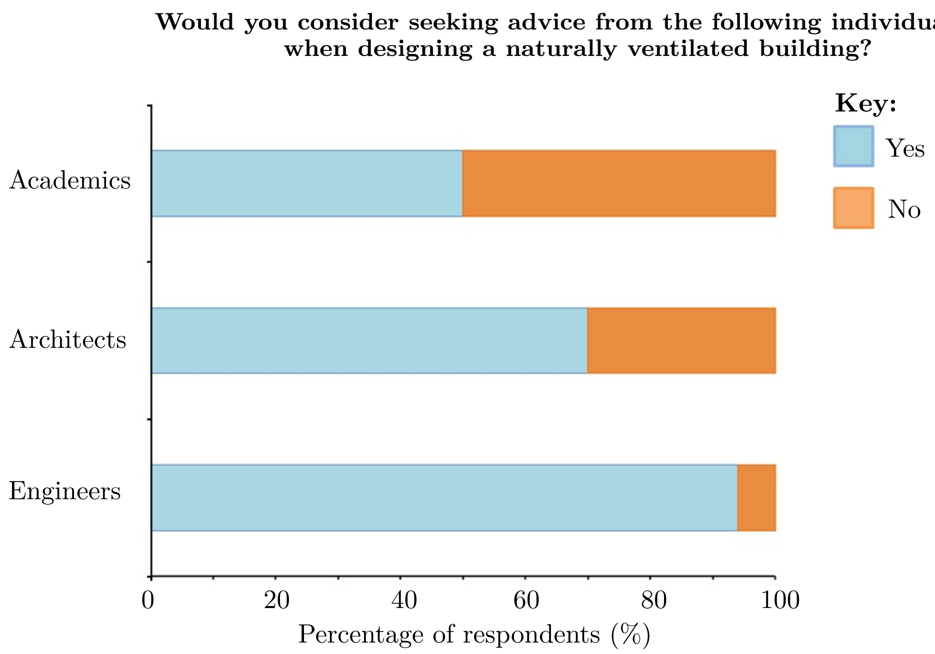


FIGURE 2.4: Stacked bar chart showing the percentage of architectural students who would consider (in blue), or would not consider (in orange), seeking the advice of research academics in low-energy building ventilation, practising architects and practising engineers in industry.

to provide architects with the "exact numbers and dimensions" required in a design. On the other hand, 6% perceived engineers' guidance as "too standardised" and that it "lacks innovation and awareness of architectural issues".

70% perceived practising architects in industry as "practical" and as practitioners who can offer solutions that are "more creative" and "outside-of-the-box" than (a perceived) "standard approach given by engineers". Despite the generally positive response to seeking advice from architects in industry/practice, 30% of the respondents expressed some reservation towards seeking their design advice. These respondents expressed concerns over their ideas being "copied" by other architects, which they perceived would jeopardise their strive to create "unique" and "signature" building designs. As Till (2005) commented, intellectual property is what defines and sustains architects, and because of this, it is understandable why they would be unwilling to give this away.

There is an equal split between students who would, and would not, consider consulting research academics for design guidance. Those who held a more positive view of academics identify them to be equipped with "in-depth theoretical know-how" and as able to provide architects with "trustworthy technical information". By contrast, others identify their advice as "too theoretical" and that they "lack practical skills and experience in the field of architecture".

2.4.3 General (perceived) knowledge of natural ventilation in buildings and design concerns

A series of questions was posed in the questionnaire that probed the student architects' perception of their own knowledge and understanding of natural ventilation, together with their confidence and ability to apply theoretical principles in order to perform key quantitative design calculations.

Designing a naturally ventilated building was perceived to enhance the creative skills of architects.

All respondents expressed their aptitude toward the inclusion of natural ventilation strategies in their own building designs. There was unanimous agreement that designing a naturally ventilated building presents "an even greater challenge for architects" compared to its air-conditioned counterpart, that it allows their "creative skills to be put into practice" and that it gives "architectural expression to a technical issue".

The majority of students were confident in their ability to size and locate ventilation openings to achieve a specific airflow rate, and regarded this know-how as integral to a natural ventilation design.

The stacked bar chart in Figure 2.5 summarises the responses regarding their perceived knowledge for sizing and locating openings to achieve (a) a specific airflow rate, (b) a comfortable indoor environment, and (c) to harness the effects of an external wind. A summary of the results is given in Table 2.2.

These findings indicate that the architectural students are generally confident in their own ability to size and locate openings, and in particular, to achieve a specific (or desired) airflow rate. This is somewhat surprising to find given that determining the actual area of openings for a naturally ventilated building is a major technical challenge in design. Even for specialist ventilation engineers, sizing openings for natural ventilation presents a highly complex task; not only is there a need to ensure that vent sizes and locations result in an airflow in the direction desired but, ultimately, a complex interplay between the heat accumulated in the space, the relative areas of the openings and the details of the opening geometry give rise to the airflow rate achieved (see, for example, Hunt & Coffey (2010)) – this all being further complicated if the building is exposed to wind (Hunt & Linden, 2001, 2005).

Of note was that only five students had come across the term 'Discharge coefficient' (see §2.4.6 and Table 2.3). Knowledge of (or, at least, an estimate of) the value for this coefficient is a key requirement for the sizing of ventilation openings (Flourentzou *et al.*, 1998; Holford & Hunt, 2001; Chiu & Etheridge, 2007). As a consequence, we may deduce that the percentage of respondents who know how to size openings to attain a specific airflow rate may be

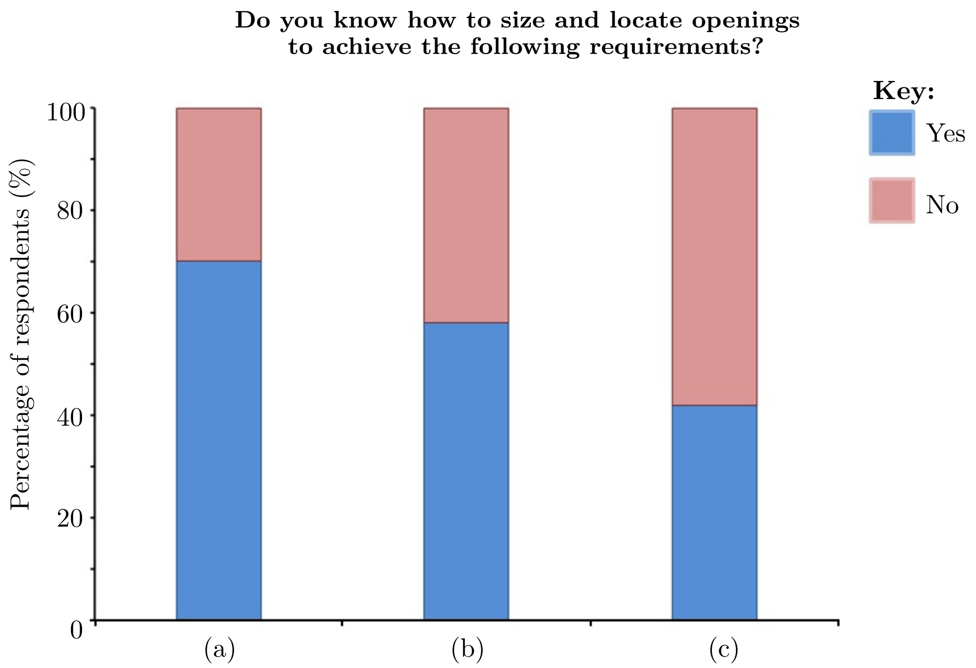


Figure 2.5: Stacked bar chart showing the percentage of respondents who perceive they 'know' (in blue) or 'do not know' (in red) how to size and locate openings to achieve one of the following requirements: (a) deliver a specific airflow (*i.e.* ventilation) rate; (b) deliver thermal comfort; and (c) harness the effects of wind.

	Do you know how to?		**Is it important?**	
Aspect/requirement	Yes	No	Yes	No
(a) Specific airflow rate	70%(23)	30%(10)		
(b) Thermal comfort	58%(19)	42%(14)	94%(31)	6%(2)
(c) Harness the wind	42%(14)	58%(19)		

Table 2.2: Summary of responses regarding perceived knowledge on sizing and locating openings for natural ventilation. Entries in the first two columns give, as a percentage of the total number surveyed, those claiming to know/not know how to size and locate openings to achieve a given requirement (a), (b) or (c). Entries in the third column give the percentage of those who attach an importance to the ability to size and locate vents. The number of respondents who chose a particular option is given in parenthesis.

somewhat below the 70% who made this claim.

Reassuringly, our results did indicate that there is a general consensus that the size and location of openings made in a façade are integral for the success of any natural ventilation design, and this know-how is of importance to architects, particularly at the early design stages. The respondents reasoned that:

> "It is a fundamental issue for us [architects] because it affects our overall design and the thermal and psychological experiences of occupants."
>
> "Architects must be able to predict these aspects so that the best ventilation strategy

> can be selected to suit the form and function of the proposed building design. Without such knowledge, there is no point to provide natural ventilation in the first place."

2.4.4 Representing airflows in buildings

In building ventilation, a fundamental challenge often confronted by architects and engineers at the early design stage is to determine the size and location of openings that will provide the necessary ventilation. A key requirement to achieve the desired ventilation is to ensure that unidirectional flow is established and maintained through the openings (*i.e.* upper openings act only as outlets for warm air, while lower openings act as inlets for cool air).

Prior to our investigation, a preliminary survey of the literature on natural ventilation revealed a common theme, namely that sketches shown in the design-based literature[8] depict 'unidirectional' flow despite there being limited (or rather, an absence of) guidance on how to ensure this pattern of flow be achieved in practice. Some examples showing typical 'airflow arrows' drawn in building sketches are highlighted in Figure 2.6.

While the airflow arrows shown in Figure 2.6 may suggest that by simply positioning openings at the upper and lower levels of a space will result in unidirectional flow, this is not guaranteed (Hunt & Coffey, 2010). Indeed this misconception is likely to have stemmed purely from the grounds that warm air rises and, hence, escapes out of upper openings.

Hunt & Coffey (2010) were amongst the first to demonstrate, both experimentally and theoretically, that unidirectional flow (*i.e.* displacement ventilation) is not always established with openings made at the upper and lower levels in the façade (see §3.5.1). Instead of unidirectional flow, they showed that exchange flow could develop at the upper opening, particularly if the upper opening area is large relative to the area of the lower opening. The occurrence of exchange flow reduces the area of the upper opening available for discharging warm air from the space, as a proportion of this area is occupied by an inflow of cool air from the exterior. From a design perspective, the occurrence of exchange flow is undesirable, as it may cause the airflow rate to reduce and for indoor temperatures to increase.

Given the work of Hunt & Coffey (2010), which focusses on the transition from unidirectional to exchange flow, is published in the Journal of Fluid Mechanics (which, according to our earlier findings is not the first reference of choice for architects), it was to be anticipated

[8] Using Google and Google Scholar, a manual search of the literature published on the topic of natural ventilation in the 'design-based' journals (*e.g.* Architecture Science Review, Building Research and Information, Journal of Architectural Research, and Journal of Architectural and Planning Research) was performed. A manual search was also conducted to find the relevant design guidelines (such as those published in CIBSE and ASHRAE) and chapters of books and snippets of web-based articles. Out of the 30 relevant articles, guidelines and books selected, almost all showed building sketches with airflow arrows depicting unidirectional flow (see, for example, Figure 2.6).

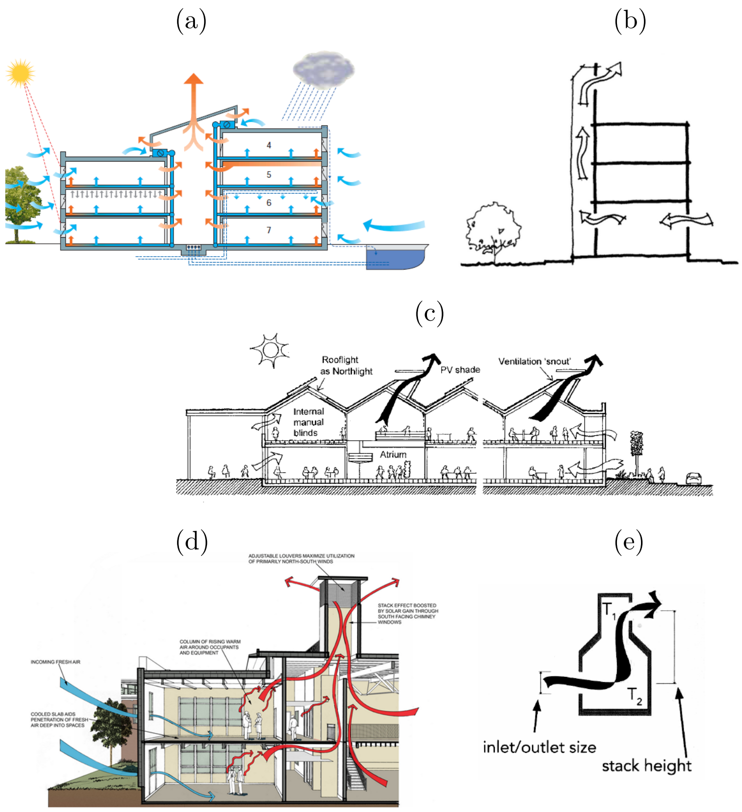


FIGURE 2.6: Examples of typical 'airflow arrows' drawn at the openings of a building envelope. These airflow arrows often depict the anticipated or the desired (as opposed to the actual) direction of airflow through openings in the façade. Sketches in the figure are taken directly from: (a) CIBSE AM10 (CIBSE, 2005), (b) Ward (2004), (c) Thomas (2006), (d) Archdaily (2011) and (e) Lam *et al.* (2006).

that the respondents may not be fully informed on how to achieve either unidirectional or exchange flow at an opening in a façade in practice. Thus, we conjectured that the respondents may have misconceptions regarding the sizing of individual openings. To test our conjecture, we wished to find out how the students expect air to flow through the upper and lower openings of a naturally ventilated space with different relative vent area configurations.

To this end, schematics were provided in the questionnaire (Q14 of Appendix) showing two possible designs for a ventilated building with openings in its façade at high and low levels. Crucially, the total opening area for both designs (sum of upper and lower areas) was set to be identical. However, the apportioning of this total, between upper and lower openings, differs between the two designs; the area of the upper opening in the design shown in Figure 2.7(b) purposely drawn to be large compared to that shown in Figure 2.7(a).

The students were required to indicate the anticipated/likely direction of flow through these openings by drawing airflow arrows. The two building envelopes are redrawn in Figure 2.8

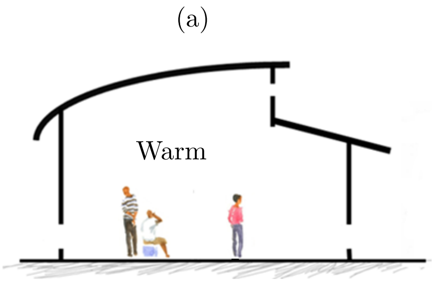


FIGURE 2.7: Schematics of an example building envelope in elevation indicating the position and relative sizes of upper and lower openings: (a) small upper opening and (b) large upper opening. The external environment considered is uniform in temperature, cooler than the interior, and wind free. Respondents were asked to indicate on (a) and (b) the anticipated direction of airflow through each opening.

with arrows superimposed to indicate the two possible solutions for the direction of airflow. Whilst, in principle, there is no correct or incorrect solution here (due to the intentionally limited information offered in the question) the primary aim was to establish whether there was an awareness of anything other than unidirectional flow.

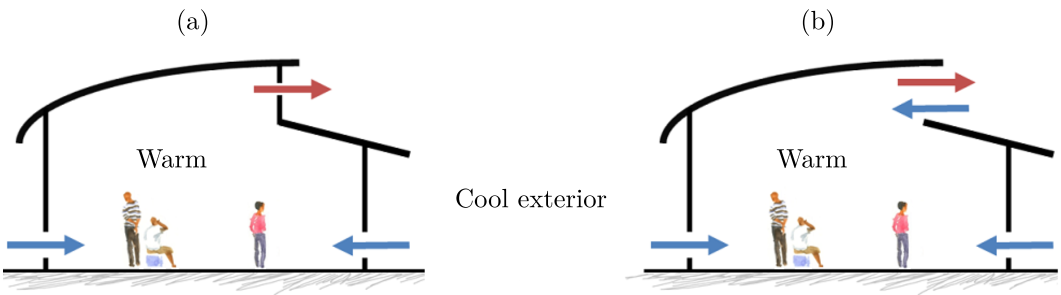


FIGURE 2.8: Building envelopes of Figure 2.7 with airflow arrows superimposed to indicate the likely direction of airflow through each opening in the façade. Red arrows indicate an outflow of warm air. Blue arrows indicate an inflow of cool air. In (a), unidirectional (out)flow is expected through the (small) upper opening. In (b), exchange flow (*i.e.* simultaneous outflow and inflow) may be expected at the upper opening as it is relatively large in area compared with the lower openings.

The direction of airflow through openings made in the façade was perceived as unidirectional, regardless of how opening areas are apportioned between the upper and lower levels in the façade.

The respondents' sketches of the perceived direction of airflow through openings in the façade of the two designs, Figures 2.7(a) and 2.7(b), were grouped in terms of whether their airflow arrows indicated solely an outflow at the upper opening (*i.e.* they expected unidirectional flow), or whether their arrows indicated an outflow and inflow at the upper opening (*i.e.* exchange flow is anticipated). Any additional flow patterns that did not fit either of the two categories were grouped as 'other'. The pie charts shown in Figures 2.9(a) and 2.9(b) summarise the perceived direction of airflow through these openings.

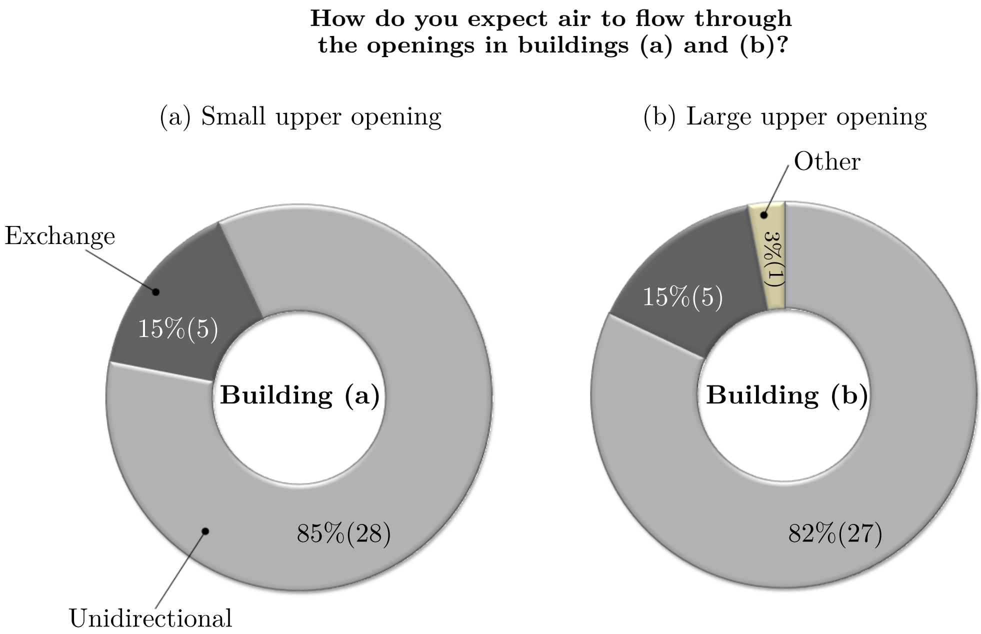


FIGURE 2.9: The percentage of respondents expecting either unidirectional flow, exchange flow or 'other' airflow patterns through openings in the façade of building designs (a) and (b) shown in Figure 2.7.

Hunt & Coffey (2010) showed that unidirectional flow is attainable only for a specific range of vent area configurations and not simply for all configurations with vents at low and high levels. However, despite the two different designs shown, an overwhelming 80% expected unidirectional flows to be established in each case, *i.e.* regardless of the relative vent area configuration. This finding is noteworthy given that 70% of the respondents perceive they know how to size ventilation openings that can achieve a specific airflow rate (see Table 2.2).

2.4.5 Perceived barriers to the design of a naturally ventilated building

In 1996 the BRE commissioned a study, as part of the pan-European project "NatVent", to identify the barriers which restrict the implementation of natural (or simple fan-assisted) ventilation systems in the design and refurbishment of office-type buildings in the UK. The perceived barriers were identified by conducting structured questionnaires and interviews with architects, as well as consultant engineers, building owners, developers, and government decision makers. The results of the study showed that problems associated with the ingress of air and noise pollution in urban environments, and the lack of "good" sources of natural ventilation knowledge (*e.g.* tailored design guidelines and building case studies) were perceived to be the greatest deterrents to the uptake of natural ventilation strategies (Kukadia *et al.*, 1998). A number of practical recommendations for encouraging a wider uptake of natural ventilation strategies were put forward by the NatVent study. Particular emphasis was placed on the need for a more comprehensive approach to improving general knowledge of natural ventilation through basic education, source books and building case studies. Moreover, a need for developing and incorporating easy-to-apply calculation procedures in design guidelines and building standards was identified.

Inspired by NatVent, we wanted to determine, more than two decades on, the factors that may possibly still deter or prevent the architectural students from electing to develop a natural ventilation design. The following six potential (or perceived) barriers to the development of a successful natural ventilation design were listed in the questionnaire:

(a) strict building standards and regulations;
(b) unpredictably and unreliability of natural ventilation to meet ventilation and comfort requirements;
(c) inner city pollution and noise;
(d) restricted design freedom;
(e) difficulty in assimilating the (vast) quantity of information on natural ventilation design; and
(f) lack of good quality natural ventilation design guidance available specifically to architects.

In a tick box beside (a)–(f) on the questionnaire, respondents could select either 'yes', *i.e.* perceived as a potential barrier, or 'no'.

The greatest perceived barriers to the design of naturally ventilated buildings were inner city pollution and noise.
Figure 2.10 summarises the overall responses to the six different barriers listed above.

These results show that concerns regarding inner city pollution and noise (85% of votes), followed by stringent building regulations and standards (70% of votes), are perceived as the two main barriers to the implementation of natural ventilation strategies in buildings. By contrast, less than half of the respondents felt hampered, in terms of making pertinent design decisions, by what they regarded as inadequacies in the information on natural ventilation design currently available to them (or that they were aware of). Reassuringly, not a single respondent perceived natural ventilation design as a topic that would constrain their freedom to create aesthetically-pleasing buildings.

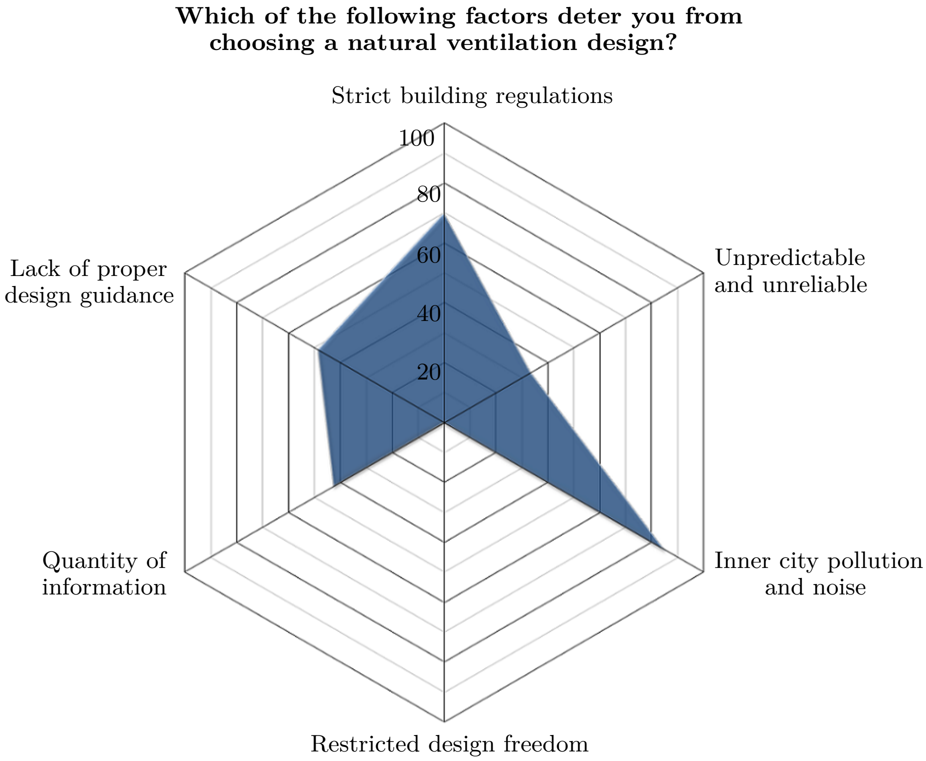


FIGURE 2.10: Radar chart showing perceived barriers to effective natural ventilation design. The percentage awarded to each barrier represents the number of votes it received divided by the total number (33) of participants.

2.4.6 Characteristics of preferred style and format for the presentation of natural ventilation design information

Terminology

Precision in scientific writing often dictates the use of technical terminology and mathematical notation. It is often difficult, if the author (*i.e.* technical researcher and/or practitioner) is deeply involved in their own subject/professional field, to realise that the most commonplace terms and ways of conveying information, widely recognised by a scientific audience, may be unfamiliar to others in different fields. This presentation style could hamper, or even prevent, the uptake and application of recent (or seasoned) research findings on natural ventilation.

Prior to the survey a list, comprising 24 terms relating to natural ventilation and aspects of its design, was devised (Table 2.3). These terms appear either in the design-based or science-based literature, and sometimes in both. Herein, we refer to terms appearing predominantly in the engineering/scientific literature as ‘technical’ terminologies, and to terms most often used in design-type literature as ‘architectural’ terminologies. The students were asked to select, amongst the 24 terms, those they are most familiar with.[9]

Technical terminologies used to describe or characterise natural ventilation flows were the least familiar.

Overall responses, ranked from most familiar to least familiar, are summarised in Table 2.3; technical terms are highlighted in red and architectural terms in blue.

Rank	Terminology	% respondents
1	Adaptive thermal comfort	100%(33)
2	Air changes per hour	100%(33)
3	Cooling load	100%(33)
4	Windcatcher	100%(33)
5	Cross ventilation	94%(31)
6	Solar chimney	91%(30)
7	Effective opening area	88%(29)
8	Single-sided ventilation	85%(28)
9	Buoyancy	85%(28)
10	Biomimicry	64%(21)
11	Exchange flow	61%(20)
12	Stratification	61%(20)
13	Heat flux	55%(18)
14	Draught Rating	48%(16)
15	Unidirectional flow	45%(15)
16	Bidirectional flow	39%(13)
17	Pressure coefficient	30%(10)
18	Displacement flow	27%(9)
19	Neutral pressure level	24%(8)
20	Streamlines	18%(6)
21	Thermal interface	15%(5)
22	Mixing flow	15%(5)
23	Discharge coefficient	15%(5)
24	Non-dimensional graph	0%(0%)

TABLE 2.3: List of 24 architectural and technical terms related to natural ventilation flows and natural ventilation design. The terms are ranked according to the number of votes each received (in parenthesis). Terms often appearing in design-type literature are highlighted in blue; those more commonly found in technical literature are in red. Terms in black are those that commonly appear in both technical and design-type literature.

The stark distinction seen, between the familiarity with architectural and technical terminologies, broadly indicates that the majority of the architectural students are unfamiliar with the technical terminologies relating to natural ventilation airflow and design that are widespread in the engineering/scientific literature. Of the 24 terms, 'Non-dimensional graph'

[9]The validity of the response is based on the premise that the respondent *understood* the meaning of the terms listed. Naturally, respondents could have deemed a particular term as 'familiar', having come across it in the open literature, without necessarily understanding the meaning of the term.

proved the least familiar. Other unfamiliar terms were 'Discharge coefficient', 'Mixing flow' and 'Thermal interface', which were each selected by five respondents.

Given 'displacement flows' (ranked a lowly 18th in terms of familiarity, Table 2.3) are regarded by design guides (*e.g.* CIBSE AM10 (CIBSE, 2005)) as one of the most effective methods of ventilation to expel excess heat and pollutants from within a building (compared with, for example, mixing flow or exchange flow, see also Hunt & Kaye (2006) and Coffey & Hunt (2007)), a somewhat surprising result was that only nine students selected the term 'Displacement flow'. In comparison, the term 'Exchange flow' received 20 ticks, again curious given that only five students expected exchange flow at the larger upper opening in the example building façade (Figure 2.7(b)).[10]

Fewer students were familiar with the term 'Thermal interface' compared with 'Stratification', also surprising given that the height of the interface above the floor is a key factor in determining occupant comfort, *e.g.* Linden *et al.* (1990), Hunt & Linden (1998), Gage *et al.* (2001), Kaye & Hunt (2004), Lomas (2007), Fitzgerald & Woods (2010), Etheridge (2011).

Schematics

The majority of respondents regarded the 'box-like' representation of a naturally ventilated space as acceptable, and not at all disrespectful to the architectural practice.

Since architects, in general, are an expertly visual audience, we conjectured that the 'box-like' depiction of a naturally ventilated space – that is, a simplified representation of a building envelope widely used in the mathematical analyses of room airflows – could be perceived by architects as 'disrespectful' to the architectural practice. After all, an architect's aspiration for creating impressive and unique building designs has, in essence, been abstracted and distilled into a simple rectangular box. With an aim of our study being to assess how best to convey information on natural ventilation effectively to architects, we were mindful that the simplified schematics used as a starting point for analysing airflows in buildings would not be perceived as discrediting their craft.

We enquired in our questionnaire as to whether the 'box-like' geometry of a ventilated space (Figure 2.11(b)) was deemed to be representative of the sketch of a building (Figure 2.11(a)). We then asked whether they perceive the 'box' (Figure 2.11(b)) to be disrespectful to their practice. The bar chart in Figure 2.12 summarises the responses.

[10] Note that the terms 'Exchange flow' and 'Bidirectional flow' are equivalent and are commonly used interchangeably in the ventilation literature, *e.g.* Linden *et al.* (1990), CIBSE (2005), Hunt & Coffey (2010). Curiously, our results indicate that the students were more familiar with the term 'Exchange flow' (20 ticks) compared to 'Bidirectional flow' (13 ticks), see Table 2.3.

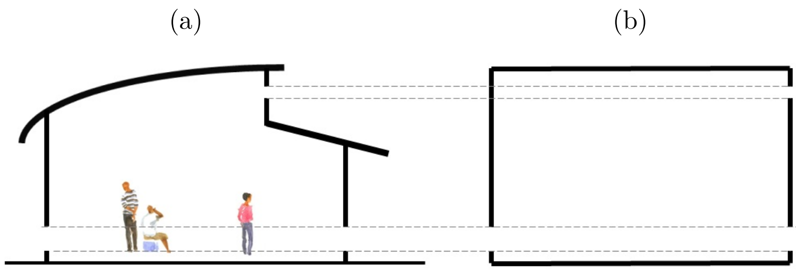


FIGURE 2.11: Two line drawings of a ventilated space in elevation with upper and lower openings. The schematic in (b) is a simplified representation of the sketch in (a). This form of simplification is typical of those used in scholarly articles which develop simplified mathematical models (and analogous experimental models) of airflow behaviour and stratification in naturally ventilated spaces, see Chapter 3 for a review. Construction lines linking (a) and (b) are drawn to indicate that the openings in both schematics are located at the same heights.

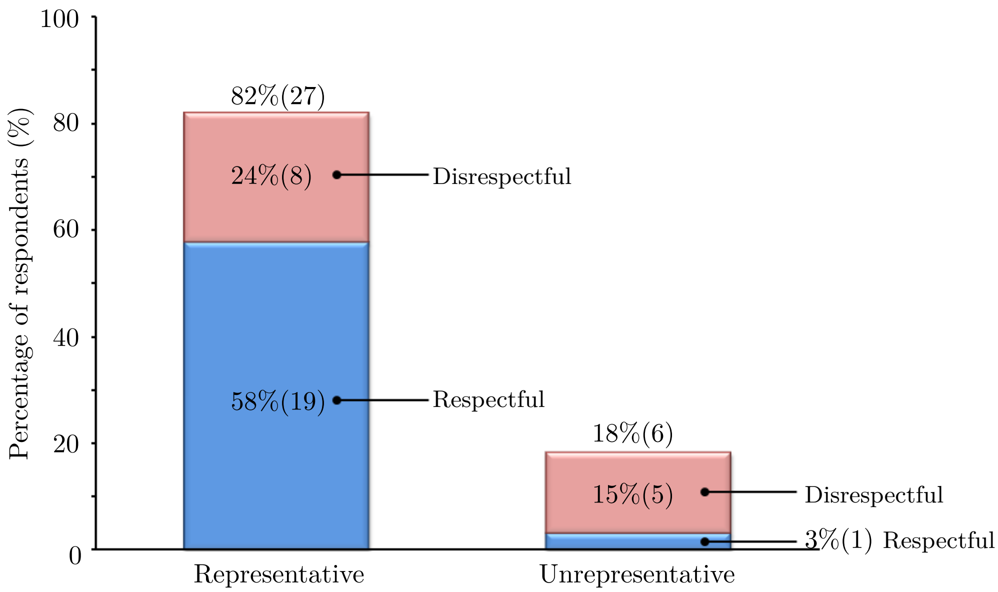


FIGURE 2.12: Stacked bar chart showing the percentage of respondents who regard the 'box-like' geometry in Figure 2.11(b) to be representative (left bar) or unrepresentative (right bar) of the building façade sketched in Figure 2.11(a). Each bar is further divided into those who regarded the box as 'respectful' (in blue) and as 'disrespectful' (in red). The number of respondents who selected a particular option is given in parenthesis.

Contrary to our initial presumption, our findings show that the respondents do not entirely reject the 'box-like' representation of a naturally ventilated space; 82% consider it to be 'representative', 58% of whom perceive it as 'respectful' (unfortunately, although invited, none of the students provided a reasoning for their choice). On the other hand, 18% rejected the 'box', 15% of whom consider it as 'disrespectful'. Two students commented that:

> "It [box-like space] is too abstract, I don't understand it."
>
> "It does not take into consideration the architectural interpretation of design strategies."

The students were then asked to resketch the 'box' in a form they saw fit. Most, if not all, included a 'ground line' to indicate the drawing is in elevation. They also included a sketch of an occupant within the space as a 'visual scale' that relates the height of a space to the height of an average person. Additionally, they included a slanted roof in their sketch to more closely represent the roof of the building in Figure 2.11(a). While there is no one ubiquitous typographical style which would be pleasing to every architect, the value of including the ground line, slanted roof and visual scale in a sketch was shared amongst the respondents. Drawing from some of their comments and suggestions, Figure 2.13 illustrates, what may be regarded as, characteristics of an 'ideal ventilated box schematic' as seen through the eyes of the architect.

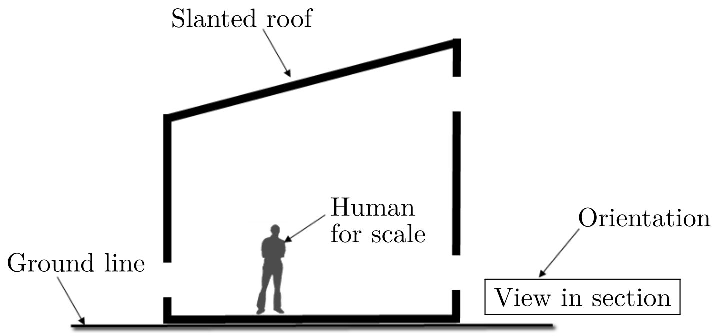


FIGURE 2.13: Illustration of an 'ideal ventilated box schematic', which may be regarded as a 'architecturally friendly' schematic of a simplified building envelope in comparison to the 'box-like' depiction in Figure 2.11(b).

Desirable qualities for future natural ventilation design guides

Our investigation revealed that there are some favoured ways of presenting information that are shared by the architectural students. Herein, we summarise the responses to their preferred format, style and level of detail for a future natural ventilation design guide perceived as congenial to their practice.

Desired format of a future design guide: published as a stand alone book.
The radar chart in Figure 2.14 indicates the responses to five different formats: a series of research papers, a stand alone (physical) book, RIBA[11] books, architectural digests, and 'other' (*e.g.* websites).

These findings indicate that over 90% would prefer a design guide to be published as a stand alone book, as opposed to alternative formats such as digests and journal articles (PDF documents) that are readily accessible online.

[11] RIBA is the acronym for the Royal Institute of British Architects.

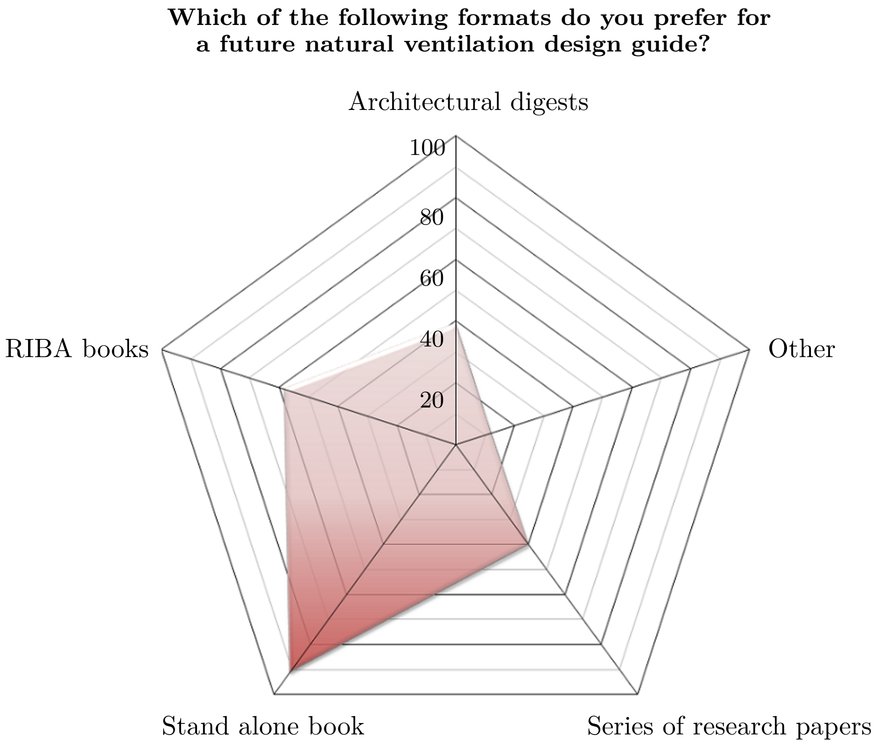


FIGURE 2.14: Radar chart showing the preferred formats for a natural ventilation design guide. Percentages represent the number of votes received divided by the total number (33) of participants.

Preferred level of detail for design guide: lengthy and detailed.
60% were in favour of a lengthy and detailed design guide on natural ventilation. Those who included a reasoning behind their choice wrote:

> "The longer the better. I like to understand what is behind the guide in detail."
> "A better understanding of principles allows for more creative solutions in design."
> "As architects, we need to justify for our design choices (to a client) and why we chose a particular ventilation strategy. It is better to know the details behind the strategy to have evidence to back us up."
> "We [architects] want to learn, and not just blindly input data into computer simulation programmes."

In contrast, 40% would prefer a short, brief and concise guide consisting of highly focussed (*i.e.* distilled) information on natural ventilation design. In particular, these respondents emphasised aspects of brevity and clarity as important since

> "Short design guides are easier and more practical to use and apply in a design."
> "They are quicker for me to read and to retrieve the right information I need. Long guides are too time-consuming."

Desired presentation style for design guide: visual information (such as diagrams, checklists, charts) with limited use of mathematical equations.
Opinions were sought on the desired style(s) of presentation of information for a future natural ventilation design guide. They could choose from a selection of styles consisting of: diagrams and schematics, charts and graphs, checklists, mathematical equations, or a combination of two or more styles. A summary of the responses is illustrated in Figure 2.15.

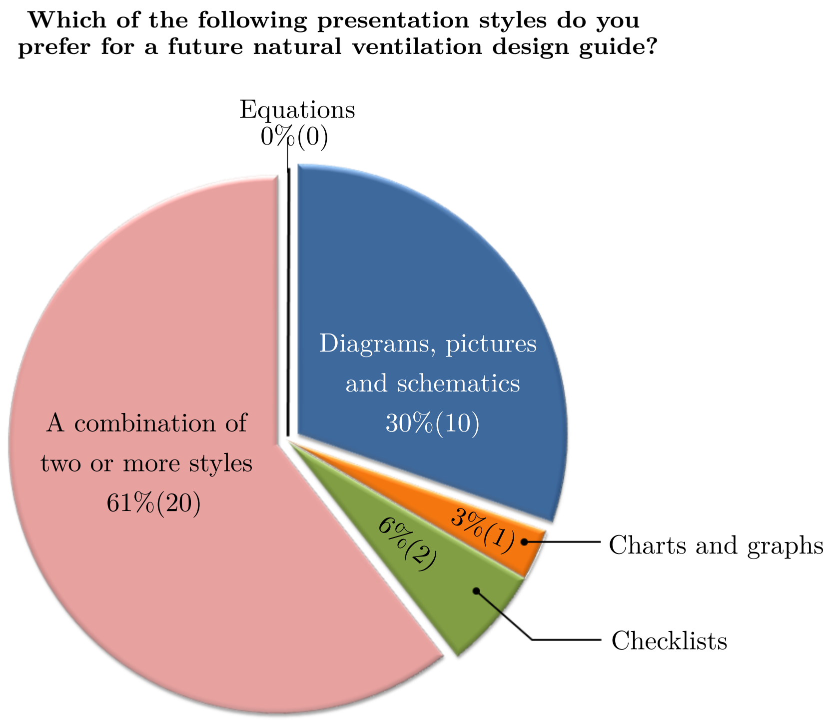


FIGURE 2.15: Pie chart illustrating the preferred presentation styles of a design guide for natural ventilation. The number who selected a particular option is given in parenthesis.

Figure 2.15 reveals that, above all others, the greatest preference is for pictorial presentation styles. Specifically, in excess of 60% would prefer a design guide to consist of a variety of diagrams, schematics, checklists, charts (and possibly equations); while 30% would prefer the guide to consist predominantly of diagrams and schematics only. A few respondents provided additional comments, giving the reasons behind their choice:

> "Use of imagery and diagrams allows me to understand concepts better, which is particularly important at the early stage of design."
>
> "Checklists help me remember the necessary information related to design."

Out of the 61% who requested for a combination of two or more styles, less than 10% desired mathematical equations, and unsurprisingly, none of the students wanted a design guide that consists solely of equations and is devoid of visual material. They commented that:

> "Too much theory and math equations only confuse me."
>
> "If I can't understand it, I can't use it. Physical concepts should be explained rather than using just formulae."

In our opinion, this particular finding does not suggest that the majority of respondents are reluctant to use mathematics, but rather that the majority prefer to understand the information they have at hand visually, particularly when trying to grasp/apply a new concept for the first time.

At the end of the questionnaire, participants were invited to offer additional suggestions for ways of enhancing the use of natural ventilation strategies in buildings by architects. The following is a synopsis of their opinions[12] in which a need was identified for:

- more user-friendly computer-aided design tools; tools specifically for predicting how the indoor climate (*e.g.* temperature and comfort) responds to changes made in design, and for enabling rapid demonstrations to clients and other architects in design meetings;
- design guidelines and guides that make greater use of rules-of-thumb. These rules-of-thumb should enable certain ventilation principles (no examples given) to be recalled quickly;
- greater access to case studies of precedent naturally ventilated buildings. These case studies should provide architects with a "proof of concept" and a broader "guidance to possible design options"; and
- greater awareness and public perception of the benefits of natural ventilation. It was stated that "occupants and architects should not view this [natural ventilation] as a step backwards, but a step forwards in making a difference to our environment."

2.5 General recommendations

The results that have emerged from this study may offer a few pointers for technical researchers/practitioners and course developers when next communicating to an architectural audience. These pointers are summarised in the form of a 'dissemination checklist' in Table 2.4.

As a general disclaimer, the checklist offers suggestions, rather than a set of requirements, which technical practitioners may consider, or refer to, when tailoring their work to be

[12] A total of five students provided this additional commentary.

read by architects. Although these suggestions may appear, at first sight, self explanatory or obvious, our findings herein would indicate that there is considerable scope to improve knowledge transfer, and as such, the checklist may prove valuable. Evidently, choices in presentation style have a significant bearing on whether work is read, appreciated and comprehended. Crucially, to enhance the uptake of research findings, it is essential that technical practitioners be aware of the conventions and terminologies that are particular to architects, as well as architects' unique means of assimilating information. For these reasons, we draw attention to the salient, likely taken-for-granted recommendations in Table 2.4.

2.6 Summary and conclusion

Our survey was conducted on a group of MA/MSc/MArch student architects to explore their current information needs regarding the design of naturally ventilated buildings. We designed the survey to be a 'sounding board' for architects' opinions; their opinions were sought on a range of natural ventilation specific matters, including on their vision for presenting technically-orientated information in a style congenial to their interests and practice. Whilst our findings cannot be regarded as representative of the viewpoints of all architects in general, they are a snapshot of the views of a small sample of talented young architects with interests in the field of sustainable building design and with some experience of life in an architectural practice/setting. Those surveyed are likely to be practising architects of the future and, as such, we regard their views as important.

The key results that emerged from our survey are as follows. Broadly, the respondents prefer to use familiar resources for early stage design guidance, specifically case studies of exemplar buildings, CIBSE guides and articles published in PLEA conference proceedings. They regard these resources as providing immediately applicable and reliable information in support of their problem-solving at the early stages of a natural ventilation design. A 'stand alone' book (physical, rather than electronic) was the most preferred form for future architect-specific design guidance, wherein it was recommended that case studies of exemplar naturally ventilated buildings be included as qualitative means of 'proof of design' and 'verification'. It was also recommended that design guidance be written in a lengthy and descriptive format with additional tailored short summaries that allow for quick retrieval of key facts and concepts. In terms of style, the preference was overwhelmingly for visual presentation – specifically using scaled drawings and familiar architectural conventions. For example, simple schematics of a naturally ventilated building envelope should include a 'human' and a 'ground line' to indicate, qualitatively, scale and orientation.

Whilst our survey has echoed the importance of 'good' presentation in the information transfer process, previous findings (§2.2) on the selective information requirements of architects emphasise that the presentation of information is simply one factor, amongst a number of others, affecting the exposure, uptake and application of research findings by architects. Constraints on architects' capacity to access and use information appear to be deeply rooted in their prior experience and training which, in turn, are externalised in their belief systems, learning styles and preferred means of obtaining information. Professional liability and the perceived inconvenience and risk associated with the use of unfamiliar sources of information may also conspire to make architects conservative in efforts to obtain and use certain types of information (Burnette, 1979). These factors are capable of crystallising architects' judgements of the perceived value of the information they have at hand.

Nevertheless, our study has made important practical contributions by identifying a number of factors that currently affect, detrimentally, the transfer and impact of technical information from engineering/scientific spheres to end users within the architectural community. Crucially, we identified that there is a need to position the key design-relevant information in the hands of the end user and this survey has (i) served to expose many avenues in which knowledge transfer can be improved and (ii) prompted and guided the specific recommendations made herein regarding the style and format for guidance that may help streamline the delivery of technical information to architects.

Recommendation	Key points
Simplify technical terminologies	• Use 'architectural' or layman vocabulary where possible • Avoid the use of 'technically-focussed' terminology and mathematical notation that are unfamiliar to architects
Make title and content relevant to architects	• Place the title and content of the research within a design context that is directly relevant to architects • Translate technical information into an appropriate format and style that is suited for a particular stage in a natural ventilation design process. For example, the use of design charts and simple schematics to provide straightforward guidance at the early stage of a natural ventilation design
Include tailored short summaries	• Include a concise summary of key facts and concepts that is straight to the point • Present a summary, or summaries, in which key information can be quickly grasped and its relevance to the design highlighted
Present information predominantly through visual means	• Use scaled drawings and illustrations that are familiar to architects. For example, include a human for scale and ground line in schematics of building form • Design charts and checklists are also a favourable means of providing information that is immediate, intuitive and easily applicable in design
Provide evidence-based reassurance	• Provide architects with concrete facts and examples that reassure them to apply (and how to apply) the results. For example, use case studies of naturally ventilated buildings that are approved and recognised by architects
Present information so that it can be easily remembered and recalled	• Assist architects in their 'memory retrieval' of information. For example, the use of mnemonics such as *aide-mémoires* (*e.g.* the "ventilation triangle" proposed by Hunt & Linden (1999), see Figure 3.8) can generate information that is immediate, easily comprehended and recalled
Publish in journals which architects recognise and value	• Publish work in journals which architects are accustomed to reading/consulting and are, therefore, regarded as trustworthy and accessible • Specifically, publish work in interdisciplinary journals such as, 'Building and Environment', 'Energy and Buildings' and 'Architectural Science Review'

Table 2.4: 'Dissemination checklist' with suggestions for enhancing the uptake of technical information on natural ventilation design by architects.

Chapter 3

Essential background and literature review

Preamble

Undeniably, there is a well-established and growing body of information on natural ventilation emanating from the technical resource base which would be useful to architects in a ventilation design. Whilst considerable efforts have been expended by the Building Research Establishment since the 1960s towards improving the communication of technical information to architects (*e.g.* Goodey & Matthew (1971), see §2.2), the findings from our survey (Chapter 2) revealed that the bulk of the information on natural ventilation, widely documented in the fluid mechanics literature, still remains largely unexploited by architects. In particular, our findings showed that architects prefer to consult design guides and case studies of precedent projects, rather than engineering/scientific journals, when seeking to understand new or unfamiliar concepts associated with natural ventilation (see Figure 2.2, for example). This may be, in part, rooted in the perception that very little academic research is made relevant or pertinent to their practice. Our findings also suggested that there is an apparent lack of knowledge on how to achieve desirable airflow rates and temperatures in buildings with regards to the correct sizing of ventilation openings in a façade. This was particularly noteworthy and has served to reinforce the need to tackle the key design questions in §1.3.1, and crucially, to develop architect-focussed design guidance specifically for the sizing of individual ventilation openings.

In this chapter we introduce the fluid mechanics literature and fundamental concepts that describe air and heat flows through naturally ventilated buildings, essential for an appreciation of the work covered in later chapters. Herein, we do not attempt to give an exhaustive review of the entire field (in terms of the range of topics discussed or the studies cited). Rather, the intention is to synthesise and summarise the information on specifically chosen (and pertinent) topics of natural ventilation in order to show where the current work sits within a broader context, and to provide the necessary theoretical background that is linked to the objectives of the work. Specifically, we describe the relevant literature and mathematical models in support of the design questions, highlighting the key results of the models, the physical implications of these and scope for applying them to inform preliminary design.

Note that the mathematical models described in this chapter can in no way capture all of the details that are required to provide a complete picture of the behaviour of an entire building ventilation system. However, as reasoned in §1.2.3, simplified mathematical models have the capacity to afford intuitive understanding by elucidating the basic relationships between key design variables, such as airflow rates, indoor temperatures/stratification, heat inputs and vent areas. Insight into the underlying relationships between key variables is an essential ingredient for establishing a fundamental understanding of natural ventilation systems, and more importantly, of how changes in design (*e.g.* increasing the floor-to-ceiling height, adjusting the area of the upper and/or lower vents, *etc.*) affect the overall ventilation. It is exactly this lack of fundamental and intuitive understanding that underpins the shortcomings of the existing, and notably accepted, design guides on natural ventilation, and the second part of this chapter focusses on exposing this aspect.

3.1 Introduction

The concept and basic principles of natural ventilation linked to cooling and ventilating are well-established and have been integrated into vernacular architecture for centuries (Short, 2017; Sayigh, 2019). In essence, natural ventilation exploits two naturally occurring forces – wind and buoyancy – to drive a flow of air through a building; the wind acting on the building creates pressure differences between openings positioned on the windward and leeward façades (*e.g.* positive pressure on the windward façade and negative pressure on the leeward façade), whereas the accumulation of warm, buoyant air within the building leads to differences in air pressure between the interior and exterior environments (*e.g.* the pressure difference between the upper and lower levels on the inside is less than the pressure difference between the upper and lower levels on the outside).

Although the basic driving mechanisms of natural ventilation may be relatively straightforward, the behaviour of ventilating flows through buildings is inherently complex and is governed by a number of interdependent variables. As discussed later in this chapter, the ventilation is sensitive not only to the size and location of the openings, but also to the strength, geometry and spatial distribution of the heat sources. Other variables affecting the ventilation include, for example, the details of the opening geometry, the thermal properties of the building fabric, and the speed and direction of the wind. These variables in turn set the pattern of air movement, such as the bulk direction of airflow through the openings and the thermal stratification. The resulting flow pattern is absolutely central to the performance of the ventilation system, as it determines not only the bulk airflow rate through the space, but also the indoor temperature distribution, all of which affect the comfort of occupants.

In the context of a natural ventilation design, one of the main challenges is to ensure that the intended airflow pattern is realised. A common misconception, as identified in our survey, is that unidirectional flow is established by simply placing openings at upper and lower levels in a façade (see, for example, Figure 2.9). As mentioned earlier, this pattern of flow is not always guaranteed. Previous experimental work of stack ventilation in rooms by Hunt & Coffey (2010) showed that ambient air could enter the interior (via either the upper and/or lower openings) leading to varying degrees of internal mixing and stratification breakdown. Moreover, *in situ* measurements of some naturally ventilated buildings reported by Fitzgerald & Woods (2007) and Eicker (2009) revealed that multiple flow patterns (other than the anticipated discharge of warm air from the interior) occurred during operation, some of which were not considered at the design stage.

Some examples of problematic flow patterns that can occur in naturally ventilated buildings are illustrated in Figure 3.1. Exchange flows, in which simultaneous outflow and inflow occur at the upper opening (Figure 3.1(a)), can reduce net ventilation flow rates and increase indoor air temperatures because an inflow occurs at what should be an outlet vent (Coffey & Hunt, 2004*b*; Larice, 2009; Hunt & Coffey, 2010). Even worse, strong winds can lead to a complete flow reversal (Figure 3.1(b)), whereby the wind drives a flow from high to low level, opposite to the stack-driven flow. In this situation, outdoor air enters the interior through the upper opening and 'pushes' warm air downwards and out through the lower opening (Hunt & Linden, 2005; Lishman & Woods, 2006; Coomaraswamy & Caulfield, 2011).

Localised overheating can occur (Figure 3.1(c)), particularly in tall open spaces, such as atria and lecture theatres, where a strong stratification is likely to exist (Kenton *et al.*, 2004). Occupants may be exposed to a significant temperature variation over their body, with higher than designed for air temperatures within the breathing zone and cold air near the feet (Linden & Cooper, 1996; Cooper & Linden, 1996; Hunt & Linden, 1998; Kaye & Hunt, 2004; Bower *et al.*, 2008; Shrinivas & Hunt, 2014*a*). A cool draught of air through openings may also pose a risk to comfort due to, for example, air moving rapidly in the vicinity of the occupants (Figure 3.1(d)). Draughts are also capable of inducing significant mixing

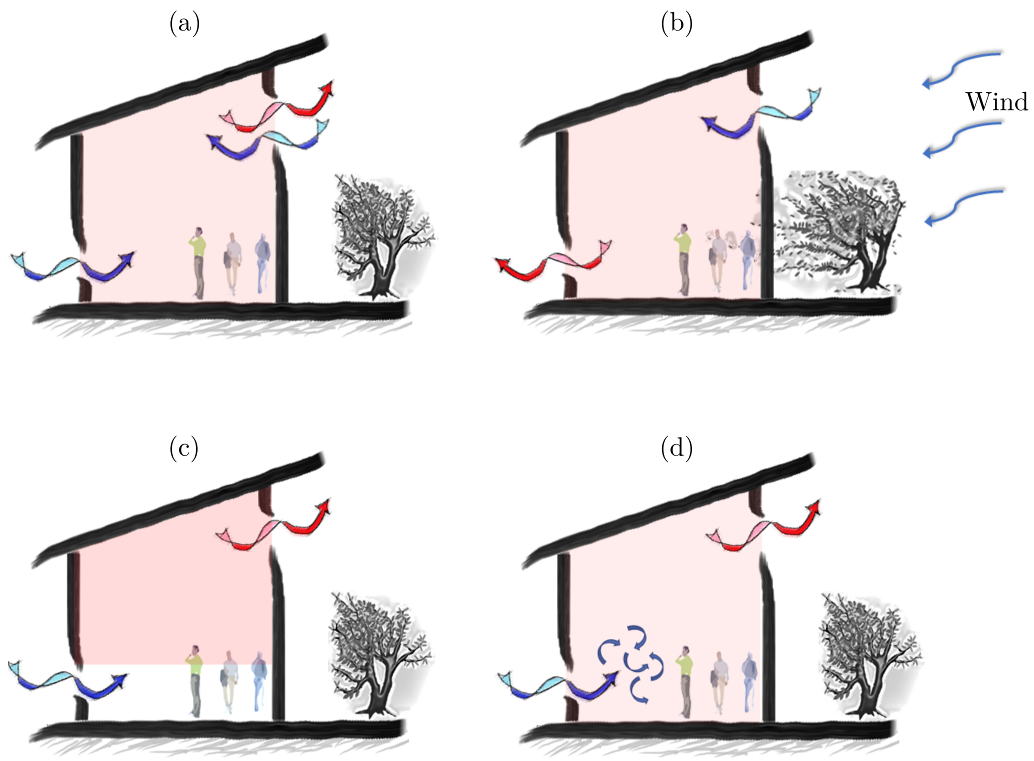


FIGURE 3.1: An artistic representation of a single storey building showing four examples of problematic airflow patterns that can occur in a naturally ventilated space. (a) Exchange flow at the upper opening, leading to reduced ventilation flow rates and higher indoor air temperatures. (b) Reversed flow through the building due to a strongly opposing wind. (c) Localised overheating in the occupied part of the building, in which occupants experience a higher than designed for air temperature. (d) High inflow velocities through low-level openings can induce significant mixing within the space, resulting in a potentially draughty indoor environment for occupants.

within a room, which can impact the form of the thermal stratification and the temperature distribution, and hence the comfort of occupants (Coffey & Hunt, 2004*a*; Larice, 2009; Coffey & Hunt, 2010).

3.1.1 Design guidance, or a lack thereof

The examples in Figure 3.1 are intended to highlight that, even within a single space, a range of airflow patterns is possible, other than the anticipated unidirectional (out)flow. In particular, these are the airflow patterns that are identified in this thesis to be generally undesirable in terms of meeting design targets for ventilation flow rates, internal air temperatures and thermal comfort; although in §3.5.2 we comment on how mixing by the cool draught of air can be advantageous in certain situations. The design questions posed in §1.3.1, which are addressed in the subsequent chapters, are aimed at avoiding (or, at least, minimising) some of these problems.

Identifying the key variables that govern airflows in naturally ventilated buildings, if undesirable airflow patterns are to be avoided, is therefore an essential step in design. Several key studies have focussed on combining simplified mathematical models with small-scale analogue laboratory experiments in water tanks in order to gain fundamental insights into the fluid mechanics that control ventilation flows; the references cited above are some examples of these. However, while significant headway has been made in the science underlying and explaining natural ventilation, the question of how to exploit this technical knowledge base to provide coherent, intuitive and accessible design guidance for architects (as well as ventilation engineers and consultants) has remained open for some time now.

Indeed, building standards and design guides/manuals, such as the British Standard (BSI, 1991) and CIBSE AM10 (CIBSE, 2005), are underpinned by the technical research base. In addition to outlining design criteria for natural ventilation, design guides typically present a number of recommendations or *modus operandi* for determining airflow rates and opening areas. However, while some do claim to specify the total opening area required to achieve a specific airflow rate, in this chapter we show that they only do so erroneously, with limited appreciation of the basic fluid mechanics underlying ventilation flows. An oversight of the underlying physics is critical, as it may lead to unintended errors in design specifications, leading (in turn) to the possibility of undesirable flow patterns, such as those shown in Figure 3.1.

In an effort to identify and thereby address the pertinent information gaps on natural ventilation between the technical- and design-based journals, this chapter is separated into two parts. In Part I we review the existing fluid mechanics literature and mathematical models which capture the fundamental physics of natural ventilation. Only literature directly relevant to the thesis is addressed in detail, although core concepts crucial to developing a broader understanding of natural ventilation flows are introduced. The intention is to lay down the 'building blocks' that comprise the mathematical modelling of room airflows, which we use in the later chapters to answer the key design questions. In Part II we draw on the key studies and concepts introduced in Part I to highlight a number of potentially misleading recommendations from the existing design guides on natural ventilation.

Part I: the fluid mechanics of natural ventilation

3.2 A simplified mathematical model

This review focusses on the airflow patterns established in a single storey building. Whilst real buildings come in an array of shapes and sizes, and often comprised of an interconnection of multiple spaces, it is simplest to start by considering the airflow through a single space, and the vast majority of the work on natural ventilation to date focusses on this situation. This simplified approach is not unreasonable as an understanding of the flow behaviour in a single space is absolutely rudimentary for more complex building geometries.

Figure 3.2 shows a simplified representation of a naturally ventilated enclosure, which is commonly used in the mathematical modelling of room airflows (*e.g.* Linden *et al.* (1990), Cooper & Linden (1996), Hunt & Linden (2001) and Hunt & Coffey (2010), amongst others). The enclosure is 'box-like' in geometry with either (a) horizontal openings or (b) vertical openings positioned at high and low levels in the façade. When air inside the enclosure is heated above that of the outside air, the arrangement of openings at high and low levels encourages air to flow through the space via the stack effect. The simplified abstraction of a real building shown in Figure 3.2, which is applied extensively throughout the thesis, will form the focus of much of this review.

In general, a standard simplified mathematical model of this description (Figure 3.2) is comprised of three fundamental components: (1) a pressure balance – based on tracing the change in total pressure along a streamline as it passes through each opening and applying the hydrostatic pressure relationship both inside and outside the box – to relate the drop in pressure across the openings to the driving stack pressure, (2) a flow rate balance – based on the conservation of volume within the box – to link the pressure drop across the openings to the bulk ventilation flow rate and opening areas, and (3) a heat balance – based on the conservation of buoyancy within the box – to relate heat inputs (and losses) to indoor air temperatures and ventilation flow rates. The subsequent sections will expand on each of the components listed above.

Pressure (and flow rate) balance: We begin in §3.3 by focussing on the steady stack ventilation in an isolated room comprised of a general temperature distribution. We outline the main controlling mechanisms that drive ventilating flows, and introduce a number of key concepts and ventilation terminologies which are used in later chapters. By considering the case of a room ventilated by stack effect only, we show how the balance between the

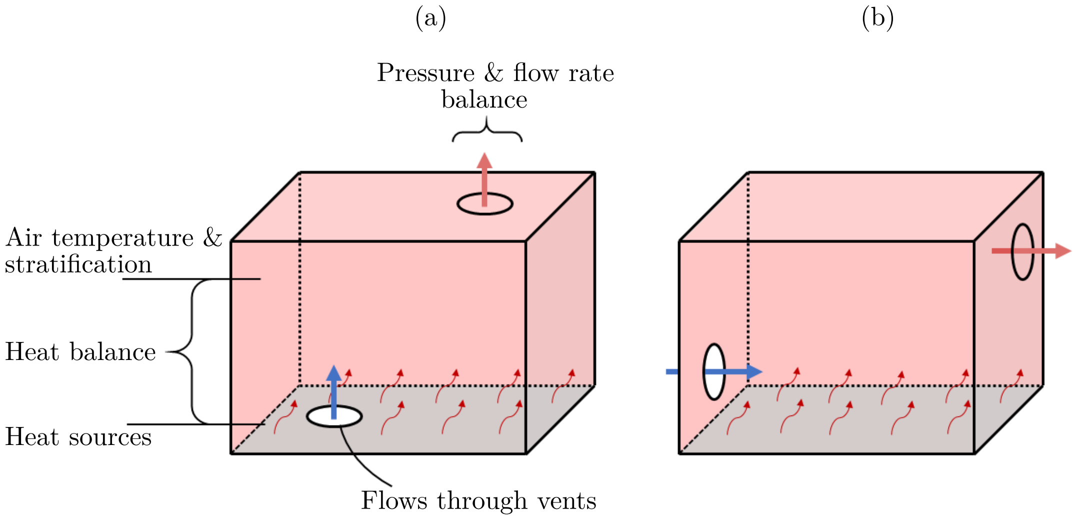


FIGURE 3.2: Schematics showing an idealised naturally ventilated box with (a) horizontal openings and (b) vertical openings made at the upper and lower levels. Internal sources of heat (depicted by curly arrows) lead to vertical gradients in air temperature (thermal stratification). The accumulation of warm, buoyant air inside the box, in turn, generates differences in temperature between the internal and external environments. This difference in air temperature provides the stack pressure to drive a flow of air through the openings. Arrows drawn at the openings depict the direction of airflow through the box.

driving stack pressure and the drop in pressure across the openings can be expressed in terms of the bulk ventilation flow rate, the effective area of the openings and the differences in air temperature between the indoor and outdoor environments (*cf.* Linden *et al.* (1990), Acred (2014)).

Flows through vents: In §3.3.3 we review the literature on the discharge coefficient, which accounts for the loss in total pressure experienced by the flow through an opening. We describe the significance of the discharge coefficient and the potential impact of its associated uncertainty in ventilation flow rate predictions.

Heat balance: In §3.3.4 we introduce the general heat balance for a single room and show how it can be expressed in terms of a balance between the heat input within the space, the heat losses associated with the ventilating flow and through the building fabric.

Heat sources and stratification: The manner in which heat sources stratify a space is closely linked to the geometry and spatial distribution of the heat sources. In §3.4 we provide an overview of how the heat source geometry can affect the form of the resulting stratification, which is an essential part of indoor comfort.

Vent area configuration and airflow patterns: In §3.5 we describe how the size and relative areas of the openings influence the airflow pattern in a room. In particular, we focus on the work by Hunt & Coffey (2010), which is crucial for identifying the transition from unidirectional to exchange flow at the openings.

Wind pressure: Finally, in §3.6 we discuss the general effects of wind on the stack ventilation of a room, which can contribute significantly to assisting or, in some cases, opposing ventilation flows. We show how the pressure balance equation introduced in §3.3 for stack ventilation can be extended with an additional term to account for the wind.

3.3 Stack ventilation of rooms

3.3.1 Variation in air density

The stack effect arises due to variations in air density between the internal and external environments. This density difference, which is the result of a difference in temperature between the indoor and outdoor air, produces the buoyancy force that drives the ventilating flow. It is convenient to quantify the buoyancy of air in a room in terms of a reduced gravity. For an unstratified external environment, the reduced gravity is given by

$$g'_{\text{int}}(z) = g\left(\frac{\rho_{\text{ext}} - \rho_{\text{int}}(z)}{\rho_0}\right) \tag{3.1}$$

(*cf.* Morton *et al.* (1956), Linden *et al.* (1990)), where g is the gravitational acceleration, ρ_{ext} and ρ_0 are the external air density and reference density, respectively, and $\rho_{\text{int}}(z)$ is the density of the internal air at a vertical distance z from the floor. For typical building ventilation flows (except in situations where a strong fire is involved), it is customary to assume that density differences are small compared to ρ_0, such that $(\rho_{\text{ext}} - \rho_{\text{int}}(z))/\rho_0 \ll 1$; in fluid mechanics, this is commonly referred to as the *Boussinesq approximation*. For Boussinesq flows, the choice of ρ_0 is unimportant and is usually taken to be the density of the external air (Linden, 2000). For air, which is well-represented as an ideal gas, the reduced gravity can be expressed in terms of relative temperatures given by

$$g'_{\text{int}}(z) = g\left(\frac{T_{\text{int}}(z) - T_{\text{ext}}}{273 + T_{\text{ext}}}\right), \tag{3.2}$$

where $T_{\text{int}}(z)$ and T_{ext} are the temperatures of the internal and external air (in degrees Celsius), respectively. This definition of the reduced gravity is, in general, more intuitive for practical design.

3.3.2 Pressure balance

Indoor and outdoor pressure variations

In order to show how flow through an enclosure can be expressed in terms of a balance between the driving stack pressure and the pressure losses at the openings, we consider a simple example of a naturally ventilated room, as shown in Figure 3.3(a). Air within the room is warmer compared to the (wind-free and unstratified) external environment with density ρ_{ext}. Horizontal openings, each of area a_{t} and a_{b}, are made at the ceiling ($z = H$) and floor ($z = 0$) levels, respectively, and H denotes the vertical separation between the openings. The room is comprised of a general temperature distribution ($g'_{\mathrm{int}}(z) > 0$), with cooler air near the floor and warmer air near the ceiling. The ventilation flow rates through the floor- and ceiling-level openings are denoted Q_{b} and Q_{t}, respectively. The example room shown in Figure 3.3(a) is a direct analogue of the mathematical model, and complementary experiments, of Linden *et al.* (1990) who examined the steady stack-driven flow and stratification that arise within a ventilated box (known as the 'emptying-filling box' model).

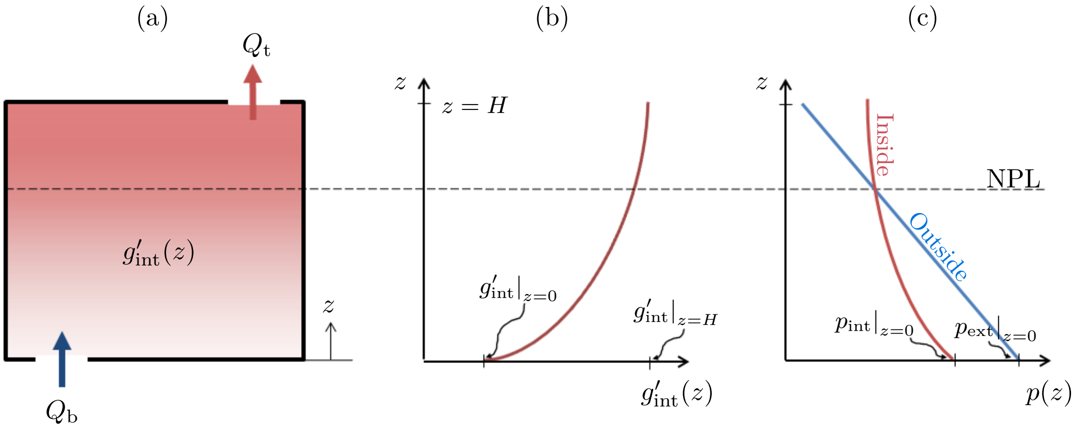


FIGURE 3.3: Schematics showing (a) a naturally ventilated room in elevation containing a general indoor temperature distribution, (b) the vertical variation of the local buoyancy (reduced gravity) with height from the floor and (c) the vertical variation of the internal and external air pressures with height. The dashed line drawn on the figure denotes the position of the neutral pressure level (NPL).

Away from the openings, the airflow velocity is typically assumed to be sufficiently small such that the pressure distribution everywhere, both inside and outside the room (except at the openings), is hydrostatic, *i.e.*

$$\frac{\mathrm{d}p}{\mathrm{d}z} = -\rho(z)g. \tag{3.3}$$

The hydrostatic pressure distribution implies that, compared with the outside, there is a higher pressure inside the room at the ceiling and a lower pressure at the floor (Figure 3.3(c)). On integrating Equation (3.3) with height, the pressure difference between the floor and ceiling levels within the room is given by

$$\Delta p_{\mathrm{int}} = g \int_0^H \rho_{\mathrm{int}}(z)\,\mathrm{d}z, \tag{3.4}$$

where $\Delta p_{\mathrm{int}} = p_{\mathrm{int}}|_{z=0} - p_{\mathrm{int}}|_{z=H}$; the subscripts '$z = 0$' and '$z = H$' reading 'at the floor' and 'at the ceiling', respectively. Assuming there is no vertical variation in ρ_{ext}, a reasonable assumption given the relatively small changes in atmospheric air density over the vertical height considered in a room (typically $< 10\,\mathrm{m}$), the outdoor pressure variation is therefore linear, *i.e.*

$$\Delta p_{\mathrm{ext}} = g\rho_{\mathrm{ext}}H, \tag{3.5}$$

where $\Delta p_{\mathrm{ext}} = p_{\mathrm{ext}}|_{z=0} - p_{\mathrm{ext}}|_{z=H}$.

There is a height at which the air pressures inside and outside the room are equal. This is commonly referred to as the 'neutral pressure level' (Linden *et al.*, 1990; Hunt & Coffey, 2010), denoted NPL in short form. Below the NPL, the pressure on the inside is less than the pressure on the outside so that the opening positioned below the NPL acts as an inlet for cool air. Conversely, above the NPL, the indoor pressure is greater than that on the outside, and so the opening positioned above the NPL acts (preferentially) as an outlet for warm air. However, note that this may not always be the case in practice. As discussed later in §3.5, the occurrence of exchange flow at the upper opening is possible even when the opening is placed above the NPL (Hunt & Coffey, 2010), *i.e.* what would typically be regarded as an 'outlet' vent for warm air.[1]

Pressure drop across openings

While openings encountered in buildings are typically of different shape, in general most purpose-provided openings (such as air vents) are characterised as 'sharp-edged' openings (Etheridge & Sandberg, 1996; Etheridge, 2011). The term 'sharp-edged' means that the depth l of the opening (the direction of airflow through it) is small compared to its diameter D, such that $l/D \ll 1$. Figure 3.4 shows a schematic of a sharp-edged opening with cross-sectional area a, diameter D and depth l.

For sufficiently high Reynolds numbers (Re $\gtrsim$ 4000), Ward-Smith (1980) and Idelchik (1986) observed that the flow through a sharp-edged opening exhibits the same general characteristics, regardless of the details of the opening geometry; the flow accelerates and contracts as it enters the opening and following the contraction there is an expansion.

There is a drop in pressure as flow contracts to pass through an opening. By tracing the change in total pressure along a streamline through each opening in Figure 3.3(a) using

[1] Hunt & Coffey (2010) showed that exchange flow at the upper opening commences when the NPL is less than approximately $0.15\sqrt{a_{\mathrm{t}}}$ below the level of the upper opening. Experimental observations by Hunt & Coffey (2010) showed that small fluctuations in the external environment may trigger 'fingers' of ambient density fluid to grow and enter through the upper opening; see the region denoted A in Figure 8(b) of their paper, for example. They suggested that if these fingers grow to reach the NPL before being advected back out of the opening, they will continue to grow and remain within the enclosure. In other words, if the NPL is sufficiently close to the upper opening, exchange flow commences. The closer the NPL to the upper opening, the greater the number of fingers expected to grow to the NPL and so the stronger the inward flow of cool air through the opening (Hunt & Coffey, 2010).

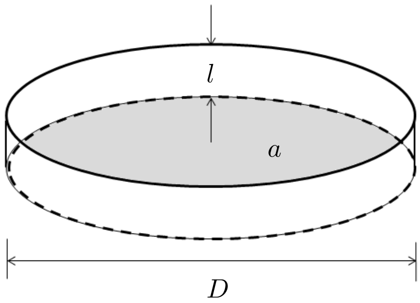


FIGURE 3.4: Schematic showing a sharp-edged circular opening with cross-sectional area a (m^2), diameter D (m) and depth l (m).

Bernoulli's theorem, by applying the Boussinesq approximation, and by assuming a uniform velocity profile across the openings, the pressure drop Δp_{vent} across the floor- and ceiling-level openings can be expressed in terms of the (unidirectional) flow rate Q and opening area a as follows (*cf.* Aynsley *et al.* (1977), Acred & Hunt (2014*a*)):

$$\Delta p_{\text{vent,b}} = \frac{\rho_{\text{ext}} Q_{\text{b}}^2}{2c_{\text{b}}^2 a_{\text{b}}^2} \quad \text{and} \quad \Delta p_{\text{vent,t}} = \frac{\rho_{\text{ext}} Q_{\text{t}}^2}{2c_{\text{t}}^2 a_{\text{t}}^2}, \tag{3.6}$$

where the subscripts 'b' and 't' on Δp_{vent}, Q, a and c denote the value of the variable at the 'floor vent' and 'ceiling vent', respectively.[2] The quantity c, which appears prominently in the above expressions, is the discharge (or loss) coefficient and accounts for all the effects that cause a drop in total pressure as flow passes through the opening; a convenient all-encompassing coefficient which essentially 'wraps up' much of the complicated physics of the flow in the region of the opening including (but not limited to) differences in air density across the opening (Hunt & Holford, 2000; Holford & Hunt, 2001), flow contraction and frictional effects (Ward-Smith, 1980; Idelchik, 1986). The significance of the discharge coefficient in ventilation flow rate calculations is discussed in greater detail in §3.3.3, with particular attention to its (empirical) value.

Driving stack pressure and ventilation flow rate

Following the "loop equation" method described by Axley (1998) and Acred (2014) – a technique based on tracing the change in pressures along a flow path around a closed ventilation 'loop' through the enclosure from the inlet opening to the outlet and from the outlet through the exterior back to the inlet again – the net change in pressure along the flow path

[2]Note that the pressure drop Δp_{vent} across the opening refers to the difference between the air pressure prior to flow contraction (away from the opening) and the air pressure immediately downstream of the opening at the *vena contracta* – that is, the plane at which the streamlines within the streamtube are parallel to the direction of flow, *i.e.* the streamlines are neither converging or diverging. At the *vena contracta*, the flow is neither accelerating or decelerating, which implies that the static pressures, both inside and outside the streamtube, are constant everywhere in the plane of the *vena contracta*.

is given by

$$\Delta p_{\text{vent,b}} + \Delta p_{\text{int}} + \Delta p_{\text{vent,t}} - \Delta p_{\text{ext}} = 0. \tag{3.7}$$

Acred (2014) showed that the net change in pressure (Equation (3.7)) can be expressed in terms of a balance between the stack pressure, which drives the ventilating flow, and the drop in pressure, which characterises the resistance the openings pose to the ventilating flow:

$$\underbrace{\Delta p_{\text{vent,b}} + \Delta p_{\text{vent,t}}}_{\substack{\text{pressure drop}\\ \text{across openings}}} = \underbrace{\Delta p_{\text{ext}} - \Delta p_{\text{int}}}_{\substack{\text{driving stack}\\ \text{pressure}}} . \tag{3.8}$$

Substituting Equations (3.4)–(3.6) into (3.8), and applying volume conservation such that the total flow rate into and out of the room are equal (*i.e.* $Q = Q_{\text{b}} = Q_{\text{t}}$),

$$\begin{aligned} Q^2 \rho_{\text{ext}} \left(\frac{1}{2c_{\text{b}}^2 a_{\text{b}}^2} + \frac{1}{2c_{\text{t}}^2 a_{\text{t}}^2} \right) &= g \int_0^H \left(\rho_{\text{ext}} - \rho_{\text{int}}(z) \right) \mathrm{d}z \\ &= \underbrace{\rho_{\text{ext}} \int_0^H g'_{\text{int}}(z)\, \mathrm{d}z}_{\substack{\text{driving stack}\\ \text{pressure}}} . \end{aligned} \tag{3.9}$$

Dividing Equation (3.9) through by ρ_{ext} and rearranging to make Q the subject, the total ventilation flow rate through the openings is given by

$$Q = A^* \left(\int_0^H g'_{\text{int}}(z)\, \mathrm{d}z \right)^{1/2} , \tag{3.10}$$

where

$$A^* = \left(\frac{1}{2c_{\text{b}}^2 a_{\text{b}}^2} + \frac{1}{2c_{\text{t}}^2 a_{\text{t}}^2} \right)^{-1/2} \tag{3.11}$$

is the total effective area for the upper and lower openings. The above expression relates the (unidirectional) flow rate to the stack pressure resulting from the accumulation of buoyancy within the space, and follows directly from the experimentally validated emptying-filling box model of Linden *et al.* (1990). Equation (3.10) essentially shows that the ventilation flow rate can be increased by increasing the vertical distance between the openings, by increasing the indoor-outdoor temperature difference, or by increasing the effective area of the openings (for albeit a limited subset of opening area combinations only, see §3.5).

3.3.3 The discharge (or loss) coefficient

The discharge coefficients, c_{b} and c_{t}, were introduced earlier in order to account for flow contraction and the loss in pressure across an opening. In general, the discharge coefficient may be regarded as the ratio of the actual airflow rate Q through an opening (found by measurement in a real flow) to the predicted airflow rate Q_{ideal} based on idealised inviscid flow theory – which assumes a uniform velocity profile across the opening and that there is no subsequent contraction after passing the opening – for a given pressure drop (*cf.* Hunt & Holford (2000), Etheridge (2011)):

$$c = \frac{Q}{Q_{\text{ideal}}} = \frac{Q}{a\sqrt{2\Delta p_{\text{vent}}/\rho}}. \tag{3.12}$$

The actual airflow rate, however, will depend additionally on the Reynolds number of the flow, the geometry and surface roughness of the opening, and the density contrast between the flow and the ambient surrounding across the opening.

Batchelor (1967) showed that the geometry and surface roughness of an opening can influence the value of the discharge coefficient. In the absence of a density contrast, Batchelor (1967) recorded that, except for some peculiar shaped openings, the discharge coefficient lies between $c = 0.5$ (for sharp-edge openings) and $c = 1$ (for smooth openings). In addition to opening geometry, Ward-Smith (1980) showed that the discharge coefficient exhibits a Reynolds number dependence. For high Reynolds number flows (in excess of 10^3) through sharp-edged openings, Ward-Smith (1980) suggests $c = 0.6$. For horizontal openings supporting unidirectional flow, Linden *et al.* (1990) reported that their experimental data fell within a range bounded by the theoretical predictions using $c = 0.5$ and $c = 1$ for sharp-edged and smooth openings, respectively. Larice (2009) considered a similar experimental configuration as Linden *et al.* (1990) and deduced $c = 0.63 \pm 0.02$ for sharp-edged horizontal openings. Full-scale tracer gas measurements of airflows in a multi-storey building by Flourentzou *et al.* (1998) found $c = 0.6 \pm 0.1$.

Variations in the value of the discharge coefficient have also been reported in the literature. For example, measurements made in a full-scale test room by Heiselberg *et al.* (2001) showed that the discharge coefficient fell in the range $0.6 \lesssim c \lesssim 1.1$ for windows hinged at the side and at the bottom; note that values of $c > 1.0$ are not physical (although Heiselberg *et al.* (2001) offer no reasoning for this).

Moreover, Hunt & Holford (2000) and Holford & Hunt (2001) showed that buoyancy effects, due to a difference in density between air on either side of an opening, may yield $c < 0.6$. They conducted a series of small-scale salt-bath experiments to examine how the discharge properties of the flow through a sharp-edged circular opening vary as buoyant fluid is driven passively out from a ventilated box, under displacement mode, into a denser ambient environment; this is analogous to a common situation in buildings where warm air from within a heated enclosure flows out through an opening made at higher elevations into a cooler outdoor environment. Both transient and steady state experiments were performed, the latter involving a single localised source of buoyancy positioned at floor level within the box. In either case, they observed that the buoyant discharge through the opening contracts in cross-section upon rising out of the box into the surrounding environment. They reasoned that this buoyancy-induced contraction in addition to the inertial contraction effectively reduces the fraction of the opening area occupied by the flow, giving rise to a reduced value of the discharge coefficient.

Hunt & Holford (2000) and Holford & Hunt (2001) characterised the behaviour of the buoyant discharge across the upper opening in terms of a dimensionless 'discharge parameter' (also known as the Richardson number in fluid mechanics) given by

$$\Gamma_{\mathrm{t}} = \frac{5}{8\pi^{1/2}\alpha_{\mathrm{P}}}\left(\frac{a_{\mathrm{t}}^{5/2}g'_{\mathrm{t}}}{Q_{\mathrm{t}}^{2}}\right), \tag{3.13}$$

where α_{P} is the (top-hat) entrainment coefficient for the outflowing 'plume' of warm air, and $g'_{\mathrm{t}} = g(\rho_{\mathrm{ext}} - \rho_{\mathrm{t}})/\rho_{\mathrm{ext}}$ is the reduced gravity associated with the density contrast between the discharging fluid and the surrounding environment.

Qualitatively, the discharge parameter describes the relative importance of the buoyancy force (due to density differences) and inertia (due to the imposed pressure difference) across the opening. For $0 \lesssim \Gamma_{\mathrm{t}} < 5$, Holford & Hunt (2001) reported that the discharge coefficient depends weakly on Γ_{t} and the assumption, namely that the buoyancy force has a negligible effect on the discharge coefficient, is valid (*i.e.* $c \approx 0.6$). Once the critical value of $\Gamma_{\mathrm{t}} \approx 5$ is exceeded, they showed that buoyancy effects become increasingly important and the discharge coefficient decreases rapidly with increasing Γ_{t} (*e.g.* an increase in Γ_{t} from 5 to 10 can result in a decrease in the discharge coefficient of around 20%).[3]

The discharge parameter Γ_{t} can also be related to the Froude number of the flow across the upper opening, Fr_{t}, given by

$$\mathrm{Fr}_{\mathrm{t}} = \left(\frac{5}{8\pi^{1/2}\alpha_{\mathrm{P}}}\right)^{-1/2}\left(\frac{Q_{\mathrm{t}}}{a_{\mathrm{t}}^{5/4}{g'_{\mathrm{t}}}^{1/2}}\right), \tag{3.14}$$

which is a measure of the competition between inertial and buoyancy effects. Since $\mathrm{Fr}_{\mathrm{t}} = {\Gamma_{\mathrm{t}}}^{-1/2}$, the criterion for c to be constant is therefore $\mathrm{Fr}_{\mathrm{t}} \gtrsim 0.45$, *i.e.* the local buoyancy effect at the opening is not significant. Note also that the requirement for a constant discharge coefficient has a similar physical basis to the critical Froude number condition for unidirectional flow, which requires $\mathrm{Fr}_{\mathrm{t}} \gtrsim 0.33$ (Hunt & Coffey, 2010); this may, in part, explain the similarity between their critical values.

[3]Note that the work of Hunt & Holford (2000) and Holford & Hunt (2001) refers to positively buoyant (out)flows through horizontal openings only, *i.e.* warm, buoyant air flowing into a region of cooler, denser air. In a heated room, however, the inflow of cool air through lower openings is denser than the air inside the room, *i.e.* the inflow is negatively buoyant. At the time of writing, we could not find any published studies that have focussed on examining the role of density contrast on the discharge coefficient associated with negatively buoyant flows.

Uncertainty in c and implication for design

As seen from Equation (3.11), the value of the discharge coefficient directly impacts the effective area A^* of the openings and therefore the ventilation flow rate Q. Indeed, in almost every expression shown in this chapter, the discharge coefficient is present (or, at least, implicitly).

Holford & Hunt (2001) and Karava *et al.* (2004) note that the value of the discharge coefficient is a major source of uncertainty in natural ventilation design. While some measurements support the use of $c \approx 0.6$ for stack-driven flows (Ward-Smith, 1980; Flourentzou *et al.*, 1998), others indicate that the use of a constant value could lead to a significant over-prediction of ventilation flow rates, if a constant discharge coefficient is assumed (Holford & Hunt, 2001). Calculations for a heated enclosure (with equal upper and lower opening areas) operating in a displacement mode of ventilation suggest that the predicted airflow rate, based on a constant-c assumption (for a buoyant discharge with $\mathrm{Fr_t} = 0.3$), is about 16% greater than its true value when the indoor-outdoor temperature difference is 5°C (Holford & Hunt, 2001).

Notwithstanding inconsistencies in the reported value of the discharge coefficient, it is reasonable to assume $c = 0.6$ for sharp-edged openings, provided the flow through the openings is at high Reynolds number, as is the case in practice,[4] and the difference in air density across each opening is small. This value is generally accepted (and recommended) as a first estimate in the majority of building design guides to date, such as CIBSE AM10 (CIBSE, 2005). For convenience, we summarise in Table 3.1 the conditions for which a constant discharge coefficient is valid.

Condition			Reference
Geometry	Sharp-edged opening	$l/D \ll 1$	Batchelor (1967); Ward-Smith (1980)
Flow nature	Negligible viscous effects (high Reynolds number)	$\mathrm{Re} \gtrsim 4000$	Ward-Smith (1980)
Density contrast	Negligible buoyancy effects (high Froude number)	$\mathrm{Fr_t} \gtrsim 0.45$	Hunt & Holford (2000); Holford & Hunt (2001)

Table 3.1: Summary of the opening geometry and flow conditions required for a constant discharge coefficient.

[4] A large Reynolds number (in excess of 10^3) indicates that inertial effects dominate the effects of viscosity, *i.e.* the flow is expected to be turbulent in nature. Etheridge (2011) tabulates typical Reynolds number Re encountered in practice for openings in low-rise buildings and as a guide give $8000 \lesssim \mathrm{Re} \lesssim 20000$ based on pressure differences of 10 Pa and 60 Pa, respectively.

3.3.4 Steady heat balance

For stack ventilation flows, the driving buoyancy force is produced by differences in temperature between the internal and external environments. Variations in temperature within a building, in turn, are generated by heat inputs produced by, for example, occupants and electrical equipment (casual/incidental gains), solar radiation admitted through glazed surfaces, or as a consequence of heating systems. For a well-insulated enclosure, the accumulated heat is removed primarily by the ventilating flow. In practice, however, insulation is not perfect and a portion of this heat may additionally be lost by conduction through the building fabric itself (such as through roofs, walls and ceilings). Secondary effects, such as convection at the surfaces and radiation to and from surfaces, can also play a role in the heat transfer process. Heat transfers between the internal air and the building fabric can affect the overall heat balance, thereby directly influencing the final temperature distribution within the enclosure (Sandbach & Lane-Serff, 2011; Lane-Serff & Sandbach, 2012).

For the enclosure shown in Figure 3.3(a) and assuming a uniform indoor temperature profile, the general heat balance at steady state is given by equating the total heat input, W (in Watts), with the advection of heat associated with the ventilation flow through the façade openings, Q, and with the total heat loss (by conduction, convection and radiation) through the fabric, W_{loss} (in Watts):

$$W = \rho_{\text{ext}} \mathrm{c_p} Q (T_{\text{int}} - T_{\text{ext}}) + W_{\text{loss}} \tag{3.15}$$

(*cf.* Livermore & Woods (2006), Woods *et al.* (2009), Partridge & Linden (2013)), where $\mathrm{c_p}$ is the specific heat capacity of ambient air. Equation (3.15) shows that heat losses W_{loss} effectively act to reduce the heat input W, and as demonstrated experimentally by Lane-Serff & Sandbach (2012), can lead to reduced indoor air temperatures and ventilation flow rates.

Internal heat inputs, W, and fabric heat losses, W_{loss}, can also be expressed in terms of heat fluxes, B and B_{loss} (in $\mathrm{m^4\,s^{-3}}$), given by, respectively,

$$B = \frac{gW}{\rho_{\text{ext}} \mathrm{c_p} (273 + T_{\text{ext}})} \quad \text{and} \quad B_{\text{loss}} = \frac{gW_{\text{loss}}}{\rho_{\text{ext}} \mathrm{c_p} (273 + T_{\text{ext}})}. \tag{3.16}$$

Equivalently, by substituting for W and W_{loss} from Equation (3.16) into (3.15), and noting that $g'_{\text{int}} = g(T_{\text{int}} - T_{\text{ext}})/(273 + T_{\text{ext}})$, the steady heat balance for the room can be rewritten in terms of heat fluxes as follows:

$$B = Qg'_{\text{int}} + B_{\text{loss}}. \tag{3.17}$$

Equation (3.17) shows that the overall heat balance for the room is dependent on the indoor temperature distribution, the strength of the heat input, the fabric heat losses and the ventilation flow rate through the openings. The ventilation flow rate, in turn, is dependent on the temperature distribution in the room, the total effective area of the upper and lower openings and the vertical distance separating them (see Equation (3.10)). The heat balance and flow rate equations are therefore interrelated, and together constitute a generalised mathematical model of stack ventilation flows through a room. Essentially, the heat balance and flow rate equations provide the foundation for the theoretical framework that will be used in later chapters.

3.4 Heat sources and thermal stratification

When designing for natural ventilation, the nature of the sources of heating in a room is a key determinant of the thermal stratification. Research has shown that the ventilation is closely linked to the geometry and spatial distribution of the heat sources, with localised and distributed sources of the same strengths producing widely differing stratification patterns and temperature profiles. The stratification pattern influences not only the apportioning of the net buoyancy within the space, but also the driving stack pressure and hence the ventilation flow rate. In this section we review the stratification patterns induced by some example heat source geometries, focussing in particular on sources at floor level.

3.4.1 Heat source geometry and stratification

In general, the geometry of heat sources encountered in buildings ranges from small localised sources (such as occupants or task lighting), to distributed over a fraction of the floor area (such as formed by a sun patch warming the floor) and to fully distributed (as in the case of an underfloor heating system). Hunt *et al.* (2002) characterised the scale of the heat source in terms of a ratio between the source area, $\mathscr{A}_{\text{source}}$, and the floor area, $\mathscr{A}_{\text{floor}}$. Heat sources whose areas are small relative to the floor area ($\mathscr{A}_{\text{source}}/\mathscr{A}_{\text{floor}} \ll 1$) are often modelled as localised point or line sources; fully distributed sources are those equal in area to the floor area ($\mathscr{A}_{\text{source}}/\mathscr{A}_{\text{floor}} = 1$), while finite area heat sources are those that fall between the localised and fully distributed limits ($0 < \mathscr{A}_{\text{source}}/\mathscr{A}_{\text{floor}} < 1$).

Examples of the stratification patterns produced by some heat source geometries within a ventilated room at steady state are illustrated in Figure 3.5. These examples are intended to highlight that a wide range of stratification patterns is possible, which can be produced by relatively simple heat source geometries and configurations.

Figure 3.5(a) shows the stratification produced by a single localised point source at floor level. The source generates a turbulent buoyant plume (as represented by the graded wedge shape), which entrains surrounding air as it rises. Linden *et al.* (1990) showed that, in

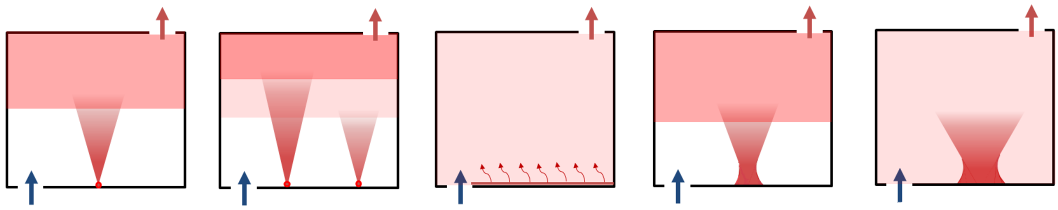


FIGURE 3.5: Examples showing the steady stratification patterns produced by different heat source geometries at floor level in an enclosure ventilated by stack effect. (a) A localised point source and (d) a finite area source (of area less than 15% of the total floor area), both producing a two-layer stratification. (b) Two localised point sources of unequal strength generating a three-layer stratification. (c) A fully distributed heat source and (e) a large area heat source (of area significantly greater than 15% of the total floor area), both generating a 'well-mixed' internal environment. Buoyant plumes above the heat sources are represented by graded wedge shapes.

a room with upper and lower openings connecting to a wind-free external environment, a localised point source generates a two-layer stratification, comprised of a buoyant upper layer above an interface and a layer at ambient temperature beneath. They referred to the resulting flow pattern as 'displacement flow', as the buoyant layer drives a flow out of the upper opening and in through the lower opening, *i.e.* unidirectional flow and in the absence of mixing. A key feature of the flow is that the height of the interface is independent of the strength of the heat source, which results from the fact that the position of the interface is controlled primarily by entrainment into the plume. On the other hand, the temperature of the upper layer increases as the strength of the heat source increases.

Cooper & Linden (1996) extended the work of Linden *et al.* (1990) to study the stratification produced by two unequal strength point source plumes in a ventilated enclosure. They showed that the plumes produce a three-layer stratification, whereby the uppermost layer is formed by the stronger plume, and thus warmer relative to the middle layer which is formed by the less buoyant, weaker plume, and the bottom layer is comprised of air at ambient temperature (Figure 3.5(b)). Similar to a single plume, they found that the interface heights are independent of the total heat flux to the enclosure and depend only on the size of the openings, the height of the enclosure and the relative strengths (or heat flux ratio) of the heat sources; the latter dependence again reflects the dependency of the interface position on plume entrainment and that the distribution of the buoyancy between the plumes is a crucial factor in determining the form of the stratification.

Conversely, for a uniformly distributed heat source, Gladstone & Woods (2001) showed that turbulent high Rayleigh number convection[5] is established above the source in which the room air is 'well-mixed' at approximately uniform temperature (Figure 3.5(c)).

Kaye & Hunt (2010) showed that the stratification produced by a finite (circular) area source can take one of two forms (Figures 3.5(d) or 3.5(e)) depending on the ratio of the heat source area to the floor area, and the ratio of the source radius to the room height. For an area source occupying less than (approximately) 15% of the total floor area and whose source radius is small compared to the room height, they showed that a two-layer stratification develops, similar to that described by Linden *et al.* (1990) for a point source plume. In contrast, for a large area source occupying significantly greater than 15% of the total floor area, the induced flow through the enclosure breaks up the stratification and an approximately uniform internal environment is established. This is analogous to the case of a uniformly distributed heat load shown by Gladstone & Woods (2001).

Numerous more complex stratification patterns can occur in practice. The presence of multiple unequal strength point sources (Linden & Cooper, 1996) or a combination of localised and distributed sources (Hunt *et al.*, 2001*b*; Chenvidyakarn & Woods, 2008) can lead to a multi-layer stratification. The resulting temperature profile and flow pattern in these cases will depend on the complex interplay between the buoyant plume flows, which carry air and heat through the space, and the surrounding thermal environment, which influences the plumes' behaviour. Consequently, the fluid dynamics involved in the mathematical modelling of the flow pattern and stratification within the room can become highly detailed and is beyond the scope of the thesis. Following the core ethos of this work, which centres on the development of an easy-to-apply framework for informing early stage design, we focus on the relatively simple stratification patterns, namely the two-layer stratification and the well-mixed indoor environment.

3.5 Vent area configuration and airflow patterns

In addition to the heat source geometry, the size and relative areas of the openings at the upper and lower levels can influence the form of the indoor stratification and the corresponding temperature profile (Hunt & Coffey, 2010). In this section we describe the effect of vent area configuration on the airflow pattern and stratification, focussing on rooms ventilated by stack effect only. Much of this section draws from the theoretical and experimental work

[5] If the destabilising effects of buoyancy are sufficiently large relative to the stabilising effects associated with viscous dissipation and diffusion of heat, then the convection is turbulent in nature. For an evenly distributed source at floor level in a ventilated box, small-scale laboratory experiments (using heat in water) of Gladstone & Woods (2001) recorded Rayleigh numbers in excess of 10^{10}.

of Hunt & Coffey (2010), although we describe their results in the context of a naturally ventilated room. Implications to indoor comfort are also highlighted.

3.5.1 Classifying airflow patterns

In the study of an emptying-filling box by Linden *et al.* (1990), they reported that for flows established with top opening areas less than twice the bottom opening areas ($a_{\rm t} < 2a_{\rm b}$), mixing by the inflowing cool air (through either top and/or bottom openings) at the interface was negligibly weak, and that a two-layer stratification and (unidirectional) displacement flow was established and maintained at steady state (see, for example, Figure 3.5(a)). However, experimental observations and theoretical predictions of Hunt & Coffey (2010) clearly indicate that the displacement flow pattern represents an idealised limiting case of no-mixing, and that unidirectional flow previously identified represents only a subset of the possible flow patterns that can occur in a ventilated enclosure with upper and lower openings.

Transient draining flows visualised in laboratory experiments by Hunt & Coffey (2010) showed that four distinct flow patterns are possible. In particular, they found that each of the flow patterns (including displacement flow) depends not only on the effective area of the openings, but also on the apportioning of this total area between upper and lower levels. Each of the flow patterns is distinct in terms of the direction of flow at the upper opening (unidirectional or exchange flow) and the extent of mixing by the inflow at the interface. Qualitatively similar findings have also been reported earlier in a conference paper by Coffey & Hunt (2004*a*), who considered the steady flow patterns induced by a localised floor-level point source of buoyancy. Table 3.2 summarises the general features of each of the four (steady) flow patterns in a ventilated enclosure.

A flow type classification method was developed by Hunt & Coffey (2010) with which to elegantly describe the specific conditions/opening geometries that lead to either exchange flow through the top, mixing at the interface, or a combination of both. They identified three controlling ratios that determine which of the four flow patterns is established, namely:

$$\frac{A^*}{H^2}, \quad R^* = \frac{c_{\rm t}a_{\rm t}}{c_{\rm b}a_{\rm b}} \quad \text{and} \quad \zeta = \frac{h}{H}, \tag{3.18}$$

where A^*/H^2 is the dimensionless effective area of the openings, R^* is the ratio between the effective areas of the top and bottom openings, and ζ is the ratio between the height of the interface (from the floor) and the vertical distance between the top and bottom openings.

Two Froude numbers were formed from these ratios. The first, $\mathrm{Fr}_{\rm t}$, characterising the relative strengths of the outflowing warm air and the downflowing ambient air through the top, sets

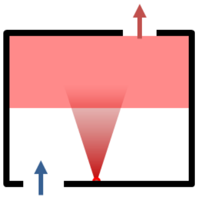
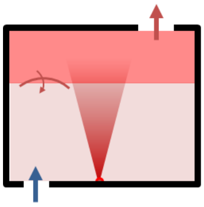
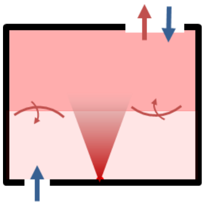
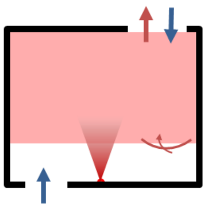
Schematic	Flow type	Description
	I	• Unidirectional flow through the openings • Negligible mixing by the inflowing air at the interface • Lower layer temperature is equal to the outdoor temperature
	II	• Unidirectional flow • Turbulent mixing by the inflowing air through the base at the interface • Lower layer temperature is greater than the outdoor temperature
	III	• Exchange flow at the top opening • Turbulent dilution of heat in the upper layer due to incoming cool air from the top • Turbulent mixing at the interface by the inflowing air through the base at the interface • Lower layer temperature is greater than the outdoor temperature
	IV	• Exchange flow • Turbulent dilution of heat in the upper layer • Negligible interfacial mixing by the inflow through the base opening • Lower layer is shallow with temperature equal to the outdoor temperature

TABLE 3.2: Summary of the general features of the four steady flow patterns in a ventilated room identified by Coffey & Hunt (2004*a*). Similar features have also been identified in the small-scale experiments of Hunt & Coffey (2010) in the absence of a localised heat source. The dome-like upwelling/depression at the interface represents turbulent mixing by the inflowing air (through either the top and/or bottom openings). Arrows drawn at the openings indicate the direction of airflow.

the direction of flow:

$$\mathrm{Fr_t} \propto \left(\frac{A^*}{H^2}\right)^{-1/4} \left(R^{*2}+1\right)^{-5/8} \left(1-\frac{h}{H}\right)^{1/2}. \tag{3.19}$$

The second, $\mathrm{Fr_b}$, characterising the relative strengths of the destabilising inertial forcing by the inflow through the bottom opening and the stabilising buoyancy force at the interface, determines the 'vigour' of mixing:

$$\mathrm{Fr_b} \propto \left(\frac{A^*}{H^2}\right)^{1/2} \left(1+\frac{1}{R^{*2}}\right)^{-1/4} \frac{(1-h/H)^{1/2}}{[(h/H)+(\pi^{1/2}\lambda)^{-1}\,(a_b/H^2)^{1/2}]^{3/2}}, \tag{3.20}$$

where λ is an empirical constant. For a detailed and a more rigorous derivation of Equations (3.19) and (3.20), the reader is referred to §5.3 of Chapter 5.

Hunt & Coffey (2010) expressed the conditions for transition between each flow pattern as critical values of the Froude numbers. The critical Froude number $\mathrm{Fr}_{\mathrm{t,c}}$ marks the transition between unidirectional and exchange flow at the top opening; above the critical value, unidirectional flow occurs (Flow types I and II), and below this value, exchange flow is established (Flow types III and IV). The onset of mixing at the interface by the incoming air through the base opening is determined by the critical Froude number $\mathrm{Fr}_{\mathrm{b,c}}$, above which mixing is 'vigorous' (Flow types II and III), and below which mixing is negligible (Flow types I and IV). Hunt & Coffey (2010) deduced from experimental measurements $\mathrm{Fr}_{\mathrm{t,c}} \approx 0.33$ and $\mathrm{Fr}_{\mathrm{b,c}} \approx 0.67$ for horizontal, sharp-edged openings.

Figure 3.6 illustrates how the critical Froude numbers divide the $\{A^*/H^2, R^*\}$-space into four regions, each region characterised by a distinct flow pattern as shown by the inset schematics. From the plot, it is clear that displacement flow (Flow type I) occurs only for a subset of pairings of $(A^*/H^2, R^*)$, and that attaining this particular (or desired) pattern of flow requires careful selection of pairs of A^*/H^2 and R^* so that they fall within the required range of Froude numbers.

3.5.2 Implications for design

Using Figure 3.6, we can now track how variations in R^* affect the room stratification for a given value of A^*/H^2. Take displacement flow (Flow type I), which occurs when the majority of the total opening area is apportioned at floor level ($R^* \ll 1$). With the top opening area (dedicated preferentially to outflowing warm air) sufficiently smaller than the bottom opening area (dedicated to inflowing cool air), unidirectional flow is established and mixing by the incoming air is negligibly weak (Coffey & Hunt, 2004*a*; Hunt & Coffey, 2010). The lack of mixing ensures that all the heat in the room is confined within the upper layer and the lower layer is at ambient temperature. Displacement flow therefore provides an efficient means to expel excess heat from within a space and to provide occupants with relatively cool air from the outdoors (Coffey & Hunt, 2004*b*; Kaye & Hunt, 2007; Coffey & Hunt, 2007).

A transition from Flow type I to II occurs when R^* is increased. By reducing the area of the bottom opening with respect to that of the top opening, the momentum of the inflowing cool air through the bottom opening increases. In contrast to displacement flow (Flow type I), the lower layer is warmer than the external environment as warm air is drawn down from the upper layer by turbulent mixing (Coffey & Hunt, 2004*a*; Hunt & Coffey, 2010). As such, Flow type II effectively allows the inflowing cool draught of air to warm the space

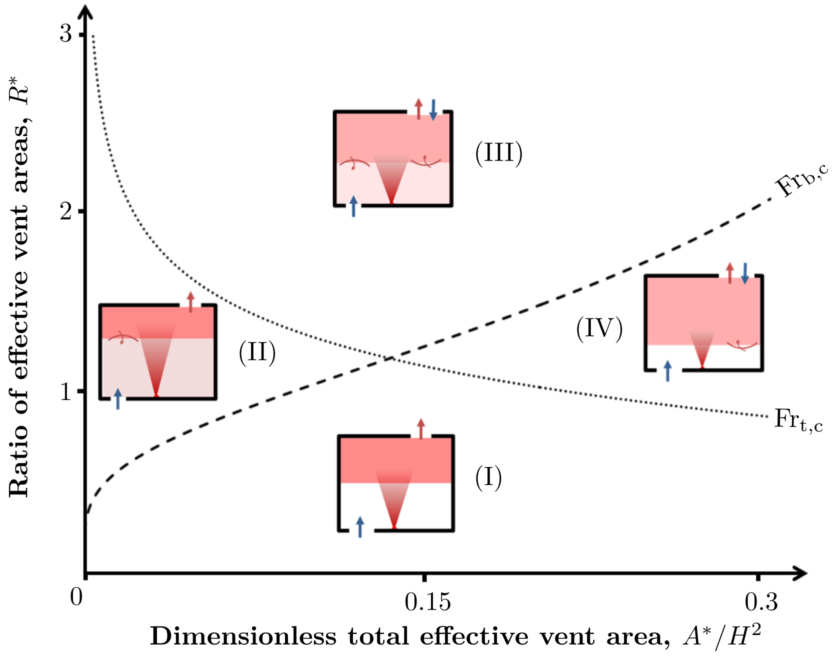


FIGURE 3.6: Visual aid showing the relationship between the ratio of effective vent areas, R^* (vertical axis), the (dimensionless) total effective vent area, A^*/H^2 (horizontal axis), and the critical top and bottom Froude numbers, $\mathrm{Fr}_{t,c}$ and $\mathrm{Fr}_{b,c}$, respectively. Below the (dotted) line denoting $\mathrm{Fr}_{t,c}$, unidirectional flow occurs through the top vent, and above this line, exchange flow occurs. Above the (dashed) line showing $\mathrm{Fr}_{b,c}$, the bottom vent supports vigorous mixing at the interface, and below this line, mixing by the inflow is negligible.

by utilising the heat contained in the upper layer. Thus, if the external temperature is too cool, Flow type II may provide a means of ensuring the occupied layer is at a comfortable temperature.

Further increases in R^* leads to a transition from Flow type II to III, and for sufficiently large values of R^* and A^*/H^2, Flow type IV is established. Both of these flow types support exchange flow at the top opening. As mentioned earlier, exchange flows are generally undesirable as they reduce the area of the upper opening dedicated to discharging heat from within the room. Exchange flows may result in periods of potentially insufficient ventilation, which in turn could reduce the efficiency with which heat and pollutants are removed from the interior (Coffey & Hunt, 2004*b*, 2007).

3.6 Combined wind and stack effects

In the previous section we focussed on rooms ventilated by stack effect only. However, when the building is exposed to wind, the behaviour of the ventilating flow may be fundamentally different to that driven by buoyancy forces alone. We now consider the case of stack ventilation in the presence of wind, extending the discussion of §3.3 to this case.

3.6.1 General effects of wind

When wind flows around a building, it produces a dynamic (wind) pressure distribution with, in general, positive pressure on the windward side and negative pressure on the leeward side. This difference in surface pressures across the building results in a pressure drop, Δp_{w}, given by (*cf.* Hunt & Linden (2001))

$$\Delta p_{\mathrm{w}} = \frac{1}{2}\rho_{\mathrm{ext}} U_{\mathrm{w}}^2 (C_{\mathrm{pw}} - C_{\mathrm{pl}}), \tag{3.21}$$

where U_{w} is the wind speed, and C_{pw} and C_{pl} are the wind pressure coefficients at the windward and leeward façades, respectively. Broadly speaking, the extent to which the wind hinders (Hunt & Linden, 2005; Lishman & Woods, 2006; Coomaraswamy & Caulfield, 2011) or enhances (Hunt & Linden, 1999, 2001) the ventilation depends on its strength and direction, as well as the location of the openings. We highlight these two situations schematically in Figure 3.7, which shows the heated enclosure from Figure 3.3(a) in the presence of wind.

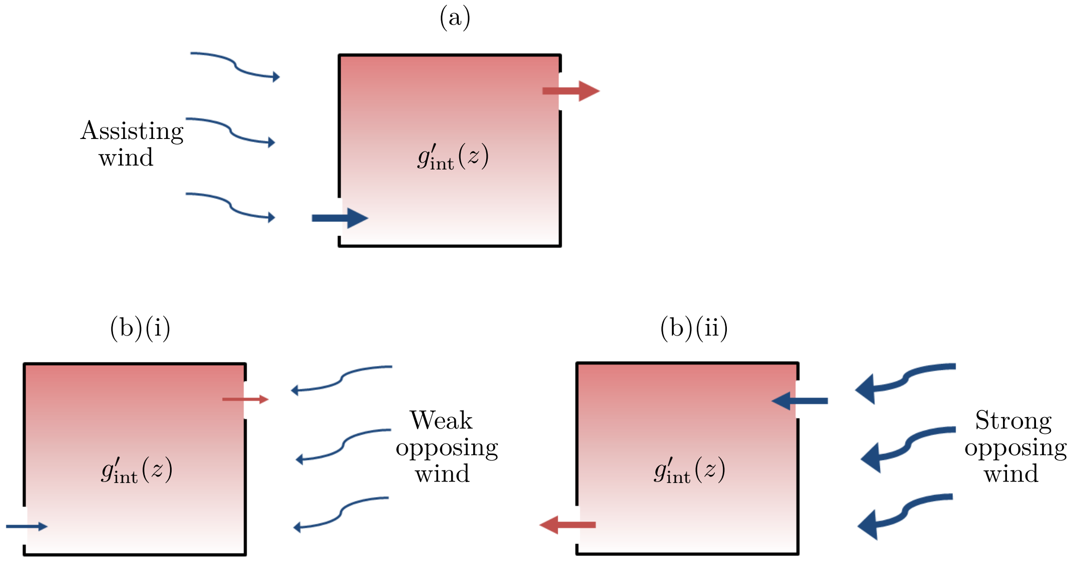


FIGURE 3.7: Schematics of a naturally ventilated enclosure in elevation showing snapshots of the steady flow regimes for (a) wind assisting and (b) wind opposing the stack-driven flow. Note the reversal in the flow direction through the openings between (b)(i) weak wind and (b)(ii) strong wind. Curly arrows drawn on the figure indicate the wind direction.

As a consequence of the pressure drop, the air inside the room is subject to both a buoyancy force and a force associated with the wind pressure drop, Δp_{w}. Hunt & Linden (2001) showed that by locating the lower opening on the windward side (positive pressure) and the upper opening on the leeward side (negative pressure), the difference in wind pressure between the openings allows a wind-driven flow from low to high level inside the room, in the same sense as the buoyancy-driven flow (Figure 3.7(a)). In this situation, the effects of wind and buoyancy reinforce one another.

Conversely, if the upper opening is located on the windward wall (Figure 3.7(b)), a situation may arise in which the wind-driven flow opposes the buoyancy-driven flow. Hunt & Linden (2005) showed that one of two distinct steady flow regimes is possible depending on – *inter alia* – the rate of change of wind speed, and the relative strengths of wind and buoyancy. Hunt & Linden (2005) characterised the relative strengths of the two forces, wind and buoyancy, in terms of a Froude number, $\mathrm{Fr_w}$, given by

$$\mathrm{Fr_w} = \sqrt{\frac{\Delta p_\mathrm{w}/\rho_\mathrm{ext}}{(B/H)^{2/3}}}, \tag{3.22}$$

where B is the strength of the heat source. For weak opposing winds ($\mathrm{Fr_w} \ll 1$), buoyancy dominates and warm air from the room exists through the upper windward opening in the opposite sense to the wind-driven flow (Figure 3.7(b)(i)). For a strongly opposing wind ($\mathrm{Fr_w} \gg 1$) or a sudden increase in wind speed, the wind-produced flow dominates, leading to a reversal in the flow direction through the enclosure. In this case, cooler external air enters through the upper windward opening and mixes with the warmer internal air, which exits through the lower leeward opening (Figure 3.7(b)(ii)); the latter case again reinforces the notion that warm air need not always exist through openings made at upper levels in the façade.

3.6.2 Ventilation flow rate resulting from wind and buoyancy effects

The general pressure balance for stack ventilation can be extended to include the wind pressure drop by adding Δp_w to the RHS of Equation (3.8) as follows:

$$\underbrace{\Delta p_\mathrm{vent,b} + \Delta p_\mathrm{vent,t}}_{\substack{\text{pressure drop}\\ \text{across openings}}} = \underbrace{\Delta p_\mathrm{ext} - \Delta p_\mathrm{int}}_{\substack{\text{driving stack}\\ \text{pressure}}} + \underbrace{\Delta p_\mathrm{w}}_{\substack{\text{driving wind}\\ \text{pressure}}}. \tag{3.23}$$

Thus, the total ventilation flow rate, driven by the combined forces of wind and buoyancy, at steady state is given by (*cf.* Hunt & Linden (2001))

$$Q = (Q_\mathrm{s}^2 + Q_\mathrm{w}^2)^{1/2}, \tag{3.24}$$

where the respective stack- and wind-driven flow rates are

$$Q_\mathrm{s} = A^* \left(\int_0^H g'_\mathrm{int}(z)\,\mathrm{d}z \right)^{1/2} \quad \text{and} \quad Q_\mathrm{w} = A^* \left(\frac{\Delta p_\mathrm{w}}{\rho_\mathrm{ext}} \right)^{1/2}. \tag{3.25}$$

Equation (3.24) shows that when the wind assists the stack-driven flow, the ventilation flow rate through the enclosure increases. A convenient *aide-mémorie* and visual representation of the relationship in (3.24) is a "natural ventilation triangle", a concept first coined by Hunt & Linden (1999). Figure 3.8 shows an adaptation of the "natural ventilation triangle". The base and vertical sides of the right angled triangle represent the wind- and buoyancy-induced flow rates, Q_w and Q_s, respectively; the magnitude of the ventilation flow rate produced by the buoyancy force reinforced by wind is then given by the length of the hypotenuse of the right angled triangle, $(Q_\mathrm{w}^2 + Q_\mathrm{s}^2)^{1/2}$, which follows a Pythagorean relationship.

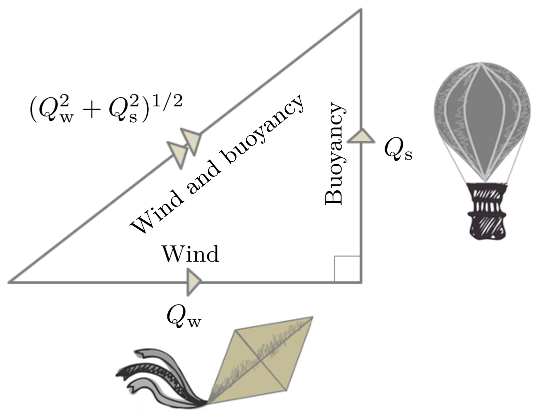


FIGURE 3.8: The "natural ventilation triangle" of Hunt & Linden (1999) for buoyancy-driven flows assisted by wind. Cartoons showing a 'flying kite' and a 'rising hot air balloon', mimicking the motion associated with the effects of wind and buoyancy, respectively, are included to aid in the interpretation.

Conversely, for opposing winds, the wind-driven flow in the enclosure is in the opposite sense to the stack-driven flow (the sign in front of Δp_w in Equation (3.23) is negative). For weak winds ($\mathrm{Fr}_\mathrm{w} \ll 1$), Hunt & Linden (2005) showed that the total ventilation flow rate Q, resulting from the wind pressure drop Δp_w opposing the flow, is given by

$$Q = (Q_\mathrm{s}^2 - Q_\mathrm{w}^2)^{1/2}. \tag{3.26}$$

In contrast to the wind-assisted case, Equation (3.26) indicates that the airflow rate reduces as the wind speed increases. For a sufficiently large opposing wind ($\mathrm{Fr}_\mathrm{w} \gg 1$), $Q_\mathrm{w} > Q_\mathrm{s}$, there is a reversal in the flow direction, and the total ventilation flow rate is then

$$Q = -(Q_\mathrm{w}^2 - Q_\mathrm{s}^2)^{1/2}. \tag{3.27}$$

In this regime, Hunt & Linden (2005) showed that increasing Fr_w (or, equivalently, wind speed) leads to an increase in the ventilation flow rate through the enclosure.

The above scenarios essentially highlight that the relative effects of wind and buoyancy play an integral role in setting the flow pattern within a room. Even when the wind appears to provide the dominant expelling force, it is clear that the strength of the buoyancy force determines the role played by the vents (whether they act as an inlet or outlet) and the behaviour (increasing or decreasing) of the airflow rate through the enclosure for increasing wind speeds. Moreover, Hunt & Linden (1999) and Hunt & Linden (2005) showed that the relative forcing strengths of wind and buoyancy can affect the form of the indoor stratification. When the wind assists (or opposes) the buoyancy-driven flow, the strength of the buoyancy force (relative to the wind force) determines whether the interior remains stratified, or whether a strong wind succeeds in breaking down the stratification and establish a well-mixed internal environment (Hunt & Linden, 1999, 2005). Whilst a breakdown of the stratification may not impact the ventilation flow rate detrimentally (as the latter is driven predominantly by the strong wind), it would affect how the heat is distributed within the room and hence the comfort of occupants. Thus, consideration of the combined effects of wind and buoyancy is crucial to the design and performance of a natural ventilation system.

Part II: identifying errors in technical translation

In this section we identify some of the common errors and inconsistencies pertaining to the translation of technical information on natural ventilation in the existing design guidance literature. We stress that the errors discussed herein are by no means exhaustive nor representative of all design guides on natural ventilation. The intention here is to highlight a few pertinent examples that reveal the misleading nature of the recommendations made by the existing design guides/manuals, and to describe the potential impact of these on the subsequent performance of a natural ventilation system. The primary motivation stems from the need to improve the transfer of information from the technical journals to architects, and the examples considered herein reflect this motivation.

3.7 Confusing ventilation terminologies and definitions

Design guides on building ventilation, such as CIBSE AM10 (CIBSE, 2005), are undoubtedly an invaluable resource to architects and engineers, as they present a number of key concepts and straightforward rules-of-thumb on natural ventilation design in a visually compact format. However, contained within these guides are a swathe of seemingly ambiguous and misleading interpretations of certain ventilation terminologies. Incongruities between the use of certain terminologies and their definitions can lead to confusion, as the architect (or others) who draws from the open literature is forced to decide on which information/definitions to trust.

As an example, Jones *et al.* (2016) highlight the different, and even contradictory, definitions regarding the area of ventilation openings that are currently used by building standards, guidelines, textbooks and software tools. They reported that the terms, including 'free area', 'effective area' and 'equivalent area' are often used interchangeably, and in some cases, a single term can be assigned multiple definitions (or vice versa).[6]

For example, Santamouris & Asimakopoulos (1996) solely use the 'free area', and the terms 'equivalent area' and 'effective area' are not used nor defined; Thomas (2006) uses the 'free area' and 'equivalent area' interchangeably, where the same definition is given to both terms; the British Standard 5925 (BSI, 1991) only uses and defines the term 'equivalent area', while the CIBSE AM10 Guide (CIBSE, 2005) uses and defines both the 'effective area' and 'free area' and even introduces a self-contradicting term, the 'effective free area', without explicitly defining it. Confusion, in this case, over terms including 'free area', 'effective area' and 'equivalent area', can lead to unintended and undesirable errors in design specifications, leading (in turn) to under (or over) ventilation, overheating, excessive energy consumption and high capital running costs (Jones *et al.*, 2016).

3.8 Misleading nature of airflow arrows

A key challenge in a natural ventilation design is to ensure that the air flows in the intended direction through all openings in the building. The CIBSE AM10 Guide (CIBSE, 2005) confirms that the first consideration in design is to plan the pathway of airflow through the openings. As discussed earlier, this involves much more than merely drawing a series of airflow arrows on a sectional view of a building. The actual direction of airflow through the openings is dictated not only by the size and location of the openings, but also by the apportioning of the total area between the upper and lower openings, and by the form of the thermal stratification (Hunt & Coffey, 2010).

[6]The 'free area' defines the actual (or physical) area of an opening. The 'effective area' characterises the resistance an opening poses to the flow and takes into account the actual area of the opening and the pressure loss experienced by the flow as it passes through the opening. Note that the effective area appears prominently in the expressions for the ventilation flow rate (Equation (3.10)) as well as the Froude numbers, $\mathrm{Fr_t}$ and $\mathrm{Fr_b}$, which characterise the transitions between flow regimes (Equations (3.19) and (3.20)). The 'equivalent area', a_{eq}, is defined in the British Standard 5925 (BSI, 1991) as "the area of a hypothetical circular sharp-edged orifice through which air would pass at the same volume flow rate, under an identical applied pressure difference, as the opening under consideration." The equivalent area is expressed as $a_{\mathrm{eq}} = ca/c_0$, where a is the free area of the opening, c is its corresponding discharge coefficient, and c_0 is the discharge coefficient for a standard circular sharp-edged orifice. Building standards and design guides, such as the British Standard 5925 (BSI, 1991) and CIBSE AM10 (CIBSE, 2005), recommend $c_0 = 0.6$.

A preliminary survey of the design-based ventilation literature (see Figure 2.6, §2.4.4) revealed the ubiquitous nature of airflow arrows drawn in typical building sketches, namely that the airflow path through openings often depict unidirectional flow. In essence, these arrows, or so-called "smart arrows" (Etheridge, 2011), are a visual interpretation of the postulated (or desired) direction of airflow and are likely based on assumptions that bear no relationship to the actual physics. Ashford (2011) points out in a CIBSE newsletter that the airflow arrows drawn in typical building sketches are misleading and indeed erroneous.

Existing research has indicated that, even in a single space, multiple flow patterns are possible, some of which supporting exchange flow at openings dedicated previously to outgoing air. For example, *in situ* temperature measurements collected at the Contact Theatre in Manchester, UK, by Fitzgerald & Woods (2007) showed that exchange flow occurred at one or more of the dedicated stack chimneys rather than the anticipated displacement flow. They reported that, whilst the mean temperature in the theatre remained comfortable during operation, the inflow of cold air through high-level vents resulted in localised pockets of cold air within the occupied zone. These observations therefore cast doubt on the simple picture of upward displacement flow on which the ventilation concept for this theatre was initially based.

3.9 Erroneous guidance on how to achieve displacement (unidirectional) flow

Displacement ventilation is typically advocated by design guides (*e.g.* CIBSE AM10) as one of the most efficient means of providing passive cooling. Accompanying this recommendation is a straightforward equation for calculating the total area of the façade openings based on the vertical separation between the openings H, the specific (or desired) ventilation flow rate Q, and the indoor-outdoor temperature difference ΔT. For a 'well-mixed' indoor environment, CIBSE AM10 (CIBSE, 2005) gives the total (free) area of the openings, A, as

$$A = \frac{Q}{c}\left(\frac{273 + T_{\text{ext}}}{gH\Delta T}\right)^{1/2}, \tag{3.28}$$

where c is the discharge coefficient for the openings (assumed constant for all openings). Unfortunately, the guidance ends there and no further advice is given on how to determine the areas of *each* opening that comprise the total area of A. Consequently, the architect is forced to choose based on expectation, or, at best, educated guesses, the area of each opening that combines to give the total opening area specified.

As discussed in §3.5, displacement ventilation, *i.e.* unidirectional flow with negligible internal mixing, is attainable only within a limited range of opening area configurations, and not for all configurations with openings made at the upper and lower levels in the façade. Relatively small departures from vent area ratios that result in displacement flow can lead to significant internal mixing (draught), which can impact the temperature distribution within the room (Hunt & Coffey, 2010; Coffey & Hunt, 2010). Further departures can give rise to exchange flow at the upper opening, which may lead to reduced ventilation flow rates (Hunt & Coffey, 2010). Whilst these changes in ventilation may, or may not, be detrimental to the comfort of occupants *per se*, an awareness of the possibility of producing exchange flow at the outlet vent and/or internal mixing as a result of a given combination of opening areas is likely to be beneficial for design.

3.10 Neglect of the combined effects of wind and stack

The current recommended approach given in design guides (*e.g.* the British Standard 5925 (BSI, 1991)) and architectural textbooks (*e.g.* Thomas (2006)) to estimate airflow rates still accepts that only the dominant of the two forces – wind or buoyancy – need to be considered. This approach is based on the premise that the flow through the building is either purely wind-driven or purely buoyancy-driven, never in combination, assisting or opposing. The choice of the dominant driving force is determined by a dimensionless number, which is denoted here by the symbol $\mathbb{X}$, given by (*cf.* Table 11 (p. 22) in BSI (1991))

$$\mathbb{X} = \frac{U_{\rm w}}{\Delta T}\left(\frac{\Delta C_{\rm p}}{H}\right)^{1/2}\left(\frac{a_{\rm w}}{a_{\rm l}}\right)^{1/2}, \tag{3.29}$$

where $a_{\rm w}$ and $a_{\rm l}$ are the windward and leeward opening areas, respectively, and $\Delta C_{\rm p}$ is the difference in the wind pressure coefficient at the windward and leeward faces.[7] Whether the number exceeds or is less than a 'critical' value of 0.26 rules out which of the two, wind or buoyancy, should be considered, despite there being no explanation as to where the value of 0.26 originates. If $\mathbb{X} < 0.26$, only the buoyancy-driven component of the flow needs to be considered, whereas if $\mathbb{X} > 0.26$, solely the wind-driven component needs to be accounted for.

As discussed in §3.6, the relationship between the forces of wind and buoyancy is essentially non-linear and so neither the wind nor buoyancy can be treated in isolation, nor by simply adding the results of the two different processes independently (Hunt & Linden, 1999, 2001, 2005). Even on seemingly windy days, Hunt & Linden (2001, 2005) advise that the effects of buoyancy should never be ignored, as the strength of the buoyancy force has a significant

[7] Note that the dimensionless number, $\mathbb{X}$, is in fact reminiscent of the Froude number, $\mathrm{Fr}_{\rm w}$, given by Hunt & Linden (2001) and Hunt & Linden (2005) to characterise the strength of the wind relative to the driving produced by stack effect (see Equation (3.22)).

bearing on the flow direction through the openings, the ventilation flow rate and the final temperature distribution within the room. Consequently, preliminary design calculations that neglect the contribution of the effects of wind or buoyancy could lead either to (i) an underestimation of the airflow rate when the flow is wind-assisted, or (ii) an overestimation of the airflow rate when the flow is wind-opposed. Moreover, ignoring the contribution of the buoyancy force for wind-dominated flows could lead to errors in the estimation of internal temperatures. Therefore, the existing accepted approach for calculating airflow rates, whereby the dominant of the two forces (wind or buoyancy) is considered only, needs to be re-examined.

3.11 Conclusion

In this chapter the fundamental fluid mechanic concepts and core theory of natural ventilation flows, crucial to an understanding of later work, have been introduced. The key equations governing air and heat flows through an enclosure, and some of the approximations that allow for their simplification, have been amalgamated and detailed. The aim was to lay down the basic 'building blocks' that constitute the mathematical modelling of natural ventilation flows, which will be applied in the following chapters to answer the key design questions (§1.3.1).

Through reviewing and consolidating the relevant fluid mechanics and design-based literature on natural ventilation, prominent gaps were identified in which there is a clear need for rapid and intuitive early stage guidance to be developed. Specifically, we identified a scarcity of architect-focussed design guidance to size individual openings in a façade to achieve target design flow rates and air temperatures. With an overall aim of improving the communication of technical information to architects, the work presented in Chapters 4 and 5 will focus on developing straightforward guidelines to facilitate architects in the rapid sizing of ventilation openings.

Chapter 4

Sizing vents for stack ventilation: a step-by-step design approach

4.1 Introduction

The impetus for the work which follows emanated from the need to develop a simple and robust approach for the sizing of individual ventilation openings. As pointed out in Chapter 3, design guides on natural ventilation, such as CIBSE AM10 (CIBSE, 2005), limit themselves to recommending solely the total opening area A with which to ascertain the airflow rate through the enclosure, ignoring other fundamental design factors, most notably how this total area is split between the upper and lower openings. It is left to the architect or ventilation engineer to decide upon the area of each opening that comprise the total area of A. Consequently, the choice of the individual opening areas, based largely on expectation or educated guesses, may lack the evidence-based reassurance needed to ensure the intended airflow pattern (*i.e.* unidirectional flow), and hence the desired ventilation flow rate and indoor temperature be achieved.

In this chapter we build on the existing body of work reviewed in Chapter 3 to develop a generalised approach to inform the sizing of individual openings for any distribution of heat inputs. Focus is on ensuring the intended airflow rate, indoor temperature and flow pattern are realised in a room ventilated by stack effect only. Specifically, we base our approach on two well-established, experimentally validated mathematical models of stack ventilation; the emptying-filling box model of Linden *et al.* (1990) is used to provide a generalised description of the physics governing air and heat flows through a single building enclosure, and the flow type classification method of Hunt & Coffey (2010) is employed to determine the opening areas at which the transition from unidirectional to exchange flow occur. Following the theme of this thesis, which centres on fostering architect-engineer communication, we present our approach in an easy-to-follow format with visual graphs embedded in order to encourage its uptake by both architects and engineers at the early stages of a natural ventilation design.

4.1.1 Notation

We frame the majority of the work in this chapter in terms of both 'architectural' and 'technical' notation and terminologies. 'Technical' terms, such as 'reduced gravity', g'_{int} ($\mathrm{m\,s^{-2}}$), and 'heat flux', B ($\mathrm{m^4\,s^{-3}}$), are used as they simplify mathematical expressions and are relatively widespread in the fluid mechanics literature. Since the reduced gravity is a measure of the temperature difference relative to the external environment, and the heat flux is a measure of the strength of the heat source, we have converted reduced gravities and heat fluxes to equivalent temperature differences, ΔT (°C), and heating power, W (Watts), respectively. The terms 'temperature difference' and 'heating power' are hereinafter referred to as 'architectural' terminologies as they are, in general, more commonplace in design.

Hunt & Coffey (2010) showed that two Froude numbers, $\mathrm{Fr_t}$ and $\mathrm{Fr_b}$, associated with flows through upper and lower openings, respectively, determine the direction of airflow through the openings and the vigour of mixing by the inflow of cool air in a room. Hereinafter, we refer $\mathrm{Fr_t}$ and $\mathrm{Fr_b}$ to as the 'Direction number', $\mathscr{D}ir$, and the 'Draught number', $\mathscr{D}ra$, respectively. This conversion was done intentionally in order to couple an easy-to-remember term with the Froude number that conjures a 'mental image' reflecting its general meaning, *i.e.* flow 'direction' (exchange or unidirectional flow) and 'draught' (vigour of internal mixing). We anticipate that the particular choice of terminologies adopted herein will be more readily applicable to, and appreciated by, a design-orientated audience. We summarise the conversion between 'architectural' and 'technical' notation and terminologies in Table 4.1.

'Architectural'				**'Technical'**
Temperature difference (°C)	ΔT	$\Longleftrightarrow$	g'	Reduced gravity ($\mathrm{m\,s^{-2}}$)
Heating power (Watts)	W	$\Longleftrightarrow$	B	Heat flux ($\mathrm{m^4\,s^{-3}}$)
Direction number (-)	$\mathscr{D}ir$	$\Longleftrightarrow$	$\mathrm{Fr_t}$	Froude number at the upper opening (-)
Draught number (-)	$\mathscr{D}ra$	$\Longleftrightarrow$	$\mathrm{Fr_b}$	Froude number at the lower opening (-)

Table 4.1: Conversion between 'architectural' and 'technical' notation and terminologies.

4.1.2 Chapter structure

This chapter is organised in the following manner. In §4.2 we give an overview of our approach to size ventilation openings using visual charts, illustrating the steps taken to determine the opening areas required to ensure unidirectional flow and a draught-free indoor environment. In §4.3 we present a simplified mathematical model of stack ventilation in a room, focussing on the relationship between the 'primary' variables, namely ventilation flow rates, air temperatures, heat inputs, building geometry and vent sizes. By combining the model of stack ventilation with the flow type classification method of Hunt & Coffey (2010), we place a constraint on the allowable range of opening areas, such that exchange flows and draughts are avoided. In §4.4 we summarise the design procedure based on our approach described in §4.3 and in §4.5 a worked example to show how the design procedure can be applied is presented.

4.2 Overview of our general approach

The four plots in Figure 4.1 summarise our general approach developed in this chapter to size ventilation openings. We frame our approach in terms of three geometric ratios, namely a_t/H^2, a_b/H^2 and A^*/H^2, where a_t and a_b are the areas of the upper and lower openings, respectively, A^* is their combined effective area and H is the vertical distance separating them. By framing our approach in terms of geometric ratios, we ensure that it can be applied to any room with a similar geometry, regardless of physical size (*e.g.* room height).

Hunt & Coffey (2010) showed that the type of airflow pattern established in a room is dependent on the choice of the (dimensionless) total effective area A^*/H^2 of the openings and the ratio of effective vent areas, $R^* = c_\mathrm{t}a_\mathrm{t}/c_\mathrm{b}a_\mathrm{b}$ (see, for example, Figure 3.6). Taken together, they inform the architect of the total effective area available to the ventilating flow and how this total area is apportioned between the upper and lower openings; the upper opening supporting (preferentially) outflowing warm air and the lower opening supporting the inflow of relatively cooler air from the exterior. Note that both A^*/H^2 and R^* are functions of the physical area of the upper and lower openings, a_t and a_b, respectively, and their corresponding discharge (or loss) coefficients, c_t and c_b. Since the goal here is to derive expressions for the *physical* area of the individual openings (rather than an effective area), we frame our approach in terms of a_t/H^2 and a_b/H^2. This requires an estimate of the loss coefficients, by making reasonable assumptions regarding the opening geometry and the nature of the flow through each opening (see §4.3.4).

The relationship between a_t/H^2, a_b/H^2 and A^*/H^2 is shown in Figure 4.1(a), which plots a_t/H^2 against a_b/H^2. When a_t/H^2 and a_b/H^2 are plotted, Figure 4.1(a) shows that their

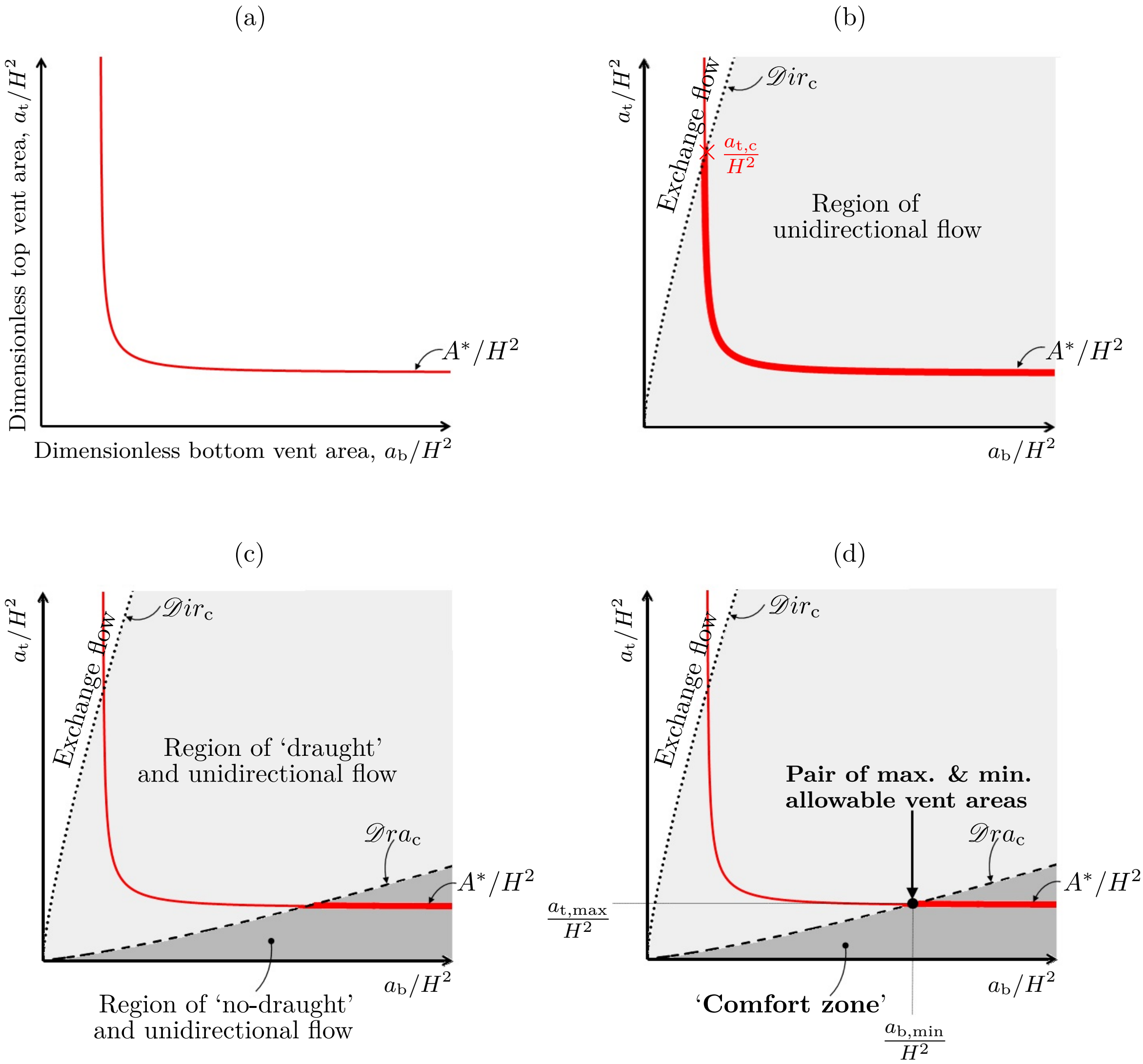


FIGURE 4.1: Plots of a_t/H^2 against a_b/H^2, illustrating our general approach to size ventilation openings for a single room ventilated by stack effect only. The red contour line shows a constant value of A^*/H^2. The dotted and dashed black lines denote the critical Direction and Draught numbers, $\mathscr{D}ir_c$ and $\mathscr{D}ra_c$, respectively, which divide the plot into distinct regions. Each region is characterised by a distinct flow pattern. Above the dotted line denoting $\mathscr{D}ir_c$, exchange flow occurs at the upper opening, and below this line, unidirectional flow is established (the region shaded in light grey). To the left of the dashed line denoting $\mathscr{D}ra_c$, draughts are likely to occur, and to the right of this line, draughts are unlikely (the region shaded in dark grey). The pair of maximum and minimum allowable vent areas is marked by the symbol '•' in (d), which is determined by identifying the intersection of the lines of $\mathscr{D}ra_c$ and A^*/H^2.

combined values collapse onto a single curve corresponding to a constant value of A^*/H^2, as indicated by the red contour line.[1] Whilst this might suggest that there is an infinite

[1]Given the inherent uncertainty in estimating the loss coefficient (see §3.3.3) and therefore the (effective) size of a vent, it may be practical to represent the line of constant A^*/H^2 in Figure 4.1 as a 'tolerance band', which quantifies the maximum and minimum deviations in vent areas. However, for the purposes of simplicity, we will assume that the loss coefficients take roughly a constant value, such that the value of A^*/H^2 remains constant.

number of possible combinations of a_t/H^2 and a_b/H^2 which would all give the same value of A^*/H^2 and therefore the same ventilation flow rate, this is not always the case. Instead of the anticipated unidirectional flow, exchange flow at the upper opening – in which cool inflow and warm outflow occur simultaneously across the upper opening – could develop (Hunt & Coffey, 2010). As mentioned earlier, exchange flows are generally undesirable, as they may lead to reduced ventilation flow rates and increased indoor air temperatures.

Hunt & Coffey (2010) showed that, at a given upper opening, the transition from unidirectional to exchange flow is determined by the 'Direction number', $\mathscr{D}ir$, which is dependent on the area of the opening, the ventilation flow rate through it and the temperature difference across it (see Equation (4.7)). For a given ventilation flow rate and indoor-outdoor temperature difference, increasing the area of the upper opening (relative to the area of the lower opening) will decrease the value of $\mathscr{D}ir$ of flows across the upper opening, and for sufficiently small values of $\mathscr{D}ir$, exchange flows can develop. Specifically, exchange flows occur when $\mathscr{D}ir < \mathscr{D}ir_c$, where $\mathscr{D}ir_c$ is the critical value of the Direction number.

The critical Direction number, $\mathscr{D}ir_c$, as indicated by the dotted line in Figure 4.1(b), divides the $\{a_b/H^2, a_t/H^2\}$-space into a region of exchange flow and a region of unidirectional flow. Above the dotted line, exchange flow occurs, and below this line, unidirectional flow is established. For a given value of A^*/H^2, the critical Direction number therefore determines the largest permissible (or critical) area of the upper opening, $a_{t,c}/H^2$, at which unidirectional flow can be maintained. In order to avoid the possibility of exchange flow at the upper opening, this requires $a_t/H^2 < a_{t,c}/H^2$.

Tracing along the line of A^*/H^2 away from $a_{t,c}/H^2$, we find that there are certain combinations of opening areas that might result in draughts. In particular, draughts are more likely to develop when the lower opening area is small relative to the upper opening area. This is primarily due to the associated increase in the velocity of the cool air ingress, which occurs when the area of the lower opening is reduced. From a comfort perspective, draughts are generally undesirable as they create significant air movement and mixing within the room, which can be perceived as uncomfortable (Fanger *et al.*, 1988).

In order to provide an indication as to when draughts might arise, we use the Draught number of Hunt & Coffey (2010) to determine the opening areas at which the transition between 'mixing' ('draught') and 'no-mixing' ('no-draught') occurs. Similar in form to the expression of the Direction number, Hunt & Coffey (2010) showed that the Draught number, $\mathscr{D}ra$, is related to the area of the lower opening, the airflow rate through it and the temperature difference across it (see Equation (4.10)). For a given ventilation flow rate and temperature difference, reducing the area of the lower opening (relative to the upper opening) will increase the value of $\mathscr{D}ra$ of flows across the opening. Specifically, draughts may develop when $\mathscr{D}ra > \mathscr{D}ra_c$, where $\mathscr{D}ra_c$ is the critical value of the Draught number.

The critical Draught number, $\mathscr{D}ra_c$, as indicated by the dashed line in Figure 4.1(c), separates the plot further into a region of 'draught' (above the line) and a region of 'no-draught' (below the line). In particular, note how the region of 'no-draught' coincides with the region of the plot where purely unidirectional flow occurs. This region, as shaded in dark grey in Figures 4.1(c) and 4.1(d), is referred to as the 'comfort zone' and defines the allowable range of opening areas to select from. In order to determine this range of areas, we employ the critical Draught number condition of Hunt & Coffey (2010) to place a constraint on the maximum and minimum allowable opening areas, $a_{\mathrm{t,max}}/H^2$ and $a_{\mathrm{b,min}}/H^2$, for a given A^*/H^2 such that exchange flows *and* draughts are avoided. By selecting the opening areas that satisfy the constraints $a_{\mathrm{t}} \leqslant a_{\mathrm{t,max}}/H^2$ and $a_{\mathrm{b}} \geqslant a_{\mathrm{b,min}}/H^2$, the requirements for unidirectional flow, ventilation flow rate *and* a draught-free indoor environment can be satisfied simultaneously.

The methodology outlined above is designed to enable individual openings to be sized rapidly based on any given room height, temperature difference and heat input. The entire calculation procedure to determine $a_{\mathrm{t,max}}/H^2$ and $a_{\mathrm{b,min}}/H^2$, and hence the allowable range of opening areas for a given design, is laid out in a step-by-step format in §4.4.

4.3 A mathematical model of stack ventilation

In this section we present the fundamental components of the mathematical model for stack ventilation in rooms, which underpin our approach to size ventilation openings. The model of the ventilating flow is comprised of two key parts: a steady heat balance, based on the conservation of buoyancy within the room, which is used to link heat inputs to ventilation flow rates and air temperatures, and a pressure balance, based on the familiar Bernoulli theorem and the hydrostatic pressure relationship, to calculate ventilation flow rates. Finally, we combine the simplified model of stack ventilation with the flow type classification method of Hunt & Coffey (2010), based on the use of the Direction and Draught numbers, to derive simple algebraic expressions for the opening areas required to provide the desired ventilation.

We stress that the model presented herein is intentionally simplified, since the primary focus of the work is on providing rapid guidance for preliminary design use only. Notably, the effects of heat transfer through the building fabric, wind pressure and thermal stratification are not accounted for in our model. For convenience and where appropriate, we reiterate some of the key equations and underlying assumptions from Chapter 3.

4.3.1 Room layout and distribution of heat inputs

Figure 4.2 shows the geometry of the enclosure we consider and the notation used. Ventilation openings, of area a_{b} and a_{t}, placed at the floor and ceiling levels, respectively, connect the interior to an unstratified, wind-free external environment with temperature T_{ext} and density ρ_{ext}. The vertical distance separating the openings is denoted H. Note that the openings need not necessarily be aligned in the same manner as shown in Figure 4.2; it is the vertical separation of the openings, rather than their horizontal position, that is important here.

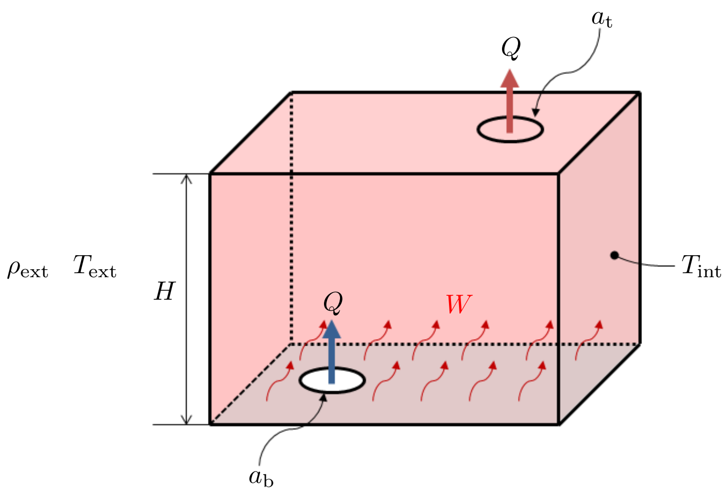


FIGURE 4.2: Schematic of a naturally ventilated room showing the geometry we consider and the notation used. The room is located in an unstratified, wind-free external environment with temperature T_{ext} and density ρ_{ext}. Horizontal openings, of area a_{b} and a_{t}, are located in the floor and ceiling of the façade, respectively. The openings are separated by a vertical distance H. There is a distributed heat source of strength W at floor level, which drives turbulent convective motion, such that the air inside the room is well-mixed and at uniform temperature T_{int}. The bulk airflow rate through the openings is Q.

For simplicity, we restrict our attention to a 'well-mixed', uniform temperature internal environment. In practice, buildings are likely to contain a variety of heat sources with different strengths, geometry and spatial distribution, which can lead to complex patterns of vertical stratification (see, for example, Figure 3.5); the well-mixed model presented herein represents one end of this spectrum, which allows us to simplify the mathematical modelling of room airflows by removing the need to consider the generally complex interrelationship between the indoor stratification and the geometry/spatial distribution of heat sources. After all, the core focus of this work is to develop a quick and straightforward route to informing the size of openings, and as such, a well-mixed model is a reasonable starting point.

Since we know that a uniformly distributed heat load at floor level generates a well-mixed interior at steady state (*cf.* Gladstone & Woods (2001)), we can model the various heat sources (*e.g.* occupants, electrical devices, solar gains, *etc.*) as a single, uniformly distributed source of strength W at floor level. The strength of the heat source (or heating power, W (Watts)) can be described in terms of a heat flux, B ($\mathrm{m^4\,s^{-3}}$), which we recall from Equation (3.16) is given by

$$B = \frac{gW}{\rho_{\mathrm{ext}}\mathrm{c_p}(273 + T_{\mathrm{ext}})}, \tag{4.1}$$

where ρ_{ext} and $\mathrm{c_p}$ are the density and specific heat capacity of ambient air, respectively. For air temperatures between 15°C and 30°C, $\mathrm{c_p} = 1007\,\mathrm{J\,kg^{-1}\,K^{-1}}$ and $\rho_{\mathrm{ext}} \approx 1.2\,\mathrm{kg\,m^{-3}}$ (Cimbala & Çengel, 2008), giving $B \approx (2.8 \times 10^{-5})W$.

We assume that the distributed heat source drives turbulent high Rayleigh number convection such that a well-mixed internal environment is established and maintained (Andersen, 1995; Gladstone & Woods, 2001). Air within the room has a uniform temperature T_{int} and is warmer than the outdoor air; this difference in air temperature, $\Delta T = T_{\mathrm{int}} - T_{\mathrm{ext}}$, can be expressed as a reduced gravity of the interior, $g'_{\mathrm{int}} = g\Delta T/(273 + T_{\mathrm{ext}})$.

Note that, whilst we focus on distributed heat sources, the model presented herein could in principle be applied to rooms for which it is reasonable to assume a uniform temperature internal environment. Examples of these may include rooms with a high density of occupants and electrical devices, such as offices and libraries, or rooms equipped with modern underfloor heating systems. In these situations, it is not unreasonable to expect that the heat sources might occupy 15% or greater of the total floor area, thereby satisfying the criterion for a well-mixed indoor environment of Kaye & Hunt (2010).

4.3.2 Steady heat balance

For simplicity, the walls, floor and ceiling comprising the room fabric are assumed to be 'perfectly insulating' such that heat losses through the fabric can be neglected (B_{loss} in Equation (3.17) is zero). We also assume that there is no thermal buffering effect of the room fabric, *i.e.* we consider a well-insulated, lightweight building with low thermal mass.

The bulk exchange of heat between the interior and exterior is carried out solely by the ventilating flow, Q, through the openings in the façade. At steady state, the rate of heat supply due to heating, B, is balanced by the rate at which the heat is removed by the ventilating flow through the upper opening, Qg'_{int}. Thus, at steady state, the heat balance for the room requires (*cf.* Equation (3.17))

$$B = Qg'_{\mathrm{int}}. \tag{4.2}$$

4.3.3 Steady ventilation flow rate

By assuming a hydrostatic pressure distribution both outside and inside the room (except at the openings), by applying Bernoulli's theorem along a streamline through each opening, and by applying volume conservation, the steady ventilation flow rate, Q, driven through the openings with combined effective area A^*, is given by (*cf.* Equation (3.10))

$$Q = A^* \sqrt{g'_{\text{int}} H}. \tag{4.3}$$

For a given heat input and opening geometry, the ventilation flow rate can be obtained directly from Equation (4.3), where on substituting $g'_{\text{int}} = B/Q$ we obtain

$$Q = A^{*2/3} (BH)^{1/3}. \tag{4.4}$$

4.3.4 Required total effective opening area

The steady heat balance and airflow rate equations in §4.3.2 and §4.3.3 together form a complete simplified mathematical model of stack ventilation in a single room, allowing ventilation flow rates to be calculated when heat inputs and opening areas are known. However, in the context of a natural ventilation design, the areas of the openings are typically unknown at the early stages. This is often referred to as the 'inverse problem' (Ghiaus & Allard, 2005), as rather than calculating the airflow rate based on a given total opening area, individual opening areas are sought which will deliver the desired ventilation flow rate and indoor temperature.

By dividing the expression for Q in (4.3) through by $\sqrt{g'_{\text{int}} H^5}$, such that $Q/\sqrt{g'_{\text{int}} H^5} = A^*/H^2$, and noting that $g'_{\text{int}} = g\Delta T/(273+T_{\text{ext}})$, the relationship between the total effective area of the openings, room geometry, air temperature and ventilation flow rate can be expressed in dimensionless form as follows:

$$\frac{A^*}{H^2} = \left(\frac{(273 + T_{\text{ext}})Q^2}{gH^5 \Delta T} \right)^{1/2}. \tag{4.5}$$

Straightforward manipulation of Equation (3.11) gives the dimensionless total effective area, A^*/H^2, of the openings as

$$\frac{A^*}{H^2} = \sqrt{2} \left(\frac{1}{c_{\text{b}}^2} \left(\frac{a_{\text{b}}}{H^2} \right)^{-2} + \frac{1}{c_{\text{t}}^2} \left(\frac{a_{\text{t}}}{H^2} \right)^{-2} \right)^{-1/2}, \tag{4.6}$$

where c_{t} and c_{b} are the loss coefficients for the upper and lower openings, respectively. As discussed in §3.3.3, the loss coefficient is affected by the geometry and surface roughness of the opening, and the Reynolds number of the flow through it (Ward-Smith, 1980). Hunt & Holford (2000) and Holford & Hunt (2001) also showed that density differences between air on either side of the opening (*e.g.* when warm, buoyant air flows through an upper opening of a heated room into a cooler, denser outdoor environment) can affect the value of the loss coefficient; the greater the density contrast across the opening, the greater the flow contraction, the smaller the area of the opening occupied by the flow, and thus the smaller the value of the loss coefficient.

For simplicity, we restrict our attention to only one type of opening, the 'sharp-edged' opening, assume a fully turbulent flow (*i.e.* a high Reynolds number flow, Re $\gtrsim$ 4000) through each opening, and assume that the difference in air density across each opening is sufficiently small such that the loss coefficients are constant (Hunt & Holford, 2000; Holford & Hunt, 2001). Typically, for 'sharp-edged' openings, the value of the loss coefficient is taken to be $c \approx 0.6$ (Ward-Smith, 1980; Flourentzou *et al.*, 1998; CIBSE, 2005) and we will use this value of c throughout. A summary of the opening geometry and flow conditions required for a constant loss coefficient is given in Table 3.1 as reference.

By linking Q and ΔT with the requirements for the fresh air supply rate and the indoor-outdoor temperature difference, respectively, Equation (4.5) can be used to determine a suitable value of A^*/H^2 to achieve the target design. Note that the expression for A^*/H^2 in (4.5) applies only to situations for which unidirectional flow occurs through all openings. As mentioned earlier, the occurrence of exchange flow at the upper opening is possible; this, in turn, could reduce the ventilation flow rate below the target design value.

4.3.5 Ensuring unidirectional flow through the openings

We use the flow type classification method of Hunt & Coffey (2010) to provide an indication as to when exchange flow occurs at the upper opening. By assuming a uniform velocity profile across the opening, a reasonable assumption for high Reynolds number flow, the Direction number, $\mathscr{D}ir$, is given by (*cf.* Equation (3.14))

$$\mathscr{D}ir = k_1 \frac{Q_{\mathrm{t}}}{a_{\mathrm{t}}^{5/4} {g'}_{\mathrm{t}}^{1/2}}, \tag{4.7}$$

where g'_{t} is the reduced gravity associated with the difference in temperature (relative to the exterior) across the upper opening, and $k_1 = (\frac{8}{5}\pi^{1/2}\alpha_{\mathrm{P}})^{1/2}$ is a constant dependent on the (top-hat) entrainment coefficient α_{P} for the outflowing 'plume' across the opening.[2] Following Turner (1986), we take $\alpha_{\mathrm{P}} \approx 0.117$, giving $k_1 \approx 0.58$. For a well-mixed internal environment, $g'_{\mathrm{t}} = g'_{\mathrm{int}}$. At steady state, volume conservation requires $Q = Q_{\mathrm{b}} = Q_{\mathrm{t}}$. Thus, by substituting for Q from Equation (4.3) into (4.7), the Direction number can be expressed solely in terms of geometric ratios as follows:

$$\mathscr{D}ir = k_1 \frac{A^*}{H^2} \left(\frac{a_{\mathrm{t}}}{H^2} \right)^{-5/4}. \tag{4.8}$$

Hunt & Coffey (2010) showed that the critical value of the Direction number, $\mathscr{D}ir_{\mathrm{c}}$, below which exchange flow would occur, is 0.33 for horizontal openings. This critical condition places a limit on the largest permissible area of the upper opening at which unidirectional flow can be maintained for a given A^*/H^2 (as illustrated schematically in Figure 4.1(b)). By setting $\mathscr{D}ir = \mathscr{D}ir_{\mathrm{c}} = 0.33$ in Equation (4.8), the largest permissible (or critical) area of the upper opening, $a_{\mathrm{t,c}}/H^2$, thus is

$$\frac{a_{\mathrm{t,c}}}{H^2} = 1.57 \left(\frac{A^*}{H^2} \right)^{4/5}. \tag{4.9}$$

In order to ensure that the upper opening supports unidirectional flow – rather than exchange flow which restricts the outflow of warm air – this requires $a_{\mathrm{t}}/H^2 < a_{\mathrm{t,c}}/H^2$.

4.3.6 Ensuring a draught-free interior

As noted previously, draughts can lead to significant air movement and mixing within a space, which can pose a risk to occupant comfort. Hunt & Coffey (2010) showed that the strength of mixing by the inflowing cool air is related to the Draught number, $\mathscr{D}ra$. For a uniform temperature internal environment, the Draught number is given by

$$\mathscr{D}ra = k_2 \frac{Q_{\mathrm{b}}}{a_{\mathrm{b}}^{5/4} \Delta {g'_{\mathrm{b}}}^{1/2}}, \tag{4.10}$$

where $\Delta g'_{\mathrm{b}} = g'_{\mathrm{int}} - g'_{\mathrm{ext}}$ is the difference in the reduced gravities between the indoor and outdoor environment across the lower opening, and $k_2 = \pi^{1/2}\lambda\gamma$ is a constant related to the dynamics of the inflow across the opening. Following Fischer *et al.* (1979), the empirical

[2] Although the entrainment coefficient α_{P} is known to vary with the 'discharge parameter' Γ_{t} (Kaye & Hunt, 2009), for simplicity, we use the pure plume ($\Gamma_{\mathrm{t}} = 1$) value of α_{P}, *i.e.* plumes arising from an idealised point source under the influence of buoyancy forces alone. A range of values of α_{P} is quoted in the literature. Morton *et al.* (1956) investigated the behaviour of turbulent pure plumes issuing from a point source of buoyancy and reported that, for Gaussian profiles, $\alpha_{\mathrm{P}} = 0.093$ agreed well with their experimental data, while similar experiments performed by Baines (1983) deduced $\alpha_{\mathrm{P}} = 0.073$. These two values of α_{P} generally lie towards the upper and lower limits of the reported range, and as pointed out by Hunt & Linden (2001), there is uncertainty regarding the most appropriate value of α_{P}. Turner (1986) surveyed a number of laboratory experiments on turbulent entrainment induced by buoyant plume flows and suggested $\alpha_{\mathrm{P}} = 0.083$ (for Gaussian profiles) is a suitable empirical value. Since $\alpha_{\mathrm{P}} = 0.083$ lies approximately midpoint of the reported range, we use $\alpha_{\mathrm{P}} = 0.083$. Taking 'top-hat' profiles for the time-averaged horizontal variation of the vertical velocity and buoyancy across the plume, $\alpha_{\mathrm{P}} = \sqrt{2}(0.083) \approx 0.117$.

constants $\lambda = 3.5$ and $\gamma = 0.15$, giving $k_2 \approx 0.93$. Conserving volume within the room, $Q = Q_{\rm b} = Q_{\rm t}$. Thus, by substituting for Q from Equation (4.3) into (4.10) and noting that $\Delta g'_{\rm b} = g'_{\rm int}$ (since $g'_{\rm ext} = 0$), the Draught number can be written in terms of geometric ratios as follows:

$$\mathscr{D}ra = k_2 \frac{A^*}{H^2}\left(\frac{a_{\rm b}}{H^2}\right)^{-5/4}. \qquad (4.11)$$

For a fixed value of A^*/H^2, Equation (4.11) shows that the Draught number of the inflow increases as the area of the lower opening is reduced. Specifically, Hunt & Coffey (2010) showed that the critical value of the Draught number, $\mathscr{D}ra_{\rm c}$, above which mixing by the inflow is significant, is 0.67 for horizontal openings. Note that the critical value of $\mathscr{D}ra_{\rm c} = 0.67$ marks the onset of mixing *at the interface* separating a buoyant upper layer and a cooler lower layer, and thus is applicable only to thermally stratified indoor environments. However, it is not unreasonable to expect that the inflow velocities required to generate significant mixing within a room may also result in uncomfortable draughts for occupants, regardless of whether the interior is stratified or well-mixed. Therefore, we use the critical Draught number condition of Hunt & Coffey (2010) to identify when draughts might occur. We later show that the opening areas which satisfy the criterion of $\mathscr{D}ra < 0.67$ can generate a relatively comfortable indoor environment for occupants.

For a given value of A^*/H^2, the critical Draught number therefore places a constraint on the minimum allowable area of the lower opening (and on the corresponding maximum allowable area of the upper opening) at which unidirectional flow *and* a draught-free interior are established simultaneously. It is, however, worth mentioning here that for very large values of A^*/H^2, the allowable range of opening areas will no longer be constrained by the critical Draught number, but instead by the critical Direction number. In order to ascertain the largest permissible effective opening area, $A^*_{\rm c}/H^2$, consider the point at which the lines corresponding to $\mathscr{D}ir_{\rm c} = 0.33$ and $\mathscr{D}ra_{\rm c} = 0.67$ intersect, as shown graphically in Figure 4.3. At this point of intersection, $a_{\rm t}/H^2 = 0.82$ and $a_{\rm b}/H^2 = 0.70$, giving $A^*_{\rm c}/H^2 = 0.45$. We therefore restrict our model to $A^*/H^2 < 0.45$, *i.e.* the region shaded in grey in Figure 4.3.

Are occupants comfortable?

In our model, the critical Draught number condition of Hunt & Coffey (2010) is used to determine the target range of opening areas for a given design. Whilst the Draught number condition helps to identify the size of the openings needed to avoid the possibility of draughts, it cannot give an indication as to whether the airflow established in the room is in fact comfortable/uncomfortable for occupants. For example, for a chosen pair of openings, the architect might wish to know *what is the percentage of occupants likely to perceive the airflow as too draughty?* Since the comfort of occupants is a key concern in a ventilation design, it

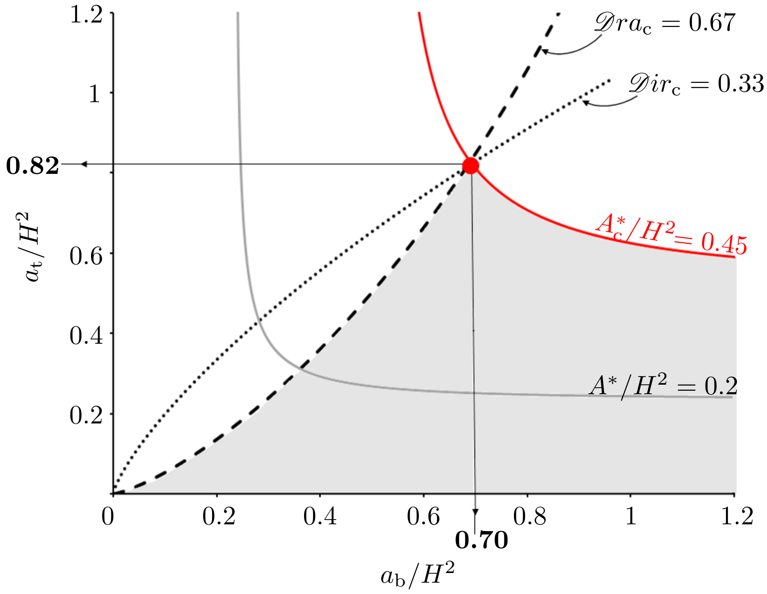


FIGURE 4.3: Plot of a_t/H^2 against a_b/H^2 showing the intersection of the critical Direction and Draught numbers, $\mathscr{D}ir_c$ and $\mathscr{D}ra_c$, respectively. The point at which the lines of $\mathscr{D}ir_c$ and $\mathscr{D}ra_c$ intersect is marked by the symbol '•' on the plot, which lies on the contour corresponding to $A_c^*/H^2 = 0.45$. The region of $\{a_b/H^2, a_t/H^2\}$-space, within which the critical Draught number constrains the allowable range of opening areas, is shaded in grey.

may be informative to illustrate how the Draught number can be interpreted in the context of comfort.

Quantifying draught-related discomfort

A number of studies have been conducted in climate chambers to investigate the effect of draught on occupants' perception of comfort, *e.g.* Fanger & Christensen (1986), Fanger *et al.* (1988), Toftum & Nielsen (1996), Griefahn *et al.* (2002), amongst many others. A broad conclusion which may be drawn from this body of work is that the level of discomfort increases with increasing velocity of the airflow and as the temperature of the airflow is decreased. Moreover, rapid changes or fluctuations in airflow velocities (*i.e.* turbulence intensity) were found to lead to an increased level of discomfort. According to Hensel (1981) and Fanger *et al.* (1988), this may partly be attributed to the increased rate of change of skin temperature associated with the rapidly fluctuating flow, which can trigger 'warning' signals to the brain to counteract the local cooling effect.

In order to quantify draught-related discomfort in ventilated spaces, an empirical model was developed by Fanger *et al.* (1988) to relate the percentage of occupants feeling dissatisfied, or Draught Rating (DR), to the mean air temperature, T (°C), mean velocity, v ($\mathrm{m\,s^{-1}}$), and turbulence intensity, Tu (%), of the flow. The Draught Rating is given by

$$DR = (34 - T)(v - 0.05)^{0.62}(0.37vTu + 3.14), \tag{4.12}$$

which is valid for $20 < T < 26$°C, $0.05 < v < 0.4\,\mathrm{m\,s^{-1}}$ and $0 < Tu < 70\%$. Melikov *et al.* (1988) conducted full-scale measurements of airflows in the occupied zone of eight different naturally ventilated buildings and reported that the mean velocity and turbulence intensity varied in the range $0.05 \lesssim v \lesssim 0.2\,\mathrm{m\,s^{-1}}$ and $10 \lesssim Tu \lesssim 70\%$, respectively. They reported that the highest draught risk occurred close to the floor, where the mean velocity was the highest and the air temperature was the lowest.

In order to illustrate how the Draught number can be linked to the Draught Rating and therefore to occupants' perception of comfort, consider the example room in Figure 4.2. For simplicity, we assume that the mean velocity of the airflow in the room is equal to the velocity of the inflow at the lower opening, such that $v = Q/a_\mathrm{b}$. This may be thought of as a 'worst-case' scenario, since flow velocities at openings are typically much higher than room-averaged flow velocities; the Draught Rating determined herein would therefore give conservative estimates, *i.e.* providing the maximum value of DR for a given combination of opening areas. Substituting $Q = v\,a_\mathrm{b}$ into Equation (4.5), the dimensionless total effective area of the openings can be expressed in terms of the velocity v across the opening as follows:

$$\frac{A^*}{H^2} = \left(\frac{(273 + T_\mathrm{ext})v^2}{gH\Delta T}\right)^{1/2} \frac{a_\mathrm{b}}{H^2}. \tag{4.13}$$

By substituting for a_b/H^2 from Equation (4.13) into (4.11), the Draught number can be related to the Draught Rating (4.12) – via the velocity v at the opening – as follows:

$$\begin{aligned} \mathscr{D}ra &= k_2 \left(\frac{A^*}{H^2}\right)^{-1/4} \left(\frac{(273 + T_\mathrm{ext})v^2)}{gH\Delta T}\right)^{5/8} \\ &= \frac{k_2}{0.96}\left[\left(\frac{a_\mathrm{b}}{H^2}\right)^{-2} + \left(\frac{a_\mathrm{t}}{H^2}\right)^{-2}\right]^{1/8} \left(\frac{(273 + T_\mathrm{ext})v^2)}{gH\Delta T}\right)^{5/8}. \end{aligned} \tag{4.14}$$

As an illustrative example, consider the room in Figure 4.2 with $H = 3.5\,\mathrm{m}$ and $W = 3\,\mathrm{kW}$. The temperature difference between the interior and exterior, ΔT, is 4°C and the outdoor air temperature, T_ext, is 20°C. Taking $Tu = 35\%$ (which is approximately midrange of the values of Tu reported by Melikov *et al.* (1988)), Figure 4.4 plots contours of constant Draught Rating DR corresponding to 15%, 30%, 35%, 40% and 45% (or, equivalently, $v = 0.14$, 0.23, 0.26, 0.29 and $0.32\,\mathrm{m\,s^{-1}}$, respectively) on a single set of axes with a_t/H^2 on the vertical axis and a_b/H^2 on the horizontal axis. To allow for comparison with the critical Draught number condition of Hunt & Coffey (2010), the contour line corresponding to $\mathscr{D}ra_\mathrm{c} = 0.67$ is also shown on the plot. To assist in this example, quantitative predictions

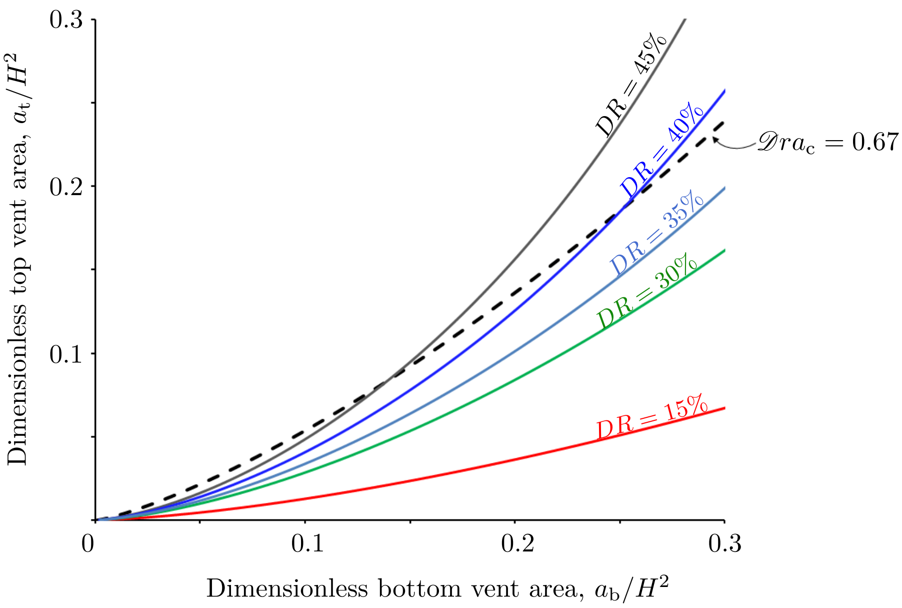


FIGURE 4.4: Plot of a_t/H^2 against a_b/H^2 showing contours of constant Draught Rating, DR. Colour contours represent: (red) $DR = 15\%$, (green) $DR = 30\%$, (light blue) $DR = 35\%$, (blue) $DR = 40\%$ and (grey) $DR = 45\%$. The dashed line represents the critical value of the Draught number, $\mathscr{D}ra_c = 0.67$. The plot applies to the example room in Figure 4.2 with $H = 3.5$ m, $W = 3$ kW and $\Delta T = 4°$C ($T_{ext} = 20°$C). We have assumed that the turbulence intensity of the inflowing cool draught of air, Tu, through the floor-level opening is 35%.

A^*/H^2	a_b/H^2	a_t/H^2	Q ($m^3\,s^{-1}$)	v ($m\,s^{-1}$)	DR (%)	$\mathscr{D}ra$ (−)
0.07	0.37	0.090	0.62	0.14	15	0.24
0.07	0.23	0.095	0.62	0.23	30	0.45
0.07	0.16	0.10	0.62	0.32	45	0.67
0.07	0.13	0.12	0.62	0.40	60	0.89

TABLE 4.2: Example calculations of the Draught Rating, DR, and Draught number, $\mathscr{D}ra$, for four different opening area combinations. In each of the four cases, the dimensionless total effective area A^*/H^2 of the openings is constant and equal to 0.07. Values have been calculated for the example room with $H = 3.5$ m, $W = 3$ kW and $\Delta T = 4°$C ($T_{ext} = 20°$C). We have taken $Tu = 35\%$ for this calculation.

of DR and $\mathscr{D}ra$ for a range of possible opening area combinations (with $A^*/H^2 = 0.07$) are given in Table 4.2.

Qualitatively, Figure 4.4 and Table 4.2 show that both DR and $\mathscr{D}ra$ decrease as the area of the lower opening is increased relative to the area of the upper opening. In particular, note how the contours corresponding to $DR < 40\%$ in Figure 4.4 lie within the region of $\{a_b/H^2, a_t/H^2\}$-space where $\mathscr{D}ra < \mathscr{D}ra_c$, *i.e.* the 'comfort zone'. Whilst the above example is an isolated case, it does serve to illustrate how changes made to the relative areas of the upper and lower openings affect the Draught number and Draught Rating in qualitatively similar ways. Provided the opening areas are selected within the 'comfort zone' ($\mathscr{D}ra < \mathscr{D}ra_{\mathrm{c}}$), we expect that the negative effects of draught on occupants' perceived comfort can be reduced.

4.3.7 Maximum and minimum allowable opening areas

Using the critical Draught number condition of Hunt & Coffey (2010), we can now derive expressions for the maximum and minimum allowable areas of the openings, which lie on the boundary of the 'comfort zone'. Setting $\mathscr{D}ra = \mathscr{D}ra_{\mathrm{c}} = 0.67$ in Equation (4.11), the minimum allowable area of the lower opening is given by

$$\frac{a_{\mathrm{b,min}}}{H^2} = 1.3\left(\frac{A^*}{H^2}\right)^{4/5}. \tag{4.15}$$

By rearranging the expression for A^*/H^2 in Equation (4.6) to make a_{t}/H^2 the subject, by assuming $c_{\mathrm{t}} = c_{\mathrm{b}} = 0.6$ and by setting $a_{\mathrm{b}}/H^2 = a_{\mathrm{b,min}}/H^2$, the maximum allowable area of the upper opening, $a_{\mathrm{t,max}}/H^2$ corresponding to $a_{\mathrm{b,min}}/H^2$ is then

$$\frac{a_{\mathrm{t,max}}}{H^2} = \left(0.72\left(\frac{A^*}{H^2}\right)^{-2} - \left(\frac{a_{\mathrm{b,min}}}{H^2}\right)^{-2}\right)^{-1/2}. \tag{4.16}$$

At this stage, it is useful to place a limit on the smallest possible area of the upper opening. In order to determine this minimum area, consider the plot in Figure 4.1(d). Note how the gradient of the curve of A^*/H^2 is close to zero in the region labelled 'comfort zone'. This suggests that the ventilation flow rate is relatively insensitive to changes in the area of the lower opening and, hence, the control of the ventilation is accomplished by the upper opening. In fact, there is a minimum value of the upper opening area at which 'absolute' control of the ventilating flow is achieved, *i.e.* the lower opening can be opened 'infinitely', provided the upper opening is unaltered, without affecting the airflow rate through the room. Mathematically, the minimum area of the upper opening can be determined by examining the expression for A^*/H^2 as a_{b} tends to (at least theoretically) to infinity. We begin by rearranging Equation (4.6) in the following form:

$$\frac{A^*}{H^2} = 0.6\sqrt{2}\frac{a_{\mathrm{t}}}{H^2}\left(1 + \frac{a_{\mathrm{t}}^2}{a_{\mathrm{b}}^2}\right)^{-1/2}. \tag{4.17}$$

The terms inside the brackets in (4.17) can be expanded as a binomial series for $|a_{\mathrm{t}}^2/a_{\mathrm{b}}^2| < 1$, giving

$$\frac{A^*}{H^2} = 0.6\sqrt{2}\frac{a_{\mathrm{t}}}{H^2}\left(1 - \frac{1}{2}\frac{a_{\mathrm{t}}^2}{a_{\mathrm{b}}^2} + \frac{3}{8}\frac{a_{\mathrm{t}}^4}{a_{\mathrm{b}}^4} - \frac{5}{16}\frac{a_{\mathrm{t}}^6}{a_{\mathrm{b}}^6} + ...\right)^{-1/2}. \tag{4.18}$$

Based on the limit as $a_{\mathrm{b}} \to \infty$, $a_{\mathrm{t}} \to a_{\mathrm{t,min}}$, the higher-order terms inside the brackets in (4.18) become insignificant. Therefore, the minimum allowable area of the upper opening to leading order is given by

$$\frac{a_{\mathrm{t,min}}}{H^2} = \frac{1}{0.6\sqrt{2}}\left(\frac{A^*}{H^2}\right). \tag{4.19}$$

4.4 Summary of design steps

The design procedure to size ventilation openings is divided into five key steps as illustrated by the flow chart in Figure 4.5 and as outlined below. For convenience, we reiterate some of the key equations from §4.3.

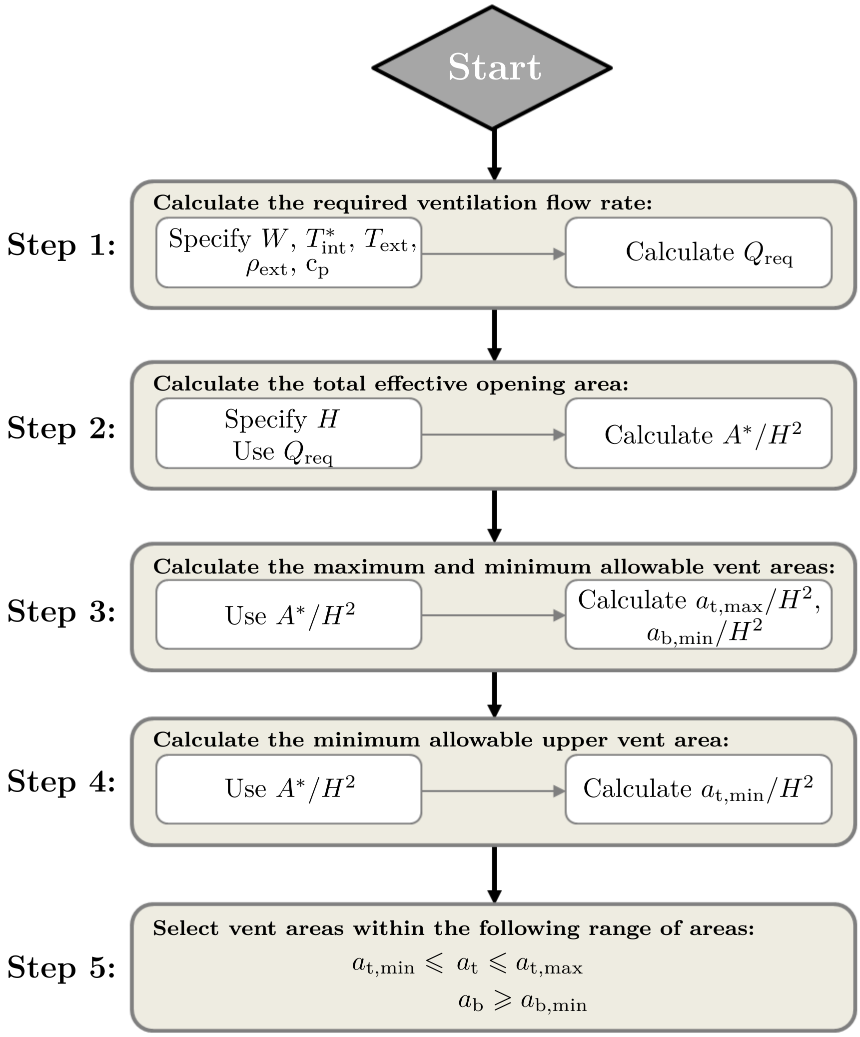


FIGURE 4.5: Flow chart summarising the general design procedure to size ventilation openings. Each step is discussed in more detail, and key equations reiterated, in the accompanying text.

Step 1: Calculate the required ventilation flow rate, Q_{req}, based on the desired temperature difference, $\Delta T^* = T^*_{\mathrm{int}} - T_{\mathrm{ext}}$, and an estimate of the heating power, W:

$$Q_{\mathrm{req}} = \frac{W}{\rho_{\mathrm{ext}} c_{\mathrm{p}} \Delta T^*}$$

Step 2: Using the value of Q_{req} from step 1, calculate the dimensionless total effective opening area, A^*/H^2:

$$\frac{A^*}{H^2} = \left(\frac{(273 + T_{\mathrm{ext}}) Q^2_{\mathrm{req}}}{g H^5 \Delta T^*} \right)^{1/2}$$

Step 3: Using the value of A^*/H^2 from step 2, calculate the minimum allowable area of the lower opening in dimensionless form:

$$\frac{a_{\mathrm{b,min}}}{H^2} = 1.3 \left(\frac{A^*}{H^2} \right)^{4/5}$$

Calculate the maximum allowable area of the upper opening corresponding to $a_{\mathrm{b,min}}/H^2$ in dimensionless form:

$$\frac{a_{\mathrm{t,max}}}{H^2} = \left(0.72 \left(\frac{A^*}{H^2} \right)^{-2} - \left(\frac{a_{\mathrm{b,min}}}{H^2} \right)^{-2} \right)^{-1/2}$$

Step 4: Using the value of A^*/H^2 from step 2, calculate the minimum allowable area of the upper opening in dimensionless form:

$$\frac{a_{\mathrm{t,min}}}{H^2} = \frac{1}{0.6\sqrt{2}} \left(\frac{A^*}{H^2} \right)$$

Step 5: Convert the dimensionless values of $a_{\mathrm{t,max}}/H^2$, $a_{\mathrm{b,min}}/H^2$ and $a_{\mathrm{t,min}}/H^2$ into physical opening areas (in m^2), by multiplying each value by H^2 (*e.g.* $a_{\mathrm{t,max}} = a_{\mathrm{t,max}}/H^2 \times H^2$). Finally, select the pair of upper and lower openings within the following range of areas:

$$a_{\mathrm{t,min}} \leqslant a_{\mathrm{t}} \leqslant a_{\mathrm{t,max}} \quad \text{and}$$
$$a_{\mathrm{b}} \geqslant a_{\mathrm{b,min}}$$

4.5 Application to an example scenario

In order to illustrate how the design procedure may be applied in practice, we consider again the example ventilated room shown in Figure 4.2.

Design scenario: The project is for an open plan office of a low rise building, which is to be naturally ventilated. The main objective at the preliminary design stage is to determine the opening areas required to deliver the necessary airflow rate and indoor temperature. Table 4.3 summarises the key design requirements for the open plan office.

Design conditions	
Net floor area	$100\,\mathrm{m}^2$
Room height, H	$3.5\,\mathrm{m}$
Total heat input, W	$3\,\mathrm{kW}$
Outdoor temperature, T_{ext}	20°C
Design requirements	
Desired indoor temperature, T^*_{int}	24°C
Minimum per person air supply rate	$10\,\mathrm{L\,s^{-1}}$

TABLE 4.3: Summary of the design conditions and specific requirements for the open plan office.

Following the design procedure in Figure 4.5, each calculation step (from 1 to 5) is shown below and the results are given to two significant figures. For clarity, we summarise the key results from each calculation step in Table 4.4.

Step 1: For outdoor air at 20°C, the air density $\rho_{\mathrm{ext}} = 1.2\,\mathrm{kg\,m^{-3}}$ and specific heat capacity $\mathrm{c_p} = 1007\,\mathrm{J\,kg^{-1}\,K^{-1}}$ (Cimbala & Çengel, 2008). Taking $W = 3000\,\mathrm{W}$ and $T^*_{\mathrm{int}} = 24$°C, the required ventilation flow rate through the space is

$$
\begin{aligned}
Q_{\mathrm{req}} &= \frac{W}{\rho_{\mathrm{ext}}\mathrm{c_p}\Delta T^*} \\
&= \frac{3000}{1.2 \times 1007 \times (24 - 20)} \\
&= 0.62\,\mathrm{m^3\,s^{-1}}
\end{aligned}
$$

which is equivalent to $620\,\mathrm{L\,s^{-1}}$. The recommended minimum air supply rate for an open place office is $10\,\mathrm{L\,s^{-1}}$ per person (CIBSE, 2006). A ventilation flow rate of $620\,\mathrm{L\,s^{-1}}$ therefore satisfies the fresh air requirements for a maximum of 62 people.

Step 2: Using $Q_{\mathrm{req}} = 0.62\,\mathrm{m}^3\,\mathrm{s}^{-1}$ from step 1, the dimensionless total effective opening area is

$$\begin{aligned}\frac{A^*}{H^2} &= \left(\frac{(273+T_{\mathrm{ext}})Q_{\mathrm{req}}^2}{gH^5\Delta T^*}\right)^{1/2} \\ &= \left(\frac{(273+20)\times(0.62)^2}{9.81\times(3.5)^5\times(24-20)}\right)^{1/2} \\ &= 0.074\end{aligned}$$

Step 3: Using $A^*/H^2 = 0.074$ from step 2, the dimensionless minimum allowable area of the lower opening is

$$\begin{aligned}\frac{a_{\mathrm{b,min}}}{H^2} &= 1.3\left(\frac{A^*}{H^2}\right)^{4/5} \\ &= 1.3\times(0.074)^{4/5} \\ &= 0.16\end{aligned}$$

The dimensionless maximum allowable area of the upper opening corresponding to $a_{\mathrm{b,min}}/H^2 = 0.16$ is

$$\begin{aligned}\frac{a_{\mathrm{t,max}}}{H^2} &= \left(0.72\left(\frac{A^*}{H^2}\right)^{-2} - \left(\frac{a_{\mathrm{b,min}}}{H^2}\right)^{-2}\right)^{-1/2} \\ &= [(0.72\times(0.074)^{-2}) - (0.16)^{-2}]^{-1/2} \\ &= 0.10\end{aligned}$$

Step 4: The dimensionless minimum allowable area of the upper opening is

$$\begin{aligned}\frac{a_{\mathrm{t,min}}}{H^2} &= \frac{1}{0.6\sqrt{2}}\left(\frac{A^*}{H^2}\right) \\ &= \frac{1}{0.6\sqrt{2}}\times 0.074 \\ &= 0.087\end{aligned}$$

Step 5: For $H = 3.5\,\mathrm{m}$, the physical areas of the openings are

$$a_{\mathrm{b,min}} = 2.0\,\mathrm{m}^2, \quad a_{\mathrm{t,max}} = 1.2\,\mathrm{m}^2, \quad a_{\mathrm{t,min}} = 1.1\,\mathrm{m}^2$$

The allowable range of the upper and lower opening areas for the open plan office thus is

$$1.1\,\mathrm{m}^2 \leqslant a_\mathrm{t} \leqslant 1.2\,\mathrm{m}^2 \quad \text{and}$$
$$a_\mathrm{b} \geqslant 2.0\,\mathrm{m}^2$$

Note how the difference between the maximum and minimum values of a_t – if the desired ventilation flow rate is to be maintained – is approximately $0.1\,\mathrm{m}^2$. In practical terms, this indicates that the ventilation system is highly sensitive to deviations in the area of the upper opening and reinforces the need for careful control of the opening area. On the other hand, there is less restrictions placed on the lower opening area. This may have important implications for providing occupants with a sense of local control over their thermal comfort. For example, occupants may adjust a local vent, provided the upper control vent is unaltered, without affecting the overall ventilation of the room.

Design step	Symbol	Value
Step 1	Q_req ($\mathrm{m}^3\,\mathrm{s}^{-1}$)	0.62
Step 2	A^*/H^2	0.074
Step 3	$a_{\mathrm{b,min}}/H^2$	0.16
	$a_{\mathrm{t,max}}/H^2$	0.10
Step 4	$a_{\mathrm{t,min}}/H^2$	0.087
Step 5	$a_{\mathrm{b,min}}$ (m^2)	2.0
	$a_{\mathrm{t,max}}$ (m^2)	1.2
	$a_{\mathrm{t,min}}$ (m^2)	1.1

Table 4.4: Example calculations of the maximum and minimum allowable opening areas for the open plan office with $H = 3.5\,\mathrm{m}$ and $W = 3\,\mathrm{kW}$. Values have been calculated for $T_\mathrm{ext} = 20^\circ\mathrm{C}$ and a desired temperature difference of $\Delta T^* = 4^\circ\mathrm{C}$.

4.6 Summary and conclusion

The motivation for this chapter stemmed from the need to develop a tractable and easy-to-apply approach that tackles specifically the sizing of individual ventilation openings in a naturally ventilated building. Our proposed approach targets design at the early stages when the building form is fluid, and when decisions regarding the design of ventilation control features, such as the size of openings, are being made.

By combining two well-established, experimentally validated mathematical models of stack ventilation in rooms, a generalised framework was developed for determining the individual opening areas needed to provide the desired ventilation flow rate, indoor air temperature, and crucially, to ensure the intended unidirectional flow through the openings is achieved. Rather than detailed design, we focussed on the preliminary sizing of openings based on a simple room geometry and an idealised indoor heat distribution. Albeit being arguably no more complex than the preliminary calculation methods given in design manuals, such as CIBSE AM10 (CIBSE, 2005), our approach proposed in §4.4 enables architects to determine the *individual* opening areas needed to achieve the target design, as opposed to merely calculating the combined area of the constituent openings. To facilitate architects in the rapid calculation of the appropriate opening areas, a step-by-step guideline was proposed and is summarised in Figure 4.5.

A number of simplifying assumptions were necessary in the development of our simplified mathematical model to ensure that it is tractable and intuitive, and that the results obtained from the model can be straightforwardly applied by architects. In the light of these, it is informative to clarify the constraints on the range of practical situations to which the model may be successfully applied.

Firstly, we assumed that there is no transfer of heat to or from the walls, floor or ceiling of the room, and as such, our model is applicable to 'highly insulated' buildings. In real buildings, insulation is not perfect and heat losses through the building fabric associated with the presence of glazing and imperfectly insulated walls can affect the overall heat balance within a room. Lane-Serff & Sandbach (2012) showed that heat transfers between the building fabric and the internal air do play a role in the overall ventilation, and that neglecting these can lead to an overestimation of the indoor temperature and ventilation flow rate. However, in the context of a naturally ventilated building where advection dominates the overall heat transport in general, the role played by the building's fabric may be of secondary importance when compared to the role of the heat input from internal sources of buoyancy and the transport of the heat by the ventilating flow through the openings in the façade.

Secondly, we restricted our attention to 'sharp-edged' openings only, and assumed that the loss coefficients are constant and equal to 0.6. The latter assumption is reasonable, given the relatively high Reynolds number flow through openings in practice (typically in excess of 10^3) and the small density differences involved. By providing an estimate of the loss coefficients for the openings, we were able to determine what physical opening areas, a_t and a_b, correspond to a given total effective opening area, A^*, and thus a given ventilation flow rate. However, openings in real buildings are unlikely to occur as 'holes' in the façade, but rather be covered by grilles or louvres. In this case, the loss coefficients would likely be quite different and may vary with, for example, the opening surface roughness; this, in turn, could affect the ventilation flow rate achieved through the openings. Designers should be aware, therefore, that the value of the loss coefficient is potentially a large source of uncertainty when sizing openings for natural ventilation.

Thirdly, we assumed that that there is no wind such that the room is ventilated by stack effect only. This may be thought of as a 'worst-case' scenario (Acred & Hunt, 2014*b*) in which there is no external wind available to assist the ventilating flow. The rationale for this assumption is that a ventilation system which essentially provides adequate fresh air supply under the action of buoyancy only would, in principle, be able to exceed, or, at least, meet the target design requirements when the flow is wind-assisted. However, as discussed in §3.6, the wind can oppose the stack-driven flow, which can affect the bulk ventilation flow rate achieved through the room (Hunt & Linden, 2005). In particular, if the opposing wind is weak ($\mathrm{Fr_w} \ll 1$, Equation (3.22)), by considering the effect of stack only and neglecting the contribution of wind when sizing ventilation openings could lead to a decrease in the airflow rate below the target design value.

Finally, we treated the internal sources of heat as a single, evenly distributed source at floor level, since we know that fully distributed sources generate an approximately 'well-mixed' internal environment at steady state (Gladstone & Woods, 2001). In practice, however, a broad range of stratification patterns are possible and are closely linked to the geometry, strength and spatial distribution of the sources within the space. For example, multiple isolated clusters of occupants and/or electrical devices in a room may result in a multi-layered stratification (Linden & Cooper, 1996). In this situation, it may be better to represent the heat load as a collection of localised point sources rather than a fully distributed source.

Whilst the 'well-mixed' model employed herein may seem like an oversimplification, it is exactly because of this simplification which allowed us to exploit a relatively straightforward approach to model, and thereby convey, the physics underlying air and heat flows through a room. By using this simplified model of stack ventilation, we showed that it is possible to derive a simple algorithm that provides a quick and direct route to informing the suitable size of individual openings, regardless of the nature of the heat sources and the effects of thermal stratification. We believe that design guidance underpinned by simplified mathematical models of room airflows can serve as an important stepping stone to designing for more complex building geometries and vertical stratification patterns. More importantly, we believe that the intuitive value afforded by simplified models can facilitate understanding by demonstrating to architects how their design decisions regarding, for example, the size of vents, can impact the subsequent performance of the ventilation system (*e.g.* bulk airflow rates and indoor temperatures), thereby enhancing the contribution of the architect and their designs.

Notwithstanding the limitations described above, the generic nature of our simplified mathematical approach developed in this chapter is robust and valid. It has usefully (i) placed explicit constraints on the individual upper and lower openings required to achieve unidirectional flow and a comfortable indoor environment for any distribution of heat inputs, and (ii) enabled a generalised framework for calculating the individual opening areas to be developed; a framework which, until now, has been entirely absent from the design-based literature on natural ventilation. We anticipate that our proposed approach can serve as a useful starting point in preliminary design.

Chapter 5

Stack ventilation of rooms involving stratification

Preamble

In the previous chapter, we focussed on the stack ventilation of a room in which the heat is distributed uniformly throughout, *i.e.* 'well-mixed', so that the temperature is the same everywhere in the room. By applying this simplified approach, we showed that it is possible to capture the intrinsic mechanisms underlying the ventilation flow whilst avoiding the need to consider the effects of thermal stratification on the ventilating flow.

However, as mentioned earlier, a uniform temperature internal environment represents one end of the spectrum of possible heat distributions within a space. The form of the thermal stratification is closely linked to – *inter alia* – the geometry and spatial distribution of the heat sources. Understanding the manner in which heat sources stratify a space is an essential ingredient for the design of energy efficient natural ventilation systems, as the stratification influences not only the stack pressure available to drive the ventilating flow, but also the indoor temperature distribution, all of which impact the comfort of occupants. Whilst the algorithm presented in the previous chapter was developed without specific reference to the geometry and location of the heat source(s) in the room, in this chapter we focus on addressing the stack ventilation driven by a heat source with a particular geometry and location, and the associated airflow pattern and thermal stratification that arise due the presence of the source.

A simplified approach to capture some of the effects of stratification is to separate the room up into distinct thermal zones; an occupied zone – typically close to the floor – in which temperatures must be carefully controlled, and an unoccupied zone – at higher levels and close to the ceiling – in which heat and pollutants preferentially accumulate. Linden *et al.* (1990) showed that a highly localised point source at floor level in a ventilated enclosure generates this type of two-layer stratification, with a lower layer comprised of air at ambient temperature, and an upper layer above a horizontal interface comprised of relatively warm air. A key result of their work is that the position of the interface depends primarily on entrainment of surrounding air into the plume as it rises above the source, but is independent of the strength of the source. Consequently, arrangements in which entrainment by the plume is significantly altered will make substantial differences to the position and symmetry of the interface, thereby impacting the form of the stratification and the ventilation of the room as a whole. One obvious example is a plume near a solid boundary where entrainment is blocked by the wall and so reduced from that of an unobstructed plume.

In this chapter we are interested in the steady flow and thermal stratification that develop in a ventilated enclosure containing a single floor-level line source of heat, whose length is equal to the length of the enclosure. This may be thought of as an idealised representation of the heat formed by a long row of computer terminals in an office, or by occupants seated in a row in a crowded theatre, for example. These sources can reasonably be modelled as a turbulent, 'two-dimensional' line plume, providing the source half-width of the plume is small compared to the characteristic length of the source (van den Bremer & Hunt, 2014).

Our focus on this particular source geometry is due to the fact that, unlike a point source plume, the line plume entrains surrounding air from two sides only, *i.e.* those that remain unobstructed by the walls of the room. In this way, we can establish a link between the heat source geometry and the placement of the floor-level openings; the former will affect the dynamics of the plume and thereby influence where the plume preferentially draws surrounding air from, while the latter will dictate where the outdoor air enters the space to replenish the air extracted by plume entrainment – the air motion induced by entrainment being paramount to maintaining the position and symmetry of the interface.

We are also interested in how the presence of mixing by the inflowing cool draught of air influences the apportioning of the accumulated heat within the room. Whilst the stack ventilation model of Linden *et al.* (1990) focussed only on the displacement flow which occurs in the absence of internal mixing, in this chapter we extend their model so that it may be applied across a wider range of opening area configurations, for which mixing by the inflow through the base significantly alters the heat distribution within the room. The primary motivation for this chapter is to provide new quantitative and qualitative insights into the mechanisms which control natural ventilation flows, and to feed these back to provide some practical guidance for design.

In order to accommodate the interests of both architects and engineers, the format of this chapter is divided into two distinct parts (I and II), each written intentionally in different styles.

In Part I we develop a simplified mathematical model to examine the steady stack ventilation and thermal stratification that arise in an enclosure containing a floor-level line source. Connections between the interior and exterior environments are via an opening at ceiling level, and two identical floor-level openings placed at each (unobstructed) side of the source. Our model is an extension from that of Linden *et al.* (1990) for a two-layer stratification and includes terms that describe internal mixing by the inflowing cool air at the interface. The aim of Part I is to explore how changes made to the size and relative areas of the openings affect internal mixing, and how these, in turn, impact the indoor temperature distribution, interface height and bulk ventilation flow rate. Part I stands out from the rest of the thesis as it mimics the style of a typical fluid mechanics research paper (*e.g.* the Journal of Fluid Mechanics). This was done deliberately to contrast the general style of writing adopted in this thesis, the intention being to provide the reader with a feel for some of the salient features of technically-orientated articles on natural ventilation, such as the use of discipline-specific vocabulary and terminologies, and the logical, analytical approach to information delivery and presentation (*i.e.* follows a 'convergent' thought process). The use of formal language and technical terminologies, and the exclusive focus on theoretical (and experimental) developments, which are all distinguishing features of engineering/scientific research papers, were identified in our survey (Chapter 2) as some of the main deterrents to effective information delivery to architects.

Following the spirit of this research, which centres on the transfer of information on natural ventilation from the fluid mechanics literature to the architectural community, Part II seeks to convey the key results of Part I into a readily accessible format for use by architects in preliminary design. This requires a shift in mindset; essentially, to focus on the needs and interests of a completely different audience, and in particular, their preferred means of communicating information (visual and written) that are more in tune with their professional group.

Part I: the 'technical' part

5.1 Technical nomenclature

We frame the work herein using 'technical' notation and terminologies only which are commonplace in the fluid mechanics literature. Table 5.1 summarises the notation and terminologies employed. We also make extensive use of dimensionless variables, which are denoted by hats (dimensionless volume flux is denoted $\widehat{Q}$, for example), as their use simplifies mathematical expressions.

Symbol	Description	Units
b	Jet half-width	m
B_{LP}	Source buoyancy flux (per unit length)	$\mathrm{m}^3\,\mathrm{s}^{-3}$
$\mathbb{B}_{\mathrm{u}}$, $\mathbb{B}_{\mathrm{l}}$	Net buoyancy (per unit cross-sectional area) of the upper layer and lower layer, respectively	$\mathrm{m}^2\,\mathrm{s}^{-2}$
C_{LP}	Entrainment constant	-
Fr_{i}	Interfacial Froude number	-
Fr_{t}	Froude number at the top opening	-
g'_{u}, g'_{l}	Reduced gravity of the upper layer and lower layer, respectively	$\mathrm{m}\,\mathrm{s}^{-2}$
G'_{LP}	Reduced gravity of a line plume	$\mathrm{m}\,\mathrm{s}^{-2}$
h	Density interface height	m
M_{b}	Source momentum flux of a jet	$\mathrm{m}^4\,\mathrm{s}^{-2}$
Pe	Péclet number	-
Q	Volume flux	$\mathrm{m}^3\,\mathrm{s}^{-1}$
Q^*	Entrained volume flux across the density interface	$\mathrm{m}^3\,\mathrm{s}^{-1}$
Q_{LP}	Volume flux of a line plume	$\mathrm{m}^3\,\mathrm{s}^{-1}$
$\mathcal{S}$	Stratification parameter	-
w	Centreline jet velocity	$\mathrm{m}\,\mathrm{s}^{-1}$
z_{v}	Virtual origin of a jet	m
GREEK		
α_{LP}	Entrainment coefficient for a line plume	-
α_{P}	Entrainment coefficient for an axisymmetric plume	-
$\Delta g'$	Interfacial buoyancy contrast	$\mathrm{m}\,\mathrm{s}^{-2}$
γ, λ	Empirical jet constants	-
ρ_{u}, ρ_{l}	Density of the upper layer and lower layer, respectively	$\mathrm{kg}\,\mathrm{m}^{-3}$

TABLE 5.1: List of technical notation and terminologies.

5.2 Introduction

Note for readers: Much of this section focusses on recapping the work of Linden *et al.* (1990), Hunt & Coffey (2010) and Coffey & Hunt (2010), which have been reviewed earlier in Chapter 3. It is, however, worthwhile to recall some of their key findings that are directly relevant to this chapter for completeness. Readers who are mainly interested in the theoretical developments and outcomes of our study may wish to omit this introductory section and to proceed straight to §5.3 and §5.4, wherein our theoretical model is developed and the results are presented, discussed and summarised.

* * *

Turbulent buoyant plumes play an instrumental role in a wide range of phenomena involving convection, from the rising column of buoyant fluid emitted above a cooling tower to the heat rising above a person's head. In many applications, particularly concerning building ventilation, the convective plume flows issuing from internal sources of buoyancy can impact the indoor environment as a whole. The plumes not only set the ventilation flow rate through the space, but also influence the form of the indoor stratification and thereby the comfort of occupants. Insight into the behaviour of convective plume flows and their interaction with the indoor thermal environment is critical for the design of energy efficient natural ventilation systems.

Motivated by a desire to gain a deeper understanding of the fluid mechanics which control air and heat flows through buildings, much of the earlier work on natural ventilation has focussed on the flow generated by buoyant plumes from highly localised point sources of buoyancy in an enclosure with openings at high and low levels. Work on air movement and buoyancy-driven flows by Linden *et al.* (1990) showed that an axisymmetric plume (in a time-averaged sense) above a point source carries fluid upwards away from the source, creating a two-layer stratification which drives a steady flow through the enclosure from the low- to high-level openings. However, not all heat sources can be modelled as point sources. A row of closely spaced axisymmetric sources is often better approximated as one line source (Radomski, 2009).

Since the initial work of Linden *et al.* (1990), considerable work has been done on examining the effect of more realistic heat source geometries. This has included the modelling of multiple point sources of buoyancy (Cooper & Linden, 1996; Linden & Cooper, 1996), line sources (Kaye & Hunt, 2004, 2007), finite (non-zero) area sources (Hunt *et al.*, 2002; Kaye & Hunt, 2010), fully distributed sources (Andersen, 1995; Gladstone & Woods, 2001), and a combination of distributed and point source geometries (Hunt *et al.*, 2001*b*; Chenvidyakarn

& Woods, 2008). A broad conclusion which may be drawn from the aforementioned studies is that the form of the thermal stratification established in a given room "depends sensitively on the heat source geometry and entrainment into the rising plume(s), and as such, is not merely dependent upon the opening/room geometry and buoyancy flux input" (Kaye & Hunt, 2010). The present work focusses on the flow induced by a localised line source of buoyancy at floor level in a ventilated enclosure. As discussed later in this introductory section, the presence of a line source presents an interesting problem regarding the placement of the openings relative to the source position, in particular the floor-level openings that provide the primary supply of external fluid for plume entrainment.

In the seminal paper by Linden *et al.* (1990), they presented an analytical model – commonly referred to as the 'emptying-filling box' model – allowing the stratification and ventilation flow rates to be predicted in an enclosure with top and bottom openings. They focussed on the steady states that developed for a single, continuous point and line source of buoyancy positioned in the centre of the floor. In particular, they showed that, similar to a point source, the stratification produced by a line source of buoyancy is comprised of two homogeneous fluid layers of different density; a buoyant upper layer and a lower layer at ambient density below a horizontal interface. The interface is stable and is sharpened continuously by entrainment into the plume as interfacial mixing induced by the inflow of ambient fluid through the base is negligibly weak. They referred to the resulting flow as 'displacement flow', whereby ambient density fluid is drawn in through the base and displaces, rather than vigorously mix with, the buoyant fluid contained in the upper layer, which escapes out of the top opening.

Linden *et al.* (1990) showed that the steady level of the interface is given by the height at which the volume and buoyancy fluxes through the top opening are equal to that supplied to the upper layer by the source at the interface. In an enclosure of height H, they showed that the position of the interface h above the floor is determined by equating the volume flux, driven by a buoyant fluid layer of depth $H-h$, and reduced gravity g'_{u} with the volume flux and reduced gravity in the rising turbulent plume at the height h. For a line source of buoyancy, they showed that the position of the interface can be expressed in terms of a dimensionless height, $\zeta = h/H$, given by

$$\mathrm{C}_{\mathrm{LP}}^{3/2}\left(\frac{\zeta^3}{1-\zeta}\right)^{1/2} = \frac{A^*}{H^2}\left(\frac{L}{H}\right)^{-1}, \tag{5.1}$$

where A^* is the effective area of the top and bottom openings, L is the length of the line source, and $\mathrm{C}_{\mathrm{LP}} = (2\alpha_{\mathrm{LP}})^{2/3}$ is a constant dependent on the (top-hat) entrainment coefficient α_{LP} for the plume. In the single line plume case, Equation (5.1) shows that the position of the interface is governed primarily by entrainment into the rising plume, and can be increased by increasing the height H of the enclosure (relative to the source length L) and/or the dimensionless effective area A^*/H^2 of the openings.

Whilst Equation (5.1) might suggest that displacement flow is established for any given combination and placement of opening areas made at the top and bottom levels, this is not always the case. There are three fundamental assumptions underpinning the model of Linden *et al.* (1990). First, it is assumed that entrainment of surrounding fluid by the line plume is unobstructed by the walls of the enclosure such that the placement of the base openings (relative to the source position) is immaterial to the bulk ventilating flow; second, that the displacement flow occurs in the absence of mixing at the interface by the replacement fluid; and third, that unidirectional flow is maintained through all openings. This chapter addresses these three pertinent issues.

First, in contrast to the aforementioned model of Linden *et al.* (1990), we explicitly impose restrictions on the length of the line source and the placement of the base openings. This was done for the following reason: if the length of the line source extends along the entire length of the enclosure, the cross-sections of the plume will be cut off by the two end walls of the enclosure and, hence, in contrast to a point source plume, the entrainment of surrounding fluid occurs from the two (unobstructed) sides of the line plume only. Thus, the placement of the base openings at both sides of the line source is imperative for establishing and maintaining a steady interface.

The second and third issues we address are the possibility of mixing within the enclosure and exchange flow at the high-level opening. Previous research by Hunt & Coffey (2010) showed that displacement flow represents an idealised limiting case of no-mixing by the replacement fluid and unidirectional flow through the openings. They found that the dynamics of the emptying process (that is, the draining of buoyant fluid from an enclosure into a quiescent denser environment) are far more complicated with turbulent inflow of fluid (through either the top and/or base openings) leading to varying degrees of mixing and stratification breakdown.

Hunt & Coffey (2010) classified the flow patterns established in an 'emptying box' in terms of two Froude numbers. The first Froude number, $\mathrm{Fr_t}$, associated with the flow at the top, sets the direction of flow through the top opening. The second Froude number, $\mathrm{Fr_b}$, based on the dynamics of the replacement fluid at the density interface, determines the 'vigour' of interfacial mixing. For clarity, we henceforth replace the subscript 'b' with 'i' to denote the value of Fr at the interface, although $\mathrm{Fr_b}$ and $\mathrm{Fr_i}$ are essentially synonymous.

Figure 5.1 shows how the $\{\mathrm{Fr_i}, \mathrm{Fr_t}\}$ parameter space divides into four regions, each region characterised by a distinct flow behaviour identified by Hunt & Coffey (2010) and is indicated by the inset schematics. We note that the flow patterns shown in Figure 5.1 are in a 'heat-in-air' frame of reference rather than in a 'salt-in-water' reference frame observed experimentally, *i.e.* the buoyancy force acts upwards. For consistency, this reference frame, with the vertical origin coincident with the base of the box and the plane of the inflow, is maintained throughout. In order to achieve unidirectional flow with interfacial mixing, this requires $\mathrm{Fr_t} > \mathrm{Fr_{t,c}}$ and $\mathrm{Fr_i} > \mathrm{Fr_{i,c}}$, where $\mathrm{Fr_{t,c}} \approx 0.33$ and $\mathrm{Fr_{i,c}} \approx 0.67$ (Hunt & Coffey, 2010). This places formal restrictions on the dimensionless effective area A^*/H^2 of the openings and the apportioning of this total area between the top and bottom openings (Hunt & Coffey, 2010).

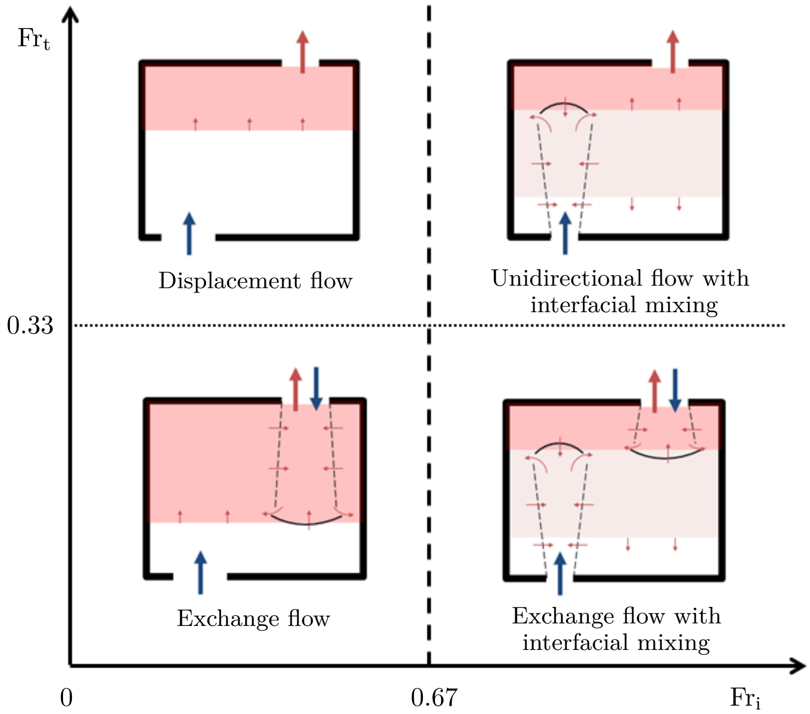


FIGURE 5.1: Plot of $\{\mathrm{Fr_i}, \mathrm{Fr_t}\}$-space indicating the four transient flow patterns identified by Hunt & Coffey (2010) in the absence of a buoyancy source. Inset schematics highlight the key features of each flow pattern. Interfacial mixing is indicated by a bowl-like upwelling at the interface. Above the horizontal (dotted) line showing $\mathrm{Fr_{t,c}} = 0.33$, purely unidirectional flow occurs through the top opening, and below this line, exchange flow is established. To the right of the vertical (dashed) line showing $\mathrm{Fr_{i,c}} = 0.67$, a middle layer of intermediate density develops due to interfacial mixing by the inflow of ambient fluid through the base.

By focussing on the portion of the $\{\mathrm{Fr_i}, \mathrm{Fr_t}\}$ parameter space where unidirectional flows occur ($\mathrm{Fr_t} > 0.33$) and interfacial mixing is vigorous ($\mathrm{Fr_i} > 0.67$), Coffey & Hunt (2010) examined, both theoretically and experimentally, the effect of interfacial mixing on the evolving stratification in a ventilated box. In their small-scale experiments involving the transient draining of dense (saline) fluid, under gravity, from a box connected to a less dense (fresh water) external environment, they observed on opening the top and base vents that localised turbulent mixing at the density interface, driven by a high Reynolds number fresh water jet (via an opening at the top), created an intermediate or mixed layer that deepened to fill the box, rather than simply draining from the box. The presence of interfacial mixing in their experiments is noteworthy, as it resulted in the redistribution of the total buoyancy contained in the box. In the context of a naturally ventilated enclosure, a redistribution of the buoyancy can influence the way in which the total heat in a room is apportioned between the upper and lower layers; this, in turn, could affect the comfort of occupants and impact the efficiency of heat removal (Coffey & Hunt, 2004*b*).

Much of the work which follows is based on the experimentally validated flow type classification model of Hunt & Coffey (2010) and is expanded herein to suit steady state flows. Rather than emptying from the box, the buoyant upper layer is maintained by a turbulent line plume in the box. Following Coffey & Hunt (2010), we restrict our attention only to the flow pattern established within the region of $\{\mathrm{Fr_i}, \mathrm{Fr_t}\}$-space where unidirectional flows through top and base openings occur ($\mathrm{Fr_t} > 0.33$), and interfacial mixing, induced by the inflow of ambient fluid through the base, is vigorous ($\mathrm{Fr_i} > 0.67$). The steady problem we consider may also prove interesting due to the presence of the turbulent plume. Unlike the transient draining problem of Hunt & Coffey (2010) and Coffey & Hunt (2010), the presence of a plume acts to stratify the interior, notably against the mixing action imposed by the inflowing fluid which tends to destabilise the interface. The two main questions we address in this work are (1) what is the relationship between interfacial mixing and the stratification imposed by the presence of a line plume, and (2) how do the competing effects of interfacial mixing and the plume stratifying the interior affect the density interface height, buoyancy distribution and volume flux through the box?

Part I is structured as follows. In §5.3 we develop a theoretical model to predict the volume flux and density stratification established in the steady state due to the presence of a localised line source of buoyancy at floor level. Our model includes terms to account for the presence of a line plume and interfacial mixing, the latter accomplished by invoking the formulation for entrainment fluxes across density interfaces by Baines (1975). Whilst a number of other proposed entrainment formulations describing turbulent entrainment across density interfaces are reviewed, we argue that the formulation developed by Baines (1975) is sufficient for the purposes of this work. We analyse our model predictions in §5.4, wherein qualitative arguments regarding the effect of interfacial mixing on the bulk ventilation are discussed and key features of the resulting flow are elucidated. Limitations on the range of applicability of our model are discussed in §5.5 and in §5.6 conclusions of our study are drawn.

5.3 Theoretical model for a line source at floor level

We consider the steady buoyancy-driven flow and density stratification subject to a continuous supply of buoyancy at floor level ($z = 0$) in a ventilated box. Internal heat inputs, representative of a localised source of heat, are modelled as a line source of buoyancy with length L and source buoyancy flux B_{LP}. Ventilation openings, made at the top and bottom faces, provide the primary connection between the interior environment and a quiescent, unbounded external environment with uniform density ρ_{ext}. The vertical distance between the top and bottom openings is denoted H. It is postulated that two layers of fluid of different density, separated by an interface, are formed in the steady state; the plume establishes and maintains the two-layer stratification and the incoming fluid through the base openings provides the source of turbulence at the interface. Figure 5.2 depicts the configuration we consider and the notation used.

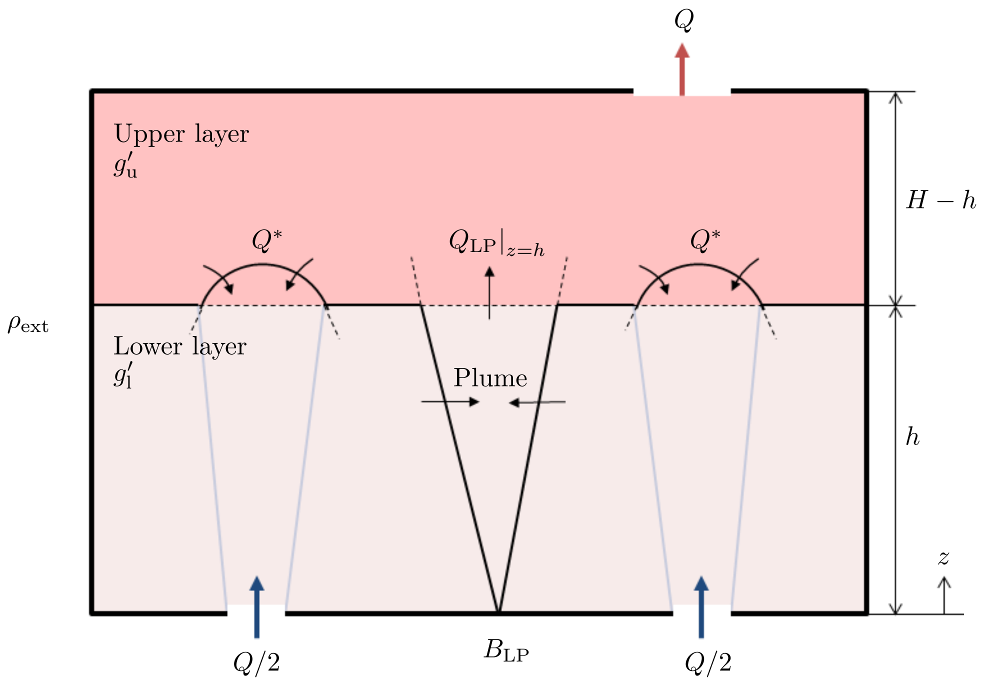


FIGURE 5.2: Schematic of a ventilated box with height H showing the nomenclature and basic two-layer stratification we consider. There is a localised line source of buoyancy positioned in the centre of the box at $z = 0$, which produces a positively buoyant plume with buoyancy flux B_{LP} at the source. Ventilation openings, made at the top and bottom faces of the box, connect the interior to a quiescent, unstratified external environment with density ρ_{ext}. Inflow of replacement fluid through the base drives turbulent interfacial mixing, which entrains a net volume flux $2Q^*$ from the upper layer into the lower layer. The transport of fluid from the lower layer into the upper layer is carried out by entrainment into the rising plume. The inward and outward fluxes of volume and buoyancy within the box are in balance so that a steady interface at $z = h$ is established and a net volume flux Q through the openings is maintained.

We restrict our attention to a specific opening arrangement for which a single opening of area a_{t} and two identical openings, each of area $a_{\mathrm{b}}/2$, are positioned at the top and bottom faces of the box, respectively. Specifically, each of the base openings is placed at the two unobstructed sides of the source so that ambient fluid is supplied to the interior, which naturally accommodates plume entrainment. Hunt & Coffey (2010) focussed on horizontal openings and we retain this orientation herein. Additionally, our model is developed for circular 'sharp-edged' openings, for which the depth l of the opening (the dimension in the direction of flow through it) is small relative to the diameter D of the opening, such that $l/D \ll 1$.

We consider the buoyancy input from the line source only and that buoyancy exchanges between the fabric of the box and the fluid in the box are negligibly small. The line source is modelled as an 'ideal' source, in that a finite flux of buoyancy is released but zero initial fluxes of volume and momentum at the source, giving rise to a fully turbulent, Boussinesq, two-dimensional pure plume. We assume that the height of the interface in the box is small relative to the length of the source (*i.e.* $h \ll L$) so that the two-dimensional nature of the plume is maintained throughout its rise. Attention is restricted to high Reynolds number and high Péclet number flows (typically $\mathrm{Re} = O(10^3)$ and $\mathrm{Pe} = O(10^6)$) so that the flow through the box is independent of viscous effects and advection dominates the effects of thermal diffusion. We anticipate that for these high Péclet number flows, turbulent interfacial mixing induced by the inflow, rather than thermal diffusion, is the dominant mechanism for the redistribution of buoyancy within the box. Numerical and experimental investigations of interface diffusion in steady state displacement ventilation by Kaye *et al.* (2010) confirmed that an assumption of zero diffusion is broadly applicable, although the effects thermal diffusion and radiation can cause the interface to smear over a finite thickness.

For an incompressible flow, volume conservation for the box requires

$$Q_{\mathrm{in}} = Q_{\mathrm{out}}, \tag{5.2}$$

where Q_{in} $(= Q/2 + Q/2)$ and Q_{out} $(= Q)$ are the inward and outward volume fluxes through the base and top openings, respectively.

A horizontal interface occurs at $z = h$, which separates two uniform fluid layers of densities ρ_{l} (lower) and $\rho_{\mathrm{u}} < \rho_{\mathrm{l}}$ (upper). Localised impingement at the density interface by the inflowing ambient fluid through the base drives entrainment of fluid from the upper layer into the lower layer. We assume that the buoyant fluid turbulently entrained across the interface induces instantaneous and 'complete' mixing of the fluid within the lower layer, thus producing a uniform distribution of buoyancy over the entire layer depth.[1] Consequently,

[1] In practice, interfacial mixing may result in the generation of a density gradient in the uppermost part of the lower layer, as confirmed experimentally by Kumagai (1984) and Cooper & Linden (1996). However, this will not affect the mean density in each layer nor the height of the interface. Consequently, we maintain the assumption that the lower layer is fully mixed for the purposes of modelling.

buoyancy and volume conservation arguments for the layers in the steady state demand that the upper layer is also of uniform buoyancy. The buoyancy of a fluid layer at any given height z (origin at floor level) is defined by the reduced gravity, $g'(z) = g(\rho_{\text{ext}} - \rho(z))/\rho_{\text{ext}}$, where g is the acceleration due to gravity and $\rho(z)$ is the density of the fluid layer at height z relative to the external fluid density. The reduced gravity at any given height z in the box (Figure 5.2) is denoted by

$$g'(z) = \begin{cases} g'_{\text{u}}, & \text{for } h \leqslant z \leqslant H \\ g'_{\text{l}}, & \text{for } 0 \leqslant z < h, \end{cases} \tag{5.3}$$

where $g'_{\text{l}} > 0$ (lower) and $g'_{\text{u}} > g'_{\text{l}}$ (upper). The plume mixes with the fluid in the upper layer and the reduced gravity g'_{u} of the layer is equal to that of the plume at the level of the interface, $G'_{\text{LP}}|_{z=h}$ (the subscript '$z = h$' reading 'at the interface').

Dense fluid from the exterior enters the box through openings at the base and rises upwards through the lower layer with reduced gravity g'_{l} (> 0). As a consequence, the impinging flow develops as turbulent fountain in the lower layer. Kaye & Hunt (2006) demonstrated that for a wide range of fountain source Froude numbers, the upward flow in a fountain is jet-like over the vast majority of its rise height (*i.e.* the momentum-driven jet flow dominates the opposing buoyancy force). Accordingly, we invoke the approximation that the inflow of replacement fluid through the base develops as a high Reynolds number, (quasi-)steady, incompressible, axisymmetric jet, and that its density at the interface is comparable with ρ_{ext} for Boussinesq flows. Based on this approximation, the classic jet scalings of Fischer *et al.* (1979) are expected to be appropriate.

As dense fluid penetrates the interface, strong local buoyancy forces arrest its upward motion, resulting in the formation of a dome-like upwelling, as shown schematically in Figure 5.2. Shrinivas & Hunt (2014*b*) postulate that this can take three distinct regimes depending on the conditions local to the interface.[2] For convenience, we recall the key features of the three flow regimes in Figure 5.3.

For weakly energetic impingements (Figure 5.3(a)), a shallow dome-like structure in the upper layer develops, in which the entrainment mechanism is attributed to the engulfment of fluid around the periphery of the impingement dome (by the energy-containing eddies).

[2] Shrinivas & Hunt (2014*b*) developed a theoretical model to describe the steady downward entrainment mechanism resulting from the localised impingement of a jet incident to a stable, horizontal density interface in an unconfined environment. They characterised the dynamics of interfacial entrainment as either weakly, moderately or highly energetic impingements depending on the magnitude of the interfacial Froude number, Fr_i. For weakly energetic impingements ($\text{Fr}_\text{i} < 1.4$), they showed that entrainment occurs primarily around the periphery of an axisymmetric, semi-ellipsoidal impingement dome above the interface, and the entrainment flux scales with Fr_i^2. In contrast, for moderately energetic ($1.4 \leqslant \text{Fr}_\text{i} \leqslant 3.8$) or highly energetic ($\text{Fr}_\text{i} > 3.8$) impingements, the jet penetrates the upper layer as a dense fountain, entraining fluid both laterally into its downflow and through its top. For both moderately and highly energetic impingements, they showed that the entrainment flux scales linearly on Fr_i.

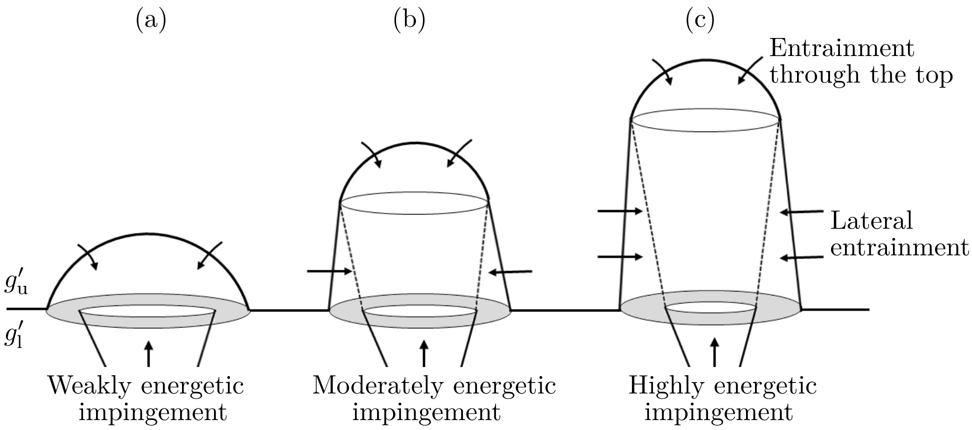


FIGURE 5.3: Schematic showing the morphology of three flow regimes, which Shrinivas & Hunt (2014*b*) postulate characterise turbulent entrainment across a density interface driven by the impingement of an axisymmetric jet from below: (a) weakly energetic impingement, in which entrainment into an interfacial dome atop the incident jet, is dominant; (b) moderately energetic impingement, in which a penetrating fountain entrains both laterally into its downflow and through its top; and (c) highly energetic impingement, in which the fountain penetrates a significant distance and lateral entrainment is dominant. Buoyant fluid entrained from the upper layer is transported downwards across the density interface through an annular region (shaded area).

In fact, this dome-like morphology of the impinging flow has been confirmed by several experimental studies, notably the shadowgraph images obtained from Hunt & Coffey's (2010) experiments; see Figure 6(c) in their paper, for example. For moderately or highly energetic impingements (Figures 5.3(b) and 5.3(c)), dense fluid carried upwards in the jet penetrates a significant vertical distance (relative to the jet half-width at the interface) before reversing its direction of motion. As the flow reverses, the upflowing jet-like core becomes shrouded by the downflowing lighter fluid, and entrainment occurs both laterally into the downflow and through the fountain top. Herein, we invoke the simplifying assumption that the downward transport of buoyant fluid across the interface does not shroud the upflow of the jet, *i.e.* we consider the morphology in Figure 5.3(a).

5.3.1 Conservation equations for the layers

The volume flux $Q_{\rm LP}|_{z=h}$ supplied to the upper layer by the plume at the interface is exactly matched by the volume flux leaving the layer, *i.e.* via the sum of that entrained $2Q^*$ by the impinging jets and driven through the top opening $Q_{\rm out}$ $(= Q)$. Hence, volume conservation for the upper layer requires

$$Q_{\rm LP}|_{z=h} = 2Q^* + Q. \tag{5.4}$$

For convenience, we henceforth drop the subscript '$z = h$' on $Q_{\rm LP}$ and $G'_{\rm LP}$. The flux of buoyancy supplied to the upper layer is comprised of (i) the source buoyancy flux of the plume over its entire length $B_{\mathrm{LP}}L$ and (ii) the flux of buoyancy $Q_{\mathrm{LP}}g'_{\mathrm{l}}$ entrained by the plume from the lower layer. The impinging jets entrain a net flux of buoyancy $2Q^*g'_{\mathrm{u}}$ from the upper layer and the outflow from the box expels buoyant fluid at a rate Qg'_{u} through the top opening. Thus, for the upper layer, buoyancy conservation requires

$$B_{\mathrm{LP}}L + Q_{\mathrm{LP}}g'_{\mathrm{l}} = 2Q^*g'_{\mathrm{u}} + Qg'_{\mathrm{u}}. \tag{5.5}$$

For the lower layer, there is a net volume flux $2Q^*$ received from the upper layer above and additionally from the jet-like inflow through the base Q_{in} ($= Q/2 + Q/2$). There is a net volume flux Q_{LP} out of the lower layer via plume entrainment. The buoyancy flux turbulently entrained from the upper layer $2Q^*g'_{\mathrm{u}}$ by the jets is supplied to the lower layer. Due to entrainment into the plume, a flux of buoyancy $Q_{\mathrm{LP}}g'_{\mathrm{l}}$ is removed from the lower layer. Thus, conservation of volume and buoyancy for the lower layer require, respectively,

$$2(Q/2) + 2Q^* = Q_{\mathrm{LP}}, \tag{5.6}$$

$$2Q^*g'_{\mathrm{u}} = Q_{\mathrm{LP}}g'_{\mathrm{l}}. \tag{5.7}$$

Substituting for $Q_{\mathrm{LP}}g'_{\mathrm{l}}$ from (5.7) into (5.5) and rearranging to make g'_{u} the subject,

$$g'_{\mathrm{u}} = \frac{B_{\mathrm{LP}}L}{Q}. \tag{5.8}$$

By substituting for Q_{LP} from (5.6) into (5.7), we obtain the ratio of reduced gravities for the layers,

$$\frac{g'_{\mathrm{l}}}{g'_{\mathrm{u}}} = \frac{2Q^*}{Q + 2Q^*}. \tag{5.9}$$

The expression in (5.9) indicates that as Q^* increases, $g'_{\mathrm{l}} \to g'_{\mathrm{u}}$, *i.e.* the reduced gravity of the lower layer approaches to that of the upper layer. We posit that, in the limit of large momentum flux, $2Q^* \gg Q$, the two-layer stratification will break down and an approximately uniform temperature internal environment is established ($g'_{\mathrm{l}}/g'_{\mathrm{u}} \approx 1$). While it is not entirely clear at this stage whether this limit is physically attainable, we return to this later in §5.4.1.

5.3.2 Volume flux through the box

The integral of the reduced gravity of each fluid layer over its depth is given by

$$\mathbb{B}_{\mathrm{u}} = \int_h^H g'_{\mathrm{u}}\,\mathrm{d}z = g'_{\mathrm{u}}(H - h), \tag{5.10}$$

$$\mathbb{B}_{\mathrm{l}} = \int_0^h g'_{\mathrm{l}}\,\mathrm{d}z = g'_{\mathrm{l}}h, \tag{5.11}$$

where $\mathbb{B}_\mathrm{u}$ and $\mathbb{B}_\mathrm{l}$ denote the net buoyancy per unit cross-sectional area of the upper and lower layers, respectively. Therefore, the net buoyancy accumulated within the box (per unit cross-sectional area) is

$$\mathbb{B}_\mathrm{N} = \mathbb{B}_\mathrm{u} + \mathbb{B}_\mathrm{l}. \tag{5.12}$$

For convenience, we herein refer to $\mathbb{B}_\mathrm{u}$, $\mathbb{B}_\mathrm{l}$ and $\mathbb{B}_\mathrm{N}$ as 'net buoyancies'. Since $Q = A^*\mathbb{B}_\mathrm{N}^{1/2}$, the total volume flux through the box thus is

$$Q = A^*[g'_\mathrm{u}(H-h) + g'_\mathrm{l}h]^{1/2}. \tag{5.13}$$

Substituting for g'_u from (5.8) into (5.13) we obtain

$$Q = \left[A^{*2}\left(H - h + \frac{g'_\mathrm{l}}{g'_\mathrm{u}}h\right)B_\mathrm{LP}L\right]^{1/3}. \tag{5.14}$$

Hunt & Coffey (2010) and Coffey & Hunt (2010) showed that interfacial mixing can affect the net buoyancy and depth of the individual fluid layers. Therefore, we anticipate that each of the layers will contribute differently to the driving of the bulk flow, where one layer may impose a stronger forcing strength relative to the other. Shrinivas & Hunt (2014*a*) showed that the relative contributions of the two fluid layers in driving the overall flow through the box can be classified in terms of a 'stratification parameter', $\mathcal{S}$, given by

$$\mathcal{S} = \sqrt{\frac{\mathbb{B}_\mathrm{l}}{\mathbb{B}_\mathrm{u}}}. \tag{5.15}$$

For $\mathcal{S} \ll 1$ buoyancy forces produced by the upper layer dominate the bulk fluid motion, whereas for $\mathcal{S} \gg 1$ the lower layer produces the dominant forcing.

5.3.3 Volume flux and reduced gravity of a line plume

We invoke the classical plume model of Morton, Taylor & Turner (1956), hereinafter referred to as MTT (1956). The MTT (1956) model describes the time-averaged vertical variation in the fluxes of volume, momentum and buoyancy of a (fully developed and self-similar) turbulent, Boussinesq, axisymmetric pure plume rising in an unbounded, quiescent and unstratified environment. From their paper, solutions for the volume flux and reduced gravity of a line plume can be recovered, as demonstrated analytically by van den Bremer & Hunt (2014), and also by Kaye & Hunt (2004) using dimensional arguments. In the lower layer, in which the density is uniform throughout, the buoyancy flux within the plume is constant (Morton *et al.*, 1956). Taking top-hat profiles for the time-averaged horizontal variation of the vertical velocity and buoyancy across the plume,[3] the buoyancy flux is given by

$$B_{\mathrm{LP}}L = Q_{\mathrm{LP}}G'_{\mathrm{LP}} = \text{constant}, \tag{5.16}$$

and the volume flux and reduced gravity at $z = h$ are, respectively,

$$Q_{\mathrm{LP}} = \mathrm{C}_{\mathrm{LP}}B_{\mathrm{LP}}^{1/3}hL, \tag{5.17}$$

$$G'_{\mathrm{LP}} = g'_1 + \mathrm{C}_{\mathrm{LP}}^{-1}B_{\mathrm{LP}}^{2/3}h^{-1}, \tag{5.18}$$

where $\mathrm{C}_{\mathrm{LP}} = (2\alpha_{\mathrm{LP}})^{2/3}$ is a constant, which we recall from §5.2, is related to the top-hat entrainment coefficient α_{LP} for the plume. A range of values of α_{LP} is quoted in the literature. A comprehensive review of these is given in van den Bremer & Hunt (2014). For completeness, the range of α_{LP} values cited in their paper is amalgamated here and summarised in Table 5.2.

	Entrainment coefficient, α_{LP}	
Reference	Gaussian	Top-hat
Ellison & Turner (1959)	0.06	0.09
Lee & Emmons (1961)*	0.16	0.23
Kotsovinos (1975)*	0.10	0.14
Chen & Rodi (1980)*	0.11-0.12	0.16-0.17
Yuana & Cox (1996)*	0.13	0.18
Paillat & Kaminski (2014)	0.07-0.08	0.10-0.11

Table 5.2: Overview of the experimentally determined values of the Gaussian entrainment coefficient for a pure line plume reported in the literature. The asterisk symbol '$*$' next to the author(s) denotes the value of α_{LP} cited in van den Bremer & Hunt (2014); see Table 1 in their paper. Values of the top-hat entrainment coefficient (right column) are calculated by multiplying the Gaussian values (middle column) by $\sqrt{2}$.

For Gaussian profiles, $\alpha_{\mathrm{LP}} = 0.06$ (Ellison & Turner, 1959) and $\alpha_{\mathrm{LP}} = 0.16$ (Lee & Emmons, 1961) generally lie towards the lower and upper limits of the reported range in Table 5.2, whereas Kotsovinos (1975) suggest $\alpha_{\mathrm{LP}} = 0.10$ is a suitable value. Since $\alpha_{\mathrm{LP}} = 0.10$ lies approximately midpoint of the limits reported, we will use this value in the present model. For top-hat profiles, we therefore have $\alpha_{\mathrm{LP}} = \sqrt{2}(0.10) \approx 0.14$, giving $\mathrm{C}_{\mathrm{LP}} \approx 0.43$.

[3] While the time-averaged profiles of velocity and buoyancy at any height within a plume are well fitted by Gaussian curves (Rouse *et al.*, 1952; Batchelor, 1954), we adopt the simpler top-hat profiles for velocity and buoyancy, in which these quantities are taken to be constant across the plume at each height and zero outside. Compared to Gaussian profiles, top-hat profiles considerably simplify the treatment of the plume conservation equations of MTT (1956) and thus provide greater insight into the bulk behaviour of the flow with height. Turner (1969) and van den Bremer & Hunt (2014) commented that the particular profile chosen (Gaussian or top-hat) changes only the numerical value of some of the coefficients of the equations without affecting the essential physics, *i.e.* the form of the plume conservation equations and the nature of the predicted behaviour are equivalent.

5.3.4 Dimensionless governing equations

At this stage, it is convenient to non-dimensionalise the governing equations. The interface height is scaled on H, and the reduced gravities of the layers on the reduced gravity within the plume at $z = H$ in an environment of uniform density ρ:

$$\zeta = \frac{h}{H}, \quad \widehat{g'_{\mathrm{l}}} = \frac{g'_{\mathrm{l}}}{\mathrm{C}_{\mathrm{LP}}^{-1} B_{\mathrm{LP}}^{2/3} H^{-1}}, \quad \widehat{g'_{\mathrm{u}}} = \frac{g'_{\mathrm{u}}}{\mathrm{C}_{\mathrm{LP}}^{-1} B_{\mathrm{LP}}^{2/3} H^{-1}}. \tag{5.19}$$

We scale the volume fluxes of interest on the volume flux within the plume at $z = H$:

$$\widehat{Q} = \frac{Q}{\mathrm{C}_{\mathrm{LP}} B_{\mathrm{LP}}^{1/3} H L}, \quad \widehat{Q^*} = \frac{Q^*}{\mathrm{C}_{\mathrm{LP}} B_{\mathrm{LP}}^{1/3} H L}. \tag{5.20}$$

Substituting for Q_{LP} (5.17) and Q (5.8) into (5.4), non-dimensionalising and rearranging to make $\widehat{g'_{\mathrm{u}}}$ the subject yields

$$\widehat{g'_{\mathrm{u}}} = (\zeta - 2\widehat{Q^*})^{-1}. \tag{5.21}$$

Similarly, substituting for $2Q^* + Q$ (5.4) and Q_{LP} (5.17) into (5.9) and non-dimensionalising gives

$$\frac{\widehat{g'_{\mathrm{l}}}}{\widehat{g'_{\mathrm{u}}}} = \frac{2\widehat{Q^*}}{\zeta}. \tag{5.22}$$

The dimensionless volume flux $\widehat{Q}$ through the box can be obtained by substituting for $g'_{\mathrm{l}}/g'_{\mathrm{u}}$ from (5.9) into (5.14), and non-dimensionalising to give

$$\widehat{Q} = \mathrm{C}_{\mathrm{LP}}^{-1} \left(\frac{L}{H}\right)^{1/3} \left(\frac{A^*}{H^2}\right)^{2/3} \left(1 - \zeta + 2\widehat{Q^*}\right)^{1/3}. \tag{5.23}$$

The steady level of the interface is given by the height at which the outward flux of volume (and buoyancy) from the upper layer equals to that supplied to the layer by the plume. Therefore, substituting for Q (5.14) and Q_{LP} (5.17) into (5.4) and rearranging to make A^*/H^2 the subject,

$$\frac{A^*}{H^2} = \mathrm{C}_{\mathrm{LP}}^{3/2} \left(\frac{L}{H}\right) \frac{(\zeta - 2\widehat{Q^*})^{3/2}}{(1 - \zeta + 2\widehat{Q^*})^{1/2}}. \tag{5.24}$$

For $\widehat{Q^*} > 0$, *i.e.* values of Q^* and B_{LP} are non-zero, Equation (5.24) shows that the position of the interface h is dependent on the total effective area A^* of the openings, the height H between the base of the box and the ceiling, the buoyancy flux B_{LP} and length L of the line source, the entrainment flux Q^* across the interface by the impinging jets, and the entrainment constant C_{LP} for the plume. This result is in contrast to the displacement flow model of Linden *et al.* (1990) where, in the absence of interfacial mixing (*i.e.* $Q^* = 0$ but $B_{\mathrm{LP}} > 0$), the interface position is independent of B_{LP} and depends only on C_{LP}, A^*, H and L (*cf.* Equation (5.1)).

The above expressions for the layer reduced gravities, interface height, and volume flux through the box, (5.21)–(5.24), highlight that the processes of entrainment are central to the performance of the ventilation system: (1) the entrainment of surrounding fluid into the rising turbulent plume above the heat source, and (2) the interfacial entrainment resulting from jet-interface interaction. In order to close the problem, an expression for the volume flux Q^* turbulently entrained across the interface is required.

5.3.5 Volume flux entrained across the density interface

We remind the reader that, while the line plume in the box is two-dimensional in nature, the time-averaged outline of the jet-like inflow through the base openings is axisymmetric, *i.e.* the jets have radial symmetry. For a comprehensive review of previous theoretical and experimental studies on interfacial entrainment induced by turbulent axisymmetric flows, including jets, plumes and fountains, the reader is referred to Shrinivas & Hunt (2014*b*). For completeness, we recount herein some of the studies cited in their paper that are relevant to this work.

* * *

We consider the formulations for entrainment fluxes across density interfaces developed by Baines (1975), Kumagai (1984) and Lin & Linden (2005). The study by Shrinivas & Hunt (2015) on the effect of box confinement on the rate of interfacial entrainment is also briefly described.

Baines (1975) performed a series of small-scale experiments investigating interfacial entrainment due to an impinging turbulent jet (or plume) incident with an interface separating two homogeneous fluid layers of different density. By tracking the position of the interface, Baines (1975) inferred that the volume flux turbulently entrained across it scales as

$$\frac{Q^*}{b_\mathrm{i}^2 w_\mathrm{i}} \propto \mathrm{Fr}_\mathrm{i}^3, \quad \mathrm{Fr}_\mathrm{i} = \frac{w_\mathrm{i}}{\sqrt{b_\mathrm{i}\Delta g'}}, \tag{5.25}$$

where Fr_i is the interfacial Froude number. The magnitude of the interfacial Froude number is dependent on three quantities local to the interface, namely the half-width and centreline vertical velocity of the jet, b_i and w_i, respectively, and the buoyancy contrast across the interface $\Delta g'$ $(= g'_\mathrm{u} - g'_\mathrm{l})$. Kumagai (1984) considered the same experimental configuration as Baines (1975) and based on the measurements of entrainment rates, proposed the empirical relationship

$$\frac{Q^*}{b_\mathrm{i}^2 w_\mathrm{i}} = \frac{\mathrm{Fr}_\mathrm{i}^3}{1 + 3.1\mathrm{Fr}_\mathrm{i}^2 + 1.8\mathrm{Fr}_\mathrm{i}^3}\,, \tag{5.26}$$

which reduces to $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \propto \mathrm{Fr}_\mathrm{i}^3$ for $\mathrm{Fr}_\mathrm{i} \ll 1$ and $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \to 0.56$ for $\mathrm{Fr}_\mathrm{i} \gg 1$. Measurements by Coffey & Hunt (2010) of interfacial entrainment induced by the impingement of an inflowing fresh water jet on a dense saline layer draining from a box are also in close agreement with Baines's (1975) and Kumagai's (1984) experimental results, suggesting $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \propto \mathrm{Fr}_\mathrm{i}^3$ for $\mathrm{Fr}_\mathrm{i} < 1$ and that the entrainment flux tends to a constant value for $\mathrm{Fr}_\mathrm{i} > 1$.

Interestingly, the steady experiments of interfacial entrainment due to impinging jets/ fountains by Lin & Linden (2005) showed that the entrainment flux is approximately constant at $Q^*/b_\mathrm{i}^2 w_\mathrm{i} = 0.65$ over the entire range of Fr_i considered in their experiments ($0.9 < \mathrm{Fr}_\mathrm{i} < 2.2$). The result that $Q^* \propto b_\mathrm{i}^2 w_\mathrm{i}$ suggests that the stability of the interface, *i.e.* buoyancy contrast $\Delta g'$, has little to no bearing on the entrainment rate across it, even at relatively low Froude numbers (*e.g.* $\mathrm{Fr}_\mathrm{i} \approx 0.9$). This result is somewhat counterintuitive as Fr_i is dependent on $\Delta g'$, which would imply that the entrainment rate Q^* is also $\Delta g'$ dependent. In this case, it would not be unreasonable to expect that the entrainment rate might decrease when $\Delta g'$ is large, as the ability of the impinging jet(s) to induce mixing is counteracted by the increased stability of the interface resulting from the increased buoyancy contrast.

The confinement of the internal environment imposed by the physical boundaries of the box is an intrinsic feature of the aforementioned experiments. Shrinivas & Hunt (2015) hypothesised that, within the confines of a box, secondary flows induced by the deflections of the interface caused by the impinging flow could influence, or even modify, interfacial entrainment. They suggested that the effect of box confinement may offer a possible explanation for the disparities between the reported entrainment laws in the literature.

In order to elucidate the dominant effects of confinement, *i.e.* the role of the box, Shrinivas & Hunt (2015) developed a theoretical model to analyse turbulent interfacial entrainment due to the impingement of a fountain with a horizontal interface and the secondary flows that are induced in the confined two-layer system. They revealed that the entrainment flux across the interface is governed not only by the interfacial Froude number, but also by a "confinement parameter", which characterises the length scale of interfacial turbulence (*i.e.* the inner radius of the fountain core at the interface) relative to the depth of the upper layer in the box. They established that for 'small' box confinement, *i.e.* a deep upper layer, the secondary flow has little influence on the entrainment rate, which follows a quadratic power law $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \propto \mathrm{Fr}_\mathrm{i}^2$. This result is also consistent with the unconfined case for weakly energetic impingements reported by Shrinivas & Hunt (2014*b*), where interfacial entrainment occurs in the absence of a secondary flow. Conversely, for 'large' box confinement, *i.e.* a relatively shallow upper layer, Shrinivas & Hunt (2015) showed that the entrainment rate across the interface is significantly influenced by a strong secondary flow and is governed by a cubic power law $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \propto \mathrm{Fr}_\mathrm{i}^3$.

Given that the $Q^*/b_\mathrm{i}^2 w_\mathrm{i} \propto \mathrm{Fr}_\mathrm{i}^3$ relationship of Baines (1975) is consistent with the experimental findings of Coffey & Hunt (2010) for $\mathrm{Fr}_\mathrm{i} < 1$, and also with the theoretical results of Shrinivas & Hunt (2015) for 'strongly' confined interfacial entrainment when $\mathrm{Fr}_\mathrm{i} < 1.4$, for the purposes of modelling we herein use the formulation describing turbulent interfacial entrainment given by Baines (1975). We assume that secondary flow effects are captured implicitly by the entrainment model of Baines (1975), thereby removing the need to model the generally complex effect of a secondary flow on the ventilation system.

* * *

Baines (1975) assumed Gaussian profiles for the velocity of the impinging flow. Following Coffey & Hunt (2010), the constant of proportionality in (5.25) can be inferred by rescaling the experimental data of Baines (1975) using $\mathrm{Fr}_\mathrm{tophat} = 2^{-5/4}\mathrm{Fr}_\mathrm{Gaussian}$ (as $w_\mathrm{tophat} = 2^{-1}w_\mathrm{Gaussian}$ and $b_\mathrm{tophat} = 2^{1/2}b_\mathrm{Gaussian}$). Thus, for top-hat profiles, the scaled entrainment flux is given by

$$\frac{Q^*}{b_\mathrm{i}^2 w_\mathrm{i}} = 0.67\mathrm{Fr}_\mathrm{i}^3, \qquad \mathrm{Fr}_\mathrm{i} = \pi^{-1/4}\frac{w_\mathrm{i}}{\sqrt{b_\mathrm{i}\Delta g'}}. \tag{5.27}$$

Modelling the inflow through the base openings as a fully developed self-similar axisymmetric turbulent jet, the classic scalings (Fischer *et al.*, 1979) give the centreline velocity and half-width of the jet as

$$w(z) = \gamma M_\mathrm{b}^{1/2}(z+z_\mathrm{v})^{-1} \quad \text{and} \quad b(z) = \lambda(z+z_\mathrm{v}), \tag{5.28}$$

respectively, where the top-hat empirical constants $\gamma = 3.5$ and $\lambda = 0.15$, and M_b is the source momentum flux of the jet.[4] Note that in (5.28) we have included an origin correction for the jet, z_v, as the fluxes of volume and momentum are non-zero at the source. Through an appropriate calculation of a virtual origin offset, the scalings in (5.28) can be used to approximate the velocity and half-width of the jet. Following Hunt & Coffey (2010) and Coffey & Hunt (2010), we use a geometric origin correction based on tracing the jet perimeter (modelled as a circular cone) back to a point, as illustrated schematically in Figure 5.4 (*cf.* Hunt & Kaye (2001)).

For a circular opening, the jet half-width is given by

$$b|_{z=0} = \pi^{-1/2}\left(\frac{a_\mathrm{b}}{2}\right)^{1/2}, \tag{5.29}$$

[4] By source we refer to the conditions at the base of the box and the plane of the inflow through the base openings, *i.e.* at $z = 0$.

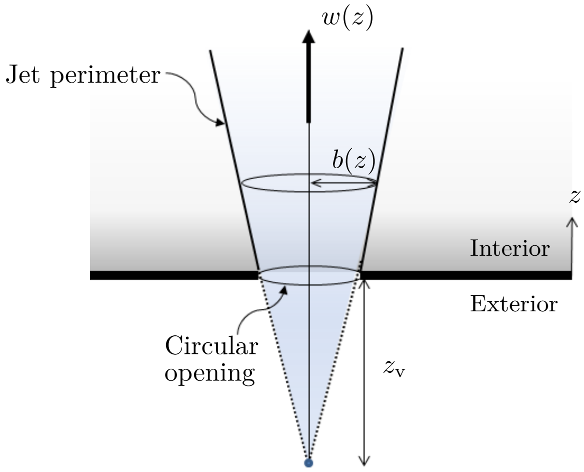


FIGURE 5.4: Schematic showing the time-averaged outline of an axisymmetric jet through a circular opening of cross-sectional area $a_b/2$. The actual source, of diameter $2\pi^{-1/2}(a_b/2)^{1/2}$, is at $z = 0$ (*i.e.* at the plane of the opening), and the position of the virtual source is at $z = -z_v$ (below the level of the opening).

where the subscript '$z = 0$' denotes 'at the source'. Substituting for $b|_{z=0}$ from (5.29) into (5.28), evaluated at $z = 0$, and rearranging to make z_v the subject, the distance between the virtual origin of the jet and the plane of the opening is given by

$$z_v = \pi^{-1/2}\lambda^{-1}\left(\frac{a_b}{2}\right)^{1/2}. \tag{5.30}$$

Assuming a uniform velocity profile across the opening, a reasonable assumption for high Reynolds number flows through (sharp-edged) openings,

$$M_b = \frac{(Q/2)^2}{a_b/2}. \tag{5.31}$$

Substituting the jet scalings from (5.28), evaluated at $z = h$, into the expression for the interfacial Froude number in (5.27) gives

$$\mathrm{Fr_i} = \pi^{-1/4}\frac{\gamma}{\lambda^{1/2}}\frac{M_b^{1/2}(h+z_v)^{-1}}{(h+z_v)^{1/2}(g'_u - g'_l)^{1/2}}, \tag{5.32}$$

and substituting for M_b (5.31) and Q (5.13) into (5.32) yields

$$\mathrm{Fr_i} = 2^{-1/2}\pi^{-1/4}\frac{\gamma}{\lambda^{1/2}}\left(\frac{A^*}{H^2}\right)\left(\frac{a_b}{H^2}\right)^{-1/2}\frac{\left(1-\zeta+\frac{g'_l}{g'_u}\zeta\right)^{1/2}}{\left(1-\frac{g'_l}{g'_u}\right)^{1/2}\left(\zeta+\frac{z_v}{H}\right)^{3/2}}. \tag{5.33}$$

The expression for $\mathrm{Fr_i}$ in (5.33) can be rewritten in terms of the entrainment flux $\widehat{Q^*}$ across the density interface, where on substituting for $\widehat{g'_l}/\widehat{g'_u}$ from (5.22) into (5.33) we obtain

$$\mathrm{Fr_i} = 2^{-1/2}\pi^{-1/4}\frac{\gamma}{\lambda^{1/2}}\left(\frac{A^*}{H^2}\right)\left(\frac{a_b}{H^2}\right)^{-1/2}\frac{\zeta^{1/2}\left(1-\zeta+2\widehat{Q^*}\right)^{1/2}}{\left(\zeta-2\widehat{Q^*}\right)^{1/2}\left(\zeta+\frac{z_v}{H}\right)^{3/2}}. \tag{5.34}$$

A convenient way to examine the relative influence of the top and base openings on interfacial mixing is to express the interfacial Froude number in terms of the ratio of effective vent areas, $R^* = c_t a_t / c_b a_b$, where c_t and c_b denote the loss coefficients associated with the flow through the top and bottom openings, respectively. Based on a simple manipulation of A^*/H^2 given in (4.6), the dimensionless effective area of the openings can be expressed in terms of a_b/H^2 and R^* as follows:

$$\frac{A^*}{H^2} = 2^{1/2} c_b \left(\frac{a_b}{H^2}\right)\left(1 + \frac{1}{{R^*}^2}\right)^{-1/2}. \tag{5.35}$$

For high Reynolds number flows through sharp-edged openings (with $l/D \ll 1$), the loss coefficients are normally assumed constant (≈ 0.6, see Ward-Smith (1980)), although Hunt & Holford (2000) and Holford & Hunt (2001) showed that the coefficients exhibit a density dependence (see §3.3.3). Provided the difference in fluid density across each opening is sufficiently small, the loss coefficients can be assumed constant and approximately equal to 0.6 (Holford & Hunt, 2001). Thus, substituting for a_b/H^2 from (5.35) into (5.34), and assuming $c_t = c_b$, the interfacial Froude number is given by

$$\mathrm{Fr_i} = 2^{-1/4}\pi^{-1/4} c_b^{1/2} \frac{\gamma}{\lambda^{1/2}} \left(\frac{A^*}{H^2}\right)^{1/2} \left(1 + R^{-2}\right)^{-1/4} \frac{\zeta^{1/2}\left(1 - \zeta + 2\widehat{Q^*}\right)^{1/2}}{\left(\zeta - 2\widehat{Q^*}\right)^{1/2}\left(\zeta + \frac{z_v}{H}\right)^{3/2}}, \tag{5.36}$$

where $R = a_t/a_b$ is the ratio of the top and bottom opening (free) areas. Using the expression for $\mathrm{Fr_i}$ from (5.33) and the $Q^*/b_i^2 w_i = 0.67\mathrm{Fr_i^3}$ relationship given in (5.27), we can proceed to derive an expression for the entrainment flux, Q^*. We begin by rearranging (5.27) to make Q^* the subject such that

$$Q^* = 0.67\mathrm{Fr_i^3} b_i^2 w_i, \tag{5.37}$$

where $b_i^2 w_i$ can be written in the following form:

$$b_i^2 w_i = 2^{-1/2}\lambda^2\gamma \left(\frac{A^*}{H^2}\right)\left(\frac{a_b}{H^2}\right)^{-1/2} H^{5/2} {g'_u}^{1/2} \left(1 - \zeta + \frac{g'_l}{g'_u}\zeta\right)^{1/2} \left(\zeta + \frac{z_v}{H}\right), \tag{5.38}$$

which is found by substituting the expressions for Q (5.13) and M_b(5.31) into the jet scalings given in (5.28). Therefore, substituting for $\mathrm{Fr_i}$ and $b_i^2 w_i$ from (5.33) and (5.38) into (5.37) and non-dimensionalising gives

$$\widehat{Q^*} = 2^{-2}\left(\frac{0.67\lambda^{1/2}\gamma^4}{\pi^{3/4}}\right) \mathrm{C_{LP}^{-3/2}} \left(\frac{A^*}{H^2}\right)^4 \left(\frac{a_b}{H^2}\right)^{-2} \widehat{g'_u}^{1/2} \frac{\left(1 - \zeta + \frac{\widehat{g'_l}}{\widehat{g'_u}}\zeta\right)^2}{\left(1 - \frac{\widehat{g'_l}}{\widehat{g'_u}}\right)^{3/2}\left(\zeta + \frac{z_v}{H}\right)^{7/2}}. \tag{5.39}$$

Finally, substituting for $\widehat{g'_u}$ (5.21), $\widehat{g'_l}/\widehat{g'_u}$ (5.22) and a_b/H^2 (5.35) into (5.39) we obtain an implicit expression in $\widehat{Q^*}$, where

$$\widehat{Q^*} = 2^{-1} c_b^2 \left(\frac{0.67\lambda^{1/2}\gamma^4}{\pi^{3/4}}\right) \mathrm{C_{LP}^{-3/2}} \left(\frac{A^*}{H^2}\right)^2 \left(1 + R^{-2}\right)^{-1} \frac{\zeta^{3/2}(1 - \zeta + 2\widehat{Q^*})^2}{\left(\zeta - 2\widehat{Q^*}\right)^2 \left(\zeta + \frac{z_v}{H}\right)^{7/2}}. \tag{5.40}$$

5.3.6 Froude number at the top opening

Hunt & Coffey (2010) compared the bulk velocity u_{out} of the outflow of buoyant fluid at the top opening to the vertical velocity w_{t} of a descending spherical thermal (denser ambient fluid) and argued that for $|u_{\mathrm{out}}| < |w_{\mathrm{t}}|$, bidirectional exchange flow would commence, whereas for $|u_{\mathrm{out}}| > |w_{\mathrm{t}}|$, the thermal is advected out of the box and unidirectional flow would occur. They related the ratio of inflow/outflow velocities across the top opening to the Froude number $\mathrm{Fr_t}$, and showed that it can be expressed in terms of the outward fluxes of volume Q_{t}, buoyancy B_{t} and momentum M_{t} (the subscript 't' on the variable reading 'at the top opening'):

$$\mathrm{Fr_t} = \frac{M_{\mathrm{t}}^{5/4}}{Q_{\mathrm{t}} B_{\mathrm{t}}^{1/2}}. \tag{5.41}$$

Substituting $Q_{\mathrm{t}} = Q$, $B_{\mathrm{t}} = Qg'_{\mathrm{u}}$, and $M_{\mathrm{t}} = Q^2/a_{\mathrm{t}}$ (assuming a uniform velocity profile across the opening) into (5.41), the Froude number at the top opening is given by (*cf.* Equation (3.14))

$$\mathrm{Fr_t} = \left(\frac{5}{8\pi^{1/2}\alpha_{\mathrm{P}}}\right)^{-1/2} \frac{Q}{{a_{\mathrm{t}}}^{5/4}{g'_{\mathrm{u}}}^{1/2}}, \tag{5.42}$$

where α_{P} is the top-hat entrainment coefficient for the outflowing plume (which is, in a time-averaged sense, axisymmetric in nature). A range of values of α_{P} is quoted in the literature, see p. 101, footnote 2). Following Chapter 4, we use $\alpha_{\mathrm{P}} \approx 0.117$ (Turner, 1986).

Substituting for Q (5.13) and $\widehat{g'_{\mathrm{l}}}/\widehat{g'_{\mathrm{u}}}$ (5.22) into (5.42) we obtain

$$\mathrm{Fr_t} = \left(\frac{5}{8\pi^{1/2}\alpha_{\mathrm{P}}}\right)^{-1/2} \left(\frac{A^*}{H^2}\right) \left(\frac{a_{\mathrm{t}}}{H^2}\right)^{-5/4} (1 - \zeta + 2\widehat{Q^*})^{1/2}. \tag{5.43}$$

Similarly, we can express $\mathrm{Fr_t}$ in terms the ratio of effective vent areas, R^*. Based on a straightforward manipulation of A^*/H^2 in (4.6), the dimensionless effective area of the openings can be written in terms of a_{t}/H^2 and R^* in the following form:

$$\frac{A^*}{H^2} = 2^{1/2} c_{\mathrm{t}} \left(\frac{a_{\mathrm{t}}}{H^2}\right) \left({R^*}^2 + 1\right)^{-1/2}. \tag{5.44}$$

By substituting for a_{t}/H^2 from (5.44) into (5.43), and assuming $c_{\mathrm{t}} = c_{\mathrm{b}}$, the Froude number at the top opening thus is

$$\mathrm{Fr_t} = 2^{5/8} c_{\mathrm{t}}^{5/4} \left(\frac{5}{8\pi^{1/2}\alpha_{\mathrm{P}}}\right)^{-1/2} \left(\frac{A^*}{H^2}\right)^{-1/4} (R^2 + 1)^{-5/8} (1 - \zeta + 2\widehat{Q^*})^{1/2}. \tag{5.45}$$

5.4 Theoretical predictions and analysis of results

The expressions for A^*/H^2 (5.24), $\mathrm{Fr_i}$ (5.36), $\widehat{Q^*}$ (5.40) and $\mathrm{Fr_t}$ (5.45) give the full solution to the problem. For the numerical analysis herein, we use the *lsqnonlin* feature of MATLAB 2014a, which is capable of solving a system of coupled non-linear algebraic equations based on a least squares analysis. Using *lsqnonlin*, Equations (5.24), (5.36), (5.40) and (5.45) are solved numerically for ζ and $\widehat{Q^*}$ in order to predict the key variables of interest, namely the interface height ζ, the entrainment flux $\widehat{Q^*}$, the volume flux $\widehat{Q}$, the reduced gravities of the lower and upper layers, $\widehat{g_\mathrm{l}'}$ and $\widehat{g_\mathrm{u}'}$, respectively, the stratification parameter $\mathcal{S}$, the interfacial Froude number $\mathrm{Fr_i}$, and the Froude number at the top opening $\mathrm{Fr_t}$. For simplicity, we consider the case in which the length of the line source is equal to the floor-to-ceiling height of the box, such that $L/H = 1$. This is done intentionally to simplify the analysis (and to shorten the computational time), whilst having little effect on the solutions. Our main focus here is to investigate how interfacial mixing influences the form of the density stratification, namely the height of the interface separating the upper layer from the fluid below (the lower layer) and the net buoyancy of the individual layers that drive fluid flow through the box.

The non-linear least squares solver described above is used to generate the plots in Figure 5.5, which show (a) ζ, (b) $\widehat{Q^*}$, (c) $\widehat{Q}$, (d) $2\widehat{Q^*}/\widehat{Q}$, (e) $\widehat{g_\mathrm{l}'}$, (f) $\widehat{g_\mathrm{u}'}$, (g) $\widehat{g_\mathrm{l}'}/\widehat{g_\mathrm{u}'}$, (h) $\widehat{\Delta g'}$, (i) $\mathcal{S}$, (j) $\mathbb{B}_\mathrm{N}$, (k) $\mathrm{Fr_i}$ and (l) $\mathrm{Fr_t}$ as functions of the vent area ratio R for $A^*/H^2 = \{0.005, 0.01, 0.02\}$. The critical Froude numbers, $\mathrm{Fr_{i,c}} = 0.67$ in Figure 5.5(k) and $\mathrm{Fr_{t,c}} = 0.33$ in Figure 5.5(l), are also plotted so that reference can be made between the values of $\mathrm{Fr_i}$ and $\mathrm{Fr_t}$ for a given pair of A^*/H^2 and R, and the critical Froude numbers marking the onset of interfacial mixing and exchange flow. In the following sections, the predicted effect of A^*/H^2 and R on interfacial mixing is presented, wherein broad features of the resulting flow behaviour and density stratification are discussed. For clarity, we summarise these key features schematically in Figure 5.6.

5.4.1 Effect of varying R

The response of the flow and stratification to changes in the vent area ratio R for a fixed value of A^*/H^2 are now elucidated. Broadly, the plots in Figure 5.5 show that the upper layer decreases in depth as R is increased (*i.e.* a_b decreases relative to a_t); the lower layer increases in depth and in buoyancy as it is fed by relatively buoyant fluid from the upper layer via interfacial entrainment. The buoyancy contrast across the interface decreases as a result; this, in turn, effectively acts to reduce the stability of the interface and thereby reinforces interfacial mixing.

By entraining buoyant fluid from the upper layer into the lower layer, interfacial mixing forces the interface away from the plume source and increases the buoyancy of the lower layer. This behaviour is clearly exhibited in Figures 5.5(a) and 5.5(e), which show that ζ and $\widehat{g'_{\mathrm{l}}}$ both increase as R is increased. Interestingly, Figure 5.5(f) shows that the buoyancy of the upper layer remains constant for all values of R considered. This result is somewhat counterintuitive given that an increase in the interface height would typically be followed by a decrease in the buoyancy of the upper layer due to the additional entrainment of fluid by the plume over an increased height (we recall that $G'_{\mathrm{LP}} \propto h^{-1}$, and at steady state $g'_{\mathrm{u}} = G'_{\mathrm{LP}}$). However, since $\widehat{g'_{\mathrm{l}}} > 0$, the decrease in $\widehat{g'_{\mathrm{u}}}$ is likely counteracted by the increase in $\widehat{g'_{\mathrm{u}}}$ brought about by entrainment of fluid from the lower layer into the upper layer by the plume. Consequently, the reduced gravity of the upper layer remains constant.

The effect of interfacial mixing on the net buoyancy accumulated within the box is shown in Figure 5.5(j), which plots $\mathbb{B}_{\mathrm{N}}$ as a function of R. The plot shows that the net buoyancy $\mathbb{B}_{\mathrm{N}}$ is invariant with R. Interfacial mixing therefore serves to redistribute the buoyancy in the box from the upper layer to the lower layer without affecting the net buoyancy contained in the box. Since $Q = A^*\mathbb{B}_{\mathrm{N}}^{1/2}$, the total volume flux $\widehat{Q}$ through the box remains constant and is independent of R (Figure 5.5(c)).

The stratification parameter $\mathcal{S} = \sqrt{\mathbb{B}_{\mathrm{l}}/\mathbb{B}_{\mathrm{u}}}$, which we recall, (5.15), is a dimensionless measure of the relative forcing strengths of the lower lower to the upper layer that drive bulk fluid flow through the box. Figure 5.5(i) shows that, for a given A^*/H^2, the stratification parameter increases as R is increased. However, since $\mathcal{S} \ll 1$, the upper layer produces the dominant forcing, despite there being a decrease in the net buoyancy $\mathbb{B}_{\mathrm{u}}$ within the layer as R increases.

From Figure 5.5(l) we see that unidirectional flow plays an ever weaker role in expelling buoyant fluid from the interior through the top opening as R increases. We recall that the Froude number $\mathrm{Fr_t}$ characterises the relative strengths of the outflowing buoyant fluid at the top and the downflowing ambient fluid through the same opening. Since $\mathrm{Fr_t} \propto Q/(a_{\mathrm{t}}^{5/4} {g'_{\mathrm{u}}}^{1/2})$, and that for a given A^*/H^2, the volume flux Q and reduced gravity g'_{u} are both invariant with R (Figures 5.5(c) and 5.5(f)), the Froude number $\mathrm{Fr_t}$ thus responds solely to variations in a_{t}. Consequently, as R increases (*i.e.* a_{t} is large relative to a_{b}), the outflow at the top poses less resistance to the incoming ambient fluid, $\mathrm{Fr_t}$ tends increasingly closer to $\mathrm{Fr_{t,c}}$, thereby increasing the potential for exchange flow at the top opening.

Limit of large momentum flux

In §5.3.1 we hypothesised that in the limit of large momentum flux, $2Q^* \gg Q$, the two-layer stratification breaks down and an approximately uniform temperature internal environment

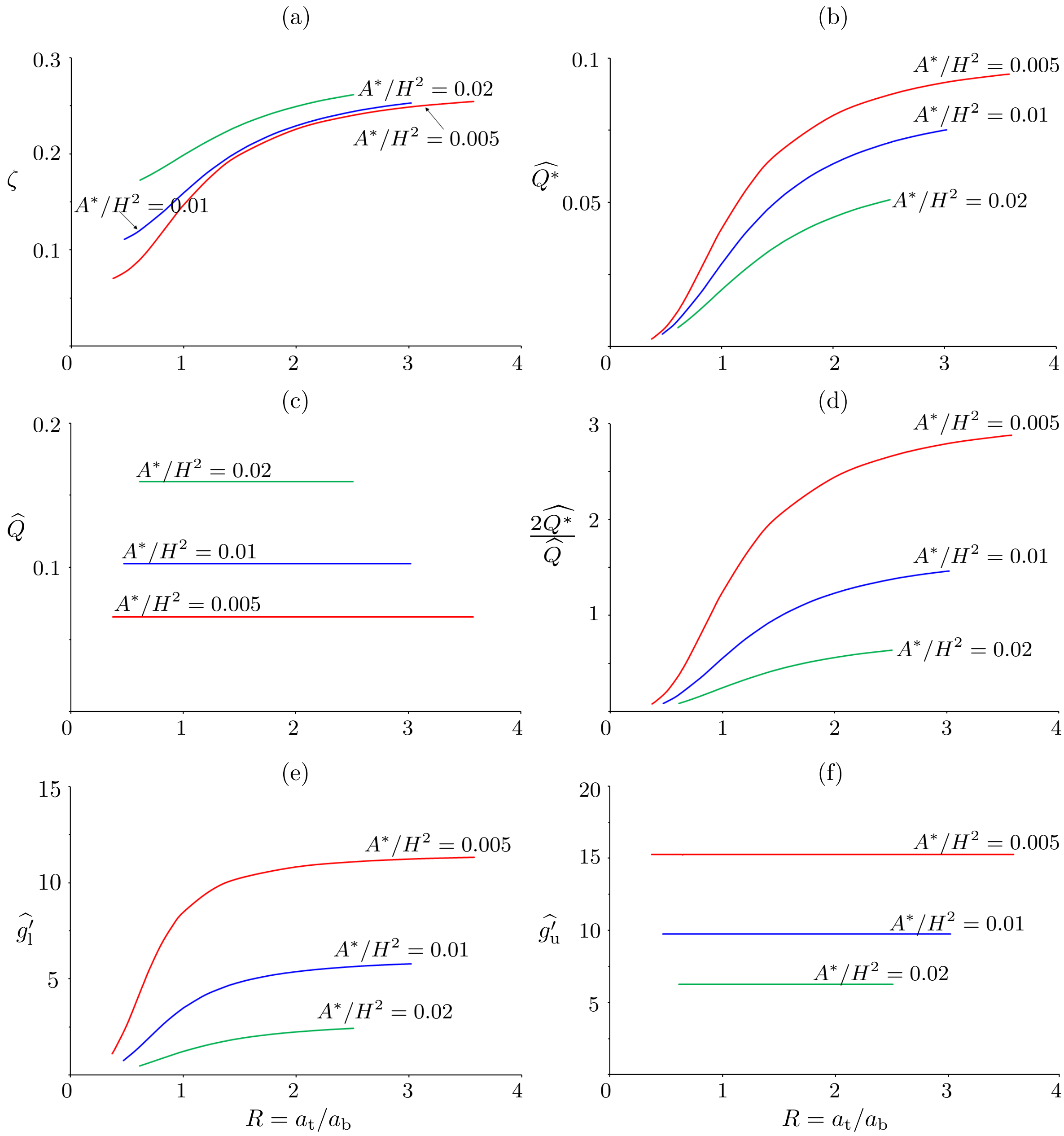


FIGURE 5.5: Plots showing (a) the interface height ζ, (b) the entrainment flux $\widehat{Q^*}$, (c) the volume flux $\widehat{Q}$ through the box, (d) the ratio of $2\widehat{Q^*}$ to $\widehat{Q}$, (e) the lower layer reduced gravity $\widehat{g'_\mathrm{l}}$, and (f) the upper layer reduced gravity $\widehat{g'_\mathrm{u}}$ as functions of R for $A^*/H^2 = \{0.005, 0.01, 0.02\}$ (continued on next page).

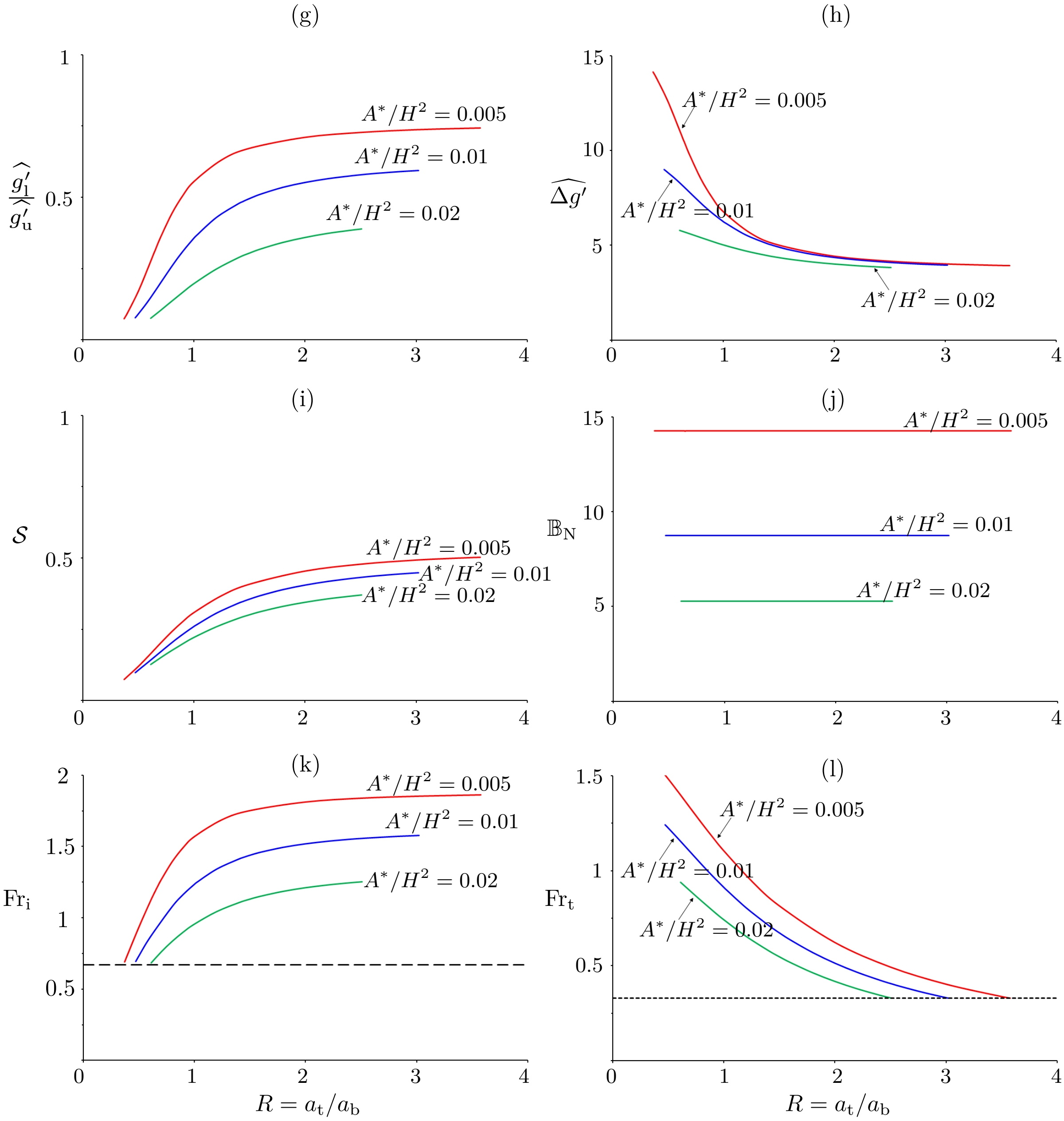


FIGURE 5.5: Plots showing (g) the ratio of reduced gravities for the layers $\widehat{g'_l}/\widehat{g'_u}$, (h) the interfacial buoyancy contrast $\widehat{\Delta g'}$, (i) the stratification parameter $\mathcal{S}$, (j) the net buoyancy accumulated within the box $\mathbb{B}_N$, (k) the interfacial Froude number Fr_i, and (l) the Froude number at the top opening Fr_t as functions of R for $A^*/H^2 = \{0.005, 0.01, 0.02\}$. The dashed and dotted lines in (k) and (l) denote $Fr_{i,c} = 0.67$ and $Fr_{t,c} = 0.33$, respectively (continued).

is established ($g'_\mathrm{l}/g'_\mathrm{u} \approx 1$). To investigate this hypothesis, we have plotted the ratio of the net entrainment flux across the interface and the volume flux through the box, $2\widehat{Q^*}/\widehat{Q}$, as a function of R for $A^*/H^2 = \{0.005, 0.01, 0.02\}$ in Figure 5.5(d).

For a given A^*/H^2, Figure 5.5(d) shows that $2\widehat{Q^*}/\widehat{Q}$ increases with R. This is likely attributed to the increase in the interfacial Froude number brought on by the increased momentum flux M_b of the impinging flow as the area of the bottom opening is reduced relative to the top. For large R ($\gg 1$), Figure 5.5(g) shows that the ratio of reduced gravities, $\widehat{g'_\mathrm{l}}/\widehat{g'_\mathrm{u}}$, tends to a constant value, and in particular for small A^*/H^2, $\widehat{g'_\mathrm{l}}/\widehat{g'_\mathrm{u}}$ tends closer to one. In fact, our theoretical model predicts that when $A^*/H^2 = 0.0002$ and $R = 7$, $2\widehat{Q^*}/\widehat{Q} = 23$, $\widehat{Q} = 0.007$ and $\widehat{g'_\mathrm{l}}/\widehat{g'_\mathrm{u}} = 0.97$ (values are not plotted in Figures 5.5(d), 5.5(c) and 5.5(g)). For a ventilated room with $L = 7\,\mathrm{m}$, $H = 7\,\mathrm{m}$ and $B_\mathrm{LP} = 0.028\,\mathrm{m^3\,s^{-3}}$ ($\approx 1\,\mathrm{kW\,m^{-1}}$), a value of $\widehat{Q} = 0.007$ corresponds to a ventilation flow rate of $0.045\,\mathrm{m^3\,s^{-1}}$ (or, equivalently, $45\,\mathrm{L\,s^{-1}}$), which is barely sufficient to satisfy the design requirements for fresh air supply rate for five people (CIBSE, 2006). Not only is an effective area of $A^*/H^2 = 0.0002$ impracticably small for ventilation openings, but also the diminutively low airflow rate achieved through them may result in an uncomfortably hot and stuffy indoor environment. Thus, we expect that the two-layer stratification will dictate the overall ventilation of the enclosure in general.

5.4.2 Effect of varying A^*/H^2

We now focus our attention on the effect of A^*/H^2 for a fixed value of R on the flow and density stratification in the box. In contrast to the aforementioned behaviour for a fixed A^*/H^2, increasing A^*/H^2 alters the form of the stratification established by increasing the total volume flux $\widehat{Q}$ through the openings and the rate at which buoyant fluid is expelled from the box. Correspondingly, the interface adjusts to a new height, so that the inward fluxes of volume and buoyancy supplied to the upper layer match those exiting the layer. This increased interface position is associated with a reduction in the velocity of the impinging flow (recalling that $w_\mathrm{i} \propto h^{-1}$), the value of the interfacial Froude number $\mathrm{Fr_i}$ decreases, and the entrainment rate $\widehat{Q^*}$ is reduced. As a consequence, the reduced gravity of the lower layer decreases. The plume entrains relatively denser fluid from the lower layer over an increased distance from the source, thereby resulting in a decrease in the reduced gravity of the upper layer as A^*/H^2 increases. However, despite there being a reduction in both the depth and buoyancy of the upper layer, the upper layer still provides the dominating forcing of the bulk flow through the box, since $\mathcal{S} \ll 1$.

For large values of A^*/H^2 (*e.g.* $A^*/H^2 \gg 0.01$), the form of the stratification is characterised by a relatively shallow upper layer overlying a deep and dense lower layer. This change in the form of the stratification established for increasing A^*/H^2 effectively acts to decrease the strength of interfacial mixing. Moreover, as a greater proportion of the net buoyancy is accumulated within the upper layer (relative to the lower layer), the neutral pressure level within the box is raised further from the floor, which works to encourage exchange flow at the top opening (Hunt & Coffey, 2010).

5.4.3 Summary of the predicted flow behaviour

Guided by the results from our analysis, we summarise the broad effects of interfacial mixing on the ventilation and density stratification as illustrated in Figures 5.6(a) and 5.6(b) and as described below:

(i) For increasing A^*/H^2 and/or R, interfacial mixing serves to redistribute the buoyancy contained in the box from the upper layer to the lower layer, and to

(ii) increase the height of the density interface from the floor;

(iii) For a fixed value of A^*/H^2, increasing R (that is, a_b is decreased relative to a_t) results in an increase in the reduced gravity of the lower layer, albeit the net buoyancy contained within the box and the total volume flux through the box remain unaffected;

(iv) Conversely, for a fixed value of R, increasing A^*/H^2 results in an increased volume flux through the openings, leading to a reduction in the net accumulated buoyancy within the box, *i.e.* the whole space cools.

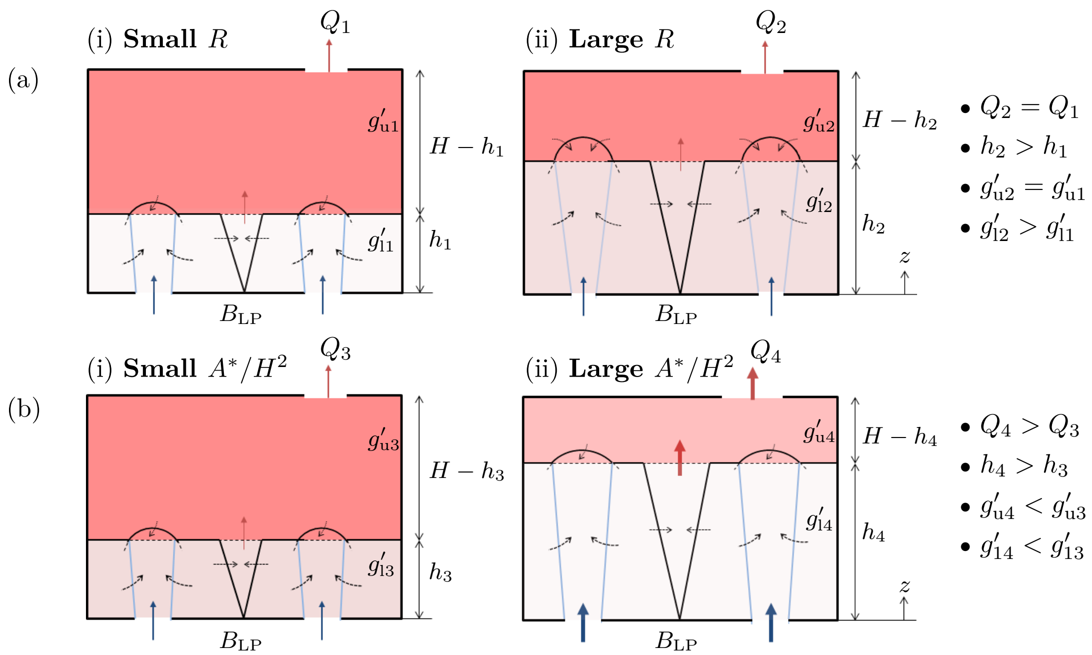


FIGURE 5.6: Schematics of a ventilated box with height H showing the impact of interfacial mixing on the flow and density stratification: (a) when R increases (for fixed A^*/H^2) and (b) when A^*/H^2 increases (for fixed R). The buoyancy flux B_{LP} and length L of the line source in (a) and (b) are identical. The key features of the resulting flow behaviour are summarised in bullet points next to the schematics.

5.5 Assumptions and limitations

The theoretical model described in §5.3 provides a means of predicting the effect of interfacial mixing on the steady buoyancy-driven flow and stratification within full-scale buildings. Whilst affording valuable insight into the key variables controlling the ventilation system, there are limitations imposed on the range of applicability due to the model's underlying assumptions. It is therefore important to clarify the constraints of our theoretical model on its range of application.

We assumed that heat inputs may be modelled as an ideal localised line source of buoyancy positioned in the centre of the room at floor level, and that heat transfers between the building fabric and the internal fluid are negligibly small. Linden *et al.* (1990) and Kaye & Hunt (2004, 2007), amongst others, have shown that this simplified approach can lend itself to an improved understanding of flows driven by localised line sources in buildings. In some situations, however, this approach may represent an oversimplification. For example, conductive, convective and radiative heat transfers to and from the boundaries of the enclosure may lead to a more gradual change in temperature from the floor to the ceiling, rather than a sharp stratification interface between the buoyant upper layer and denser lower layer (Lane-Serff & Sandbach, 2012). Moreover, the presence of multiple line sources of buoyancy (as per the rows of seated occupants in a theatre) may lead to a more complex stratification pattern due to, for example, plume-plume interactions (Rouse *et al.*, 1953; Pera & Gebhart, 1975).

The simplifying assumptions made in §5.3 also implicitly impose geometrical restrictions which limit the range of practical situations to which the model may be applied. We considered only one possible arrangement of openings in which the total area a_b is split equally between two openings at the base of the enclosure. However, since the momentum flux M_b of the inflow is inversely proportional to a_b and the number of openings at the base (see Equation (5.31)), we anticipate that the resulting flow and density stratification in the presence of interfacial mixing will be affected by the way in which a_b is split between multiple openings. For example, we expect that, for fixed values of A^*/H^2 and $R = a_\mathrm{t}/a_\mathrm{b}$, increasing the number of (equal) base openings will lead to a decrease in the momentum flux M_b of the impinging jets at the interface, which could cause the interfacial Froude number, $\mathrm{Fr_i}$, and therefore the rate of interfacial entrainment, Q^*, to decrease. Consequently, we predict that both the interface height and reduced gravity of the lower layer will decrease as a_b is split between multiple openings.

We restricted our attention to horizontal openings only so as to avoid a varying pressure gradient across the plane of each opening and plume deflection. Whilst the key features of the steady flow and stratification described in §5.4 are expected to be broadly similar for vertical openings, we anticipate that there will be some subtle differences, most notably in the behaviour of the inflow through the lower openings. As ambient fluid enters the space through the lower openings, the inflow will travel across the floor, possibly causing the plume to deflect from the vertical, before impacting on the side wall of the enclosure. On impact with the plume and the wall, the flow will likely dissipate part of its momentum before traversing upwards along the wall towards the interface. Consequently, we expect that the stratification established in spaces with vertical openings to be more 'resistant' to the onset of interfacial mixing; this, in turn, could affect the value of the critical interfacial Froude number and, thereby, influence the values of A^*/H^2 and R at which the transition between no-mixing and mixing at the interface occurs.

No restrictions were placed explicitly on L/H (*i.e.* the length of the line source relative to the room height) and the aspect ratio of the room (*i.e.* the horizontal distance between the side walls of the room relative to the room height) for which the steady flow model is valid other than to allow the plume to rise unhindered and entrain surrounding fluid freely from its two (unobstructed) sides. It is entirely conceivable that extremes in the aspect ratio of the enclosure (a tall and very narrow space, for example) may result in a mixed interior, as the plume is likely to reach the side walls before the ceiling. Furthermore, no restrictions were placed on the horizontal distance between each of the base openings and the line source other than to allow the inflowing ambient fluid through the base (which was modelled as a turbulent axisymmetric jet) to rise independently of the plume. Indeed, it is possible for the inflowing fluid and the buoyant plume to interact. Hunt *et al.* (2001*a*) showed that the form of the stratification is sensitive to the relative strengths of the sources of momentum (jet) and buoyancy (plume), and the ratio of their source separations to the room height. They showed that when the separation distance between the two sources of momentum and buoyancy is less than $0.27H$, the plume is significantly affected by the turbulence generated by the jet and the resulting stratification is horizontally inhomogeneous. For sufficiently small source separations, they showed that an approximately uniform temperature internal environment is established.

Finally, we assumed that the interfacial impingement is weakly energetic such that entrainment of fluid from the upper layer occurs solely within the impingement dome atop the incident jet and lateral entrainment is negligible (see Figure 5.3(a)). For moderately or highly energetic impingements ($\mathrm{Fr_i} \gg 1.4$), this assumption may no longer hold as the flow above the interface is likely to develop as a turbulent fountain (Shrinivas & Hunt, 2014*b*). In this case, the upflowing jet-like core would likely be shrouded by a lighter counterflow and the Baines's (1975) entrainment model adopted herein may no longer be valid.

5.6 Summary and conclusion

A theoretical model was developed to examine the effect of interfacial mixing by the inflowing ambient fluid on the steady flow and thermal stratification in a ventilated enclosure containing a single floor-level line source of buoyancy. Focus has been on an enclosure of height H, with horizontal openings at the top (area a_{t}) and bottom (each of area $a_{\mathrm{b}}/2$) faces. We considered a stably stratified interior comprised of a lower layer above ambient density and a buoyant upper layer above a horizontal interface. The plume maintains the upper layer and the localised impingement of two turbulent axisymmetric jets through the base drive entrainment of fluid from the upper layer into the lower layer. Our attention has been restricted to high Reynolds number and high Péclet number flows so that viscous effects are negligible and advection dominates the effects of thermal diffusion. We also focussed on the Boussinesq case where the density difference between the interior fluid and the ambient environment is small compared with a reference density.

Our model is an extension of the steady emptying-filling box model of Linden *et al.* (1990) and is applicable to conditions that result in both interfacial mixing and unidirectional flow through the openings. In order to characterise the particular flow pattern of interest, we have extended the flow type classification method of Hunt & Coffey (2010) for transient draining flows to suit steady state flows and was employed successfully in our study as a useful investigative tool. By focussing on the portion of the $\{\mathrm{Fr_i}, \mathrm{Fr_t}\}$ parameter space where unidirectional flow through the openings ($\mathrm{Fr_t} > 0.33$) and turbulent mixing at the interface ($\mathrm{Fr_i} > 0.67$) occur, we showed that the flow and stratification realised in a given room can be elegantly captured by the rate of interfacial entrainment Q^* by the inflow through the base, the source buoyancy flux of the line plume B_{LP}, the plume entrainment constant $\mathrm{C_{LP}}$, and three geometric quantities, namely the total effective area of the openings A^*/H^2, the vent area ratio $R = a_{\mathrm{t}}/a_{\mathrm{b}}$, and the length of the line source relative to the room height L/H. A simple stratification comprised of two homogeneous fluid layers of different density is established, and the position of the bottom openings relative to the line source was shown to be noteworthy in maintaining the two-layered stratification.

The general effects of interfacial mixing on the flow and stratification can be summarised as follows. By entraining fluid across the interface, interfacial mixing forces the interface away from the floor and leads to a redistribution of the net buoyancy contained in the enclosure from the upper layer to the lower layer. For fixed values of A^*/H^2 and L/H, we showed that increasing the vent area ratio R (that is, decreasing a_{b} relative to a_{t}) increases the interfacial entrainment rate and, hence, results in an increased lower layer depth and buoyancy. The change in the stratification established for increasing R, however, was shown not to affect the net buoyancy contained within the enclosure nor the total volume flux through the openings. This has implications for the development of control algorithms in building management systems of naturally ventilated buildings. Provided the total effective opening area A^*/H^2 remains constant, the depth and temperature of the lower occupied layer can be controlled solely by adjusting the vent area ratio R, without compromising the bulk airflow rate through the enclosure. This is in contrast to the previous results of Chapter 4 where, in the absence of internal mixing by the inflowing replacement fluid, the bulk ventilating flow through the space is controlled primarily by the top opening, as opposed to being shared between the top and bottom openings.

A number of simplifying assumptions were made in our theoretical model which restrict the range of practical situations to which it may be successfully applied to full-scale building ventilation problems. It is assumed that (i) heat transfers between the building fabric and the fluid within the enclosure are negligibly small, (ii) heat inputs can be represented by an ideal line source of buoyancy positioned in the centre of the floor, (iii) the impingement of ambient fluid at the density interface is weakly energetic (Shrinivas & Hunt, 2014*b*), and (iv) the openings are horizontally orientated, sharp-edged and are not covered by grilles, louvres or other obstacles which restrict fluid flow through the openings.

Notwithstanding the limitations listed, the approach of using a simplified mathematical model, based on the building blocks of layered stratification, convective plume flow and jet-interface interaction has provided a tractable framework for identifying the key variables that affect the performance of the ventilation system. We anticipate that the results of our model reported in this study may prove useful for informing the design of naturally ventilated buildings, based on a rational representation of the underlying physics of ventilation flows.

Part II: the 'design' part

5.7 Focus

Part II is designed specifically to convey the key results of the analysis of Part I in an accessible format for an architectural audience. Following the core ethos of this thesis, we intend to draw some intuitive understanding from our analysis and to link this back to inform design, with a view to developing an easy-to-follow and rapid guideline for the preliminary sizing of openings. To this end, we attempt to provide a straightforward presentation of the work of Part I using illustrative examples as much as possible. Attention has also been paid to the use of visually-based approaches to information presentation in order to engage the interest of the reader. Where appropriate, we provide some additional commentary on certain parts of the text, which we deem are deserving of further explanation, in an attempt to help readers gain a foothold in what may seem to be new and unfamiliar concepts. We single out and highlight this commentary in grey in order to make it distinct from the rest.

5.7.1 Notation

We remind the reader that, whilst the work of Part I has been written deliberately using 'technical' notation and terminologies, herein we use terms that are anticipated to be more intuitive, or even familiar, to a design audience. For convenience, we reiterate the specifics of the conversion between 'technical' (Part I) and 'architectural' (Part II) notation and terminologies in Table 5.3.

'Architectural'				'Technical'
Temperature difference (°C)	ΔT	$\Longleftrightarrow$	g'	Reduced gravity ($\mathrm{m\,s^{-2}}$)
Heating power (Watts)	W	$\Longleftrightarrow$	B	Heat flux ($\mathrm{m^4\,s^{-3}}$)
Direction number (-)	$\mathscr{D}ir$	$\Longleftrightarrow$	$\mathrm{Fr_t}$	Froude number at the upper opening (-)
Draught number (-)	$\mathscr{D}ra$	$\Longleftrightarrow$	$\mathrm{Fr_i}$	Interfacial Froude number (-)

TABLE 5.3: Conversion between 'architectural' (Part II) and 'technical' (Part I) notation and terminologies.

5.8 Introduction

The natural tendency for warm air to rise and cool air to sink may lead to a stable stratification in a room, with warmer air towards the ceiling and relatively cooler air near the floor. This temperature stratification, whilst providing the necessary stack pressure to drive the ventilating flow through the room, may potentially be uncomfortable for occupants.

In order to illustrate some of the effects of stratification on occupant comfort, we consider a simple example of a ventilated room with floor-to-ceiling height H, as shown schematically in Figure 5.7(a). Ventilation openings, made at the top and bottom faces, connect the interior environment to a quiescent (wind-free) external environment. There is a single row of occupants – seated shoulder-to-shoulder – along the centre of the room ('into the page').

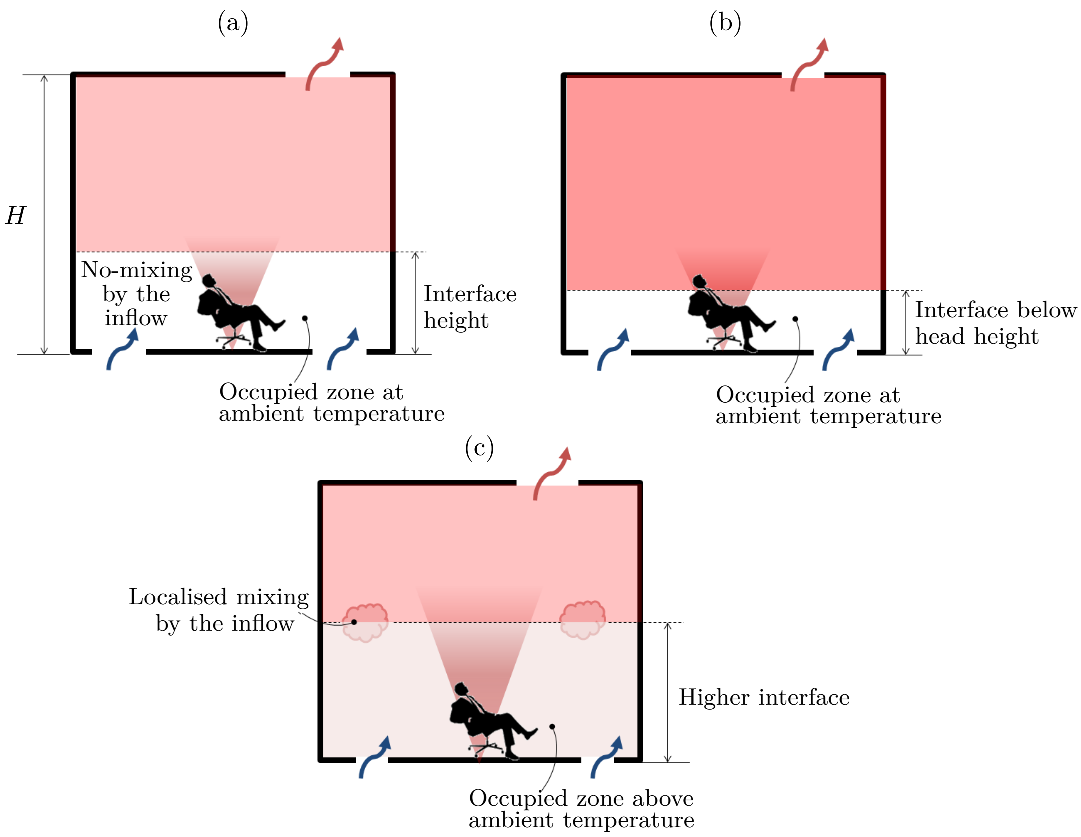


FIGURE 5.7: Schematics of a naturally ventilated room in elevation showing snapshots of the steady stratification produced by different vent area configurations. (a) The combined area of the floor-level openings is large relative to the opening at ceiling level so that cool outdoor air flows through the base openings at low velocities. Mixing by the inflowing air with the warm air in the upper layer is negligible, and the temperature of the lower layer is equal to the outdoor temperature. (b) The combined area of the ceiling and floor-level openings is decreased but the area ratio between the two stays constant; there is a net reduction in the ventilation flow rate through the room, and the upper layer deepens and increases in temperature. (c) The combined area of the floor-level openings is small relative to the ceiling-level opening; cool air from the exterior enters the room at high velocities, which mixes significantly with the warm air in the upper layer. This results in a redistribution of the heat contained in the room from the upper layer to the lower layer, and increases the temperature of the lower layer above ambient temperature.

For simplicity, we assume that the occupants are the main source of heat generation and that their combined heat input can be reasonably modelled as a single line source of heat, spanning wall-to-wall, along the room at floor level. The line source produces a buoyant plume whose convective motion is confined to a two-dimensional plane due to the presence of the end walls. As it rises from the source, the plume draws surrounding air from its two (unobstructed) sides, carrying air and heat upwards. Warm air accumulates in the upper region of the room, forming a warm upper layer above a horizontal interface and a relatively cooler lower layer beneath (Linden *et al.*, 1990).

Provided the openings are suitably sized and located, a displacement mode of ventilation may be established. In displacement mode, cool (and thus, relatively dense) air from the exterior is introduced through floor-level openings at low velocities and 'slides' beneath, rather than vigorously mix with, the warm air in the upper layer, which 'displaces' upwards and out through the openings at ceiling level (Linden *et al.*, 1990; Hunt & Coffey, 2010). The absence of mixing by the inflowing cool air ensures that all the heat in the room is contained within the upper layer so that the lower layer is at ambient temperature. This is clearly a desirable feature for summer ventilation when a cooler occupied layer is sought.

During the cooler months, however, the outdoor air temperature may lie outside the bounds of thermal comfort. In this case, a displacement ventilation strategy involving ambient air in the occupied region of the room may result in an uncomfortably cold environment for occupants. A natural reaction may be to close some of the vents with the anticipation of reducing cold discomfort. On the contrary, by decreasing the total openable area of the vents, the ventilation flow rate through the room may reduce, which in turn may cause the upper layer to deepen and to increase in temperature (Figure 5.7(b)). This can have undesirable implications for comfort as occupants may be exposed to a significant temperature variation over their bodies (*i.e.* 'localised overheating'). Olesen *et al.* (1979) showed that, for seated occupants, more than 10% of occupants may experience discomfort if the temperature difference between their head and feet is 3°C or greater. It is therefore clear that a ventilation strategy that seeks to create significant stratification can have a negative impact on occupant comfort.

In order to reduce the vertical air temperature difference in the room, a suitable ventilation strategy may involve a mixing mode of ventilation, whereby cool air is introduced at high velocities through the low-level openings so as to mix with the warm air accumulated within the upper layer. Experimental observations by Hunt & Coffey (2010) and Coffey & Hunt (2010) showed that, by suitably adjusting the relative areas of the upper and lower openings for a given total (effective) opening area, a mixing-type flow pattern can be harnessed to 'recirculate' and 'transport' some of the heat from the upper layer into the lower layer. In doing so, they showed that the temperature of the lower layer is above ambient temperature and the position of the interface is increased further from the floor (Figure 5.7(c)); these changes in the form of the stratification, in turn, effectively act to minimise the risk of localised overheating.

The concept of 'recirculating' the heat by incorporating internal mixing is hereinafter referred to as 'passive warming'. In contrast to displacement ventilation, passive warming can provide an efficient means of naturally ventilating during the cooler months as no additional input of energy is required to increase the air temperature in the occupied zone. Baker & Steemers (2003) commented that for every 1°C increase in temperature produced by passive means can contribute to approximately 5–10% savings in heating energy.

Herein, we are primarily concerned with the lower layer depth and temperature since the lower region of a room, typically, is the one that is occupied. Specifically, we focus on showing how passive warming affects the 'bulk' quantities of the ventilation, namely the airflow rate, the interface height and the lower layer temperature, and in particular, to show how these quantities can be controlled by the size and relative areas of the openings in the façade. The main purpose is to develop a straightforward methodology for determining the physical areas of the openings needed to achieve passive warming, in which the requirements for ventilation flow rate, interface height and occupied zone temperature are satisfied simultaneously. For simplicity, we focus on the stack ventilation of a (well-insulated) room containing a localised line source of heat, spanning wall-to-wall, along the centre of the room floor. Again, this may be thought of as an idealised representation of the heat generated by a long row of occupants seated in a crowded lecture hall, for example. We also focus on a specific opening arrangement, for which there is a single opening at ceiling level and two (identical) floor-level openings at each side of the line source (as shown in Figure 5.7). As mentioned earlier, this particular placement of openings at floor level is noteworthy in establishing and maintaining a two-layer stratification, which is the stratification pattern of interest here.

Before we present our design guideline for sizing openings, it may be informative to provide answers to some broad design questions regarding passive warming that may be of interest to architects. We also reiterate some of the key concepts from earlier chapters in the context of passive warming. The intention here is to give a general overview of this topic in a non-technical manner.

1. How can internal mixing be established to provide passive warming?

In order to provide passive warming of an occupied space, it is necessary to ensure that the individual openings are selected within an appropriate range of areas, and in particular, that these openings satisfy specific conditions. Hunt & Coffey (2010) showed that these conditions can be expressed in terms of two dimensionless numbers, which we refer to in this thesis as the Direction and Draught numbers, $\mathscr{D}ir$ and $\mathscr{D}ra$, respectively. We recall from Chapter 4 that the Direction number is a quantity which sets the direction of airflow through the upper opening, and the Draught number determines the strength of mixing by the inflowing cool air through the lower opening.

The first requirement is to ensure that unidirectional flow – whereby cool air from the exterior enters the room through the floor-level openings and warm air is discharged solely out through the ceiling-level opening in one direction – is established through the openings. This is absolutely central to the delivery of the desired ventilation flow rate. In order to establish unidirectional flow, this requires $\mathscr{D}ir > \mathscr{D}ir_{\rm c}$, where $\mathscr{D}ir_{\rm c} \approx 0.33$ is the critical value for horizontal openings (Hunt & Coffey, 2010).

The second requirement is to ensure that external air is introduced at sufficiently high velocities through inlets at floor level. When the inflow through the opening has enough vertical momentum, the air will penetrate into, and mix with, the warm upper layer, which induces entrainment of the surrounding air from the layer as it mixes (Shrinivas & Hunt, 2014*b*). The mixture of air and heat is then transported across the interface and floods the lower layer with this mixture. Under these conditions, Hunt & Coffey (2010) referred to the mixing as 'vigorous' and showed that this occurs when $\mathscr{D}ra > \mathscr{D}ra_{\rm c}$, where $\mathscr{D}ra_{\rm c} \approx 0.67$ is the critical value for horizontal openings. The larger the value of the Draught number $\mathscr{D}ra$ (above 0.67), the greater the available kinetic energy of the flow to induce entrainment of warm air from the upper layer across the interface, and so the greater the rate at which warm air is transported from the upper layer into the lower occupied layer.

Although inflow velocities required to produce vigorous mixing in this manner may result in uncomfortable draughts for building occupants, the indoor air temperature is regulated primarily by the magnitude of the Draught number, which we recall, Equation (5.27), is directly proportional to the velocity of the inflow. For high inflow velocities, the flow has sufficient kinetic energy to drive 'highly' vigorous mixing ($\mathscr{D}ra \gg 1$), thereby resulting in a relatively warm, albeit draughty, lower layer. On the other hand, for lower inflow velocities, cool outdoor air might be delivered with insufficient kinetic energy to give rise to vigorous mixing ($\mathscr{D}ra < 0.67$), thus resulting in a colder lower layer. Therefore, the optimal performance of the ventilation system ideally requires a delicate balance between the inflow velocities needed to generate vigorous mixing for passive warming while maintaining thermal comfort and minimising the risk of draught discomfort.

2. What is the appropriate range of opening areas to select from?

Hunt & Coffey (2010) showed that the critical values of the Direction and Draught numbers place formal restrictions on the range of suitable vent area configurations for which unidirectional flow and internal mixing can occur simultaneously. The vent area configuration is dependent on two geometric ratios, namely the total effective area A^*/H^2 of the openings

– which accounts for the combined physical area of the openings and the resistance they pose to the ventilating flow – and the ratio between the upper and lower opening areas, $R = a_t/a_b$. Here, a_t and a_b denote the physical areas of the upper opening and the two floor-level openings, respectively.[1] We recall (§3.5) that both A^*/H^2 and R are interdependent and together provide an indication of the total effective area available to the ventilating flow *and* the apportioning of this total area between the lower opening – supporting incoming cool air – and the upper opening – supporting (preferentially) outflowing warm air from the internal environment.

In order to provide a feel for the range of opening area configurations suitable for the passive warming of rooms, Figure 5.8 shows how the critical Direction and Draught numbers divide the $\{A^*/H^2, R\}$-space into four regions, each region characterised by a distinct flow pattern identified by Hunt & Coffey (2010). Note that the plot in Figure 5.8 is applicable only to the stack ventilation of rooms containing a floor-level line source of buoyancy.

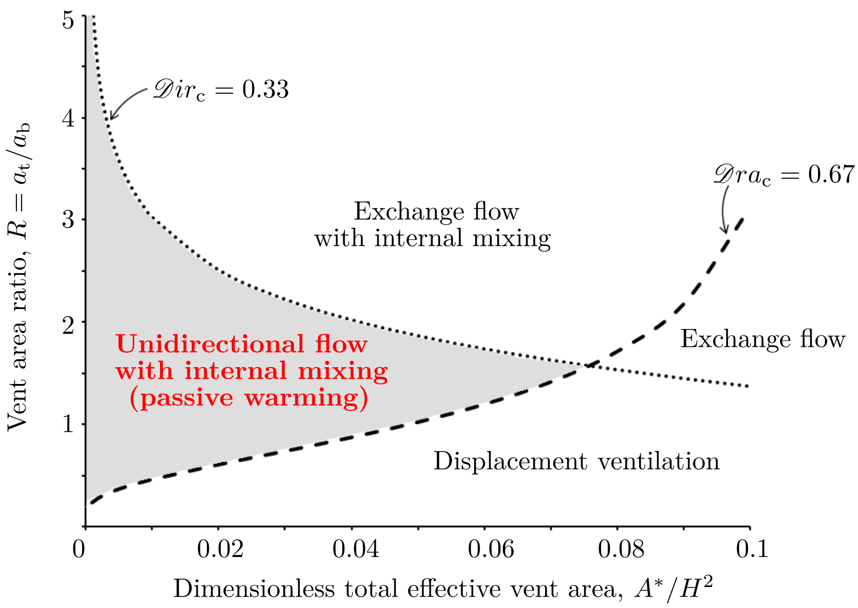


FIGURE 5.8: Plot of the vent area ratio R against the (dimensionless) total effective vent area A^*/H^2. Above the dotted line denoting $\mathscr{D}ir_c = 0.33$, exchange flow occurs, and below the line, unidirectional flow through the openings is established. Above the dashed line denoting $\mathscr{D}ra_c = 0.67$, there is turbulent mixing between the inflowing cool air and the warm upper layer, whereas below the line, mixing is absent. The target range of A^*/H^2 and R, for which both unidirectional flow and internal mixing are established, is shaded in grey.

[1] Throughout this chapter we assume that the loss coefficients, c_t and c_b, which account for the loss in total pressure experienced by the flow as it passes through the upper and lower openings, respectively, are constant and equal to 0.6 (see §3.3.3). In this case, we may assume that the loss coefficients are not influenced by the choice of the areas of the upper and lower openings, a_t and a_b, respectively.

The 'target' design range of A^*/H^2 and R, for which both unidirectional flow and mixing by the inflow occur, is shaded in grey in Figure 5.8. In §5.9 we present a straightforward algorithm for determining A^*/H^2 and R needed to provide the desired balance between the ventilation flow rate, the temperature and depth of the lower occupied layer.

3. How does the choice of A^*/H^2 and R impact passive warming?

In order to illustrate how A^*/H^2 and R affect the overall ventilation of a room, we consider the case of a naturally ventilated classroom with width $X = 7\,\mathrm{m}$, length $L = 7\,\mathrm{m}$ and floor-to-ceiling height $H = 7\,\mathrm{m}$. The key features are depicted in Figure 5.9, which shows (a) a 'birds-eye' perspective, (b) plan and (c) section views of the classroom.

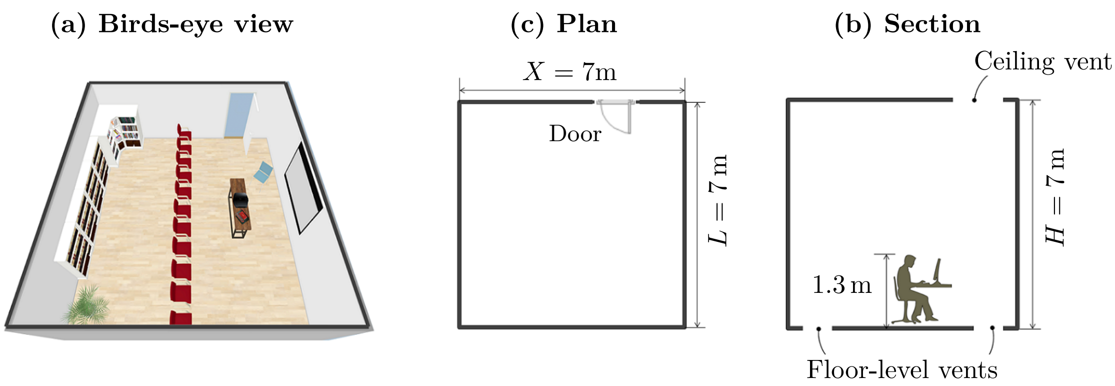


FIGURE 5.9: Drawings showing (a) a 'birds-eye' perspective, (b) a plan view, and (c) a section view of the naturally ventilated classroom. Ventilation openings at the ceiling and floor levels provide the primary connection between the internal and external (wind-free) environment. The seated head height of occupants is estimated to be at 1.3 m from the floor.

Ventilation openings, of area a_t and a_b, are made at the ceiling and floor levels of the room, respectively, which connect the interior to a wind-free outdoor environment with temperature $T_\mathrm{ext} = 15°\mathrm{C}$. At full capacity, the classroom is occupied by 15 students with laptop computers seated (shoulder-to-shoulder) in a row along the entire length of the room, and the estimated heat supply rate to the interior, W, is 14 kW. The seated head height is assumed to be at 1.3 m from the floor. Design requirements place the position of the interface above the seated head height.

Using the theoretical model developed in Part I, we can predict how variations in the size and relative areas of the openings affect passive warming, and the impact these have on the bulk ventilation flow rate, the interface position and the temperature within the classroom. These effects are summarised in Figure 5.10, which plots (a) the Draught number $\mathscr{D}ra$, (b) the interface height h_occ from the floor, (c) the occupied zone temperature T_occ, and

(d) the ventilation flow rate Q as functions of the vent area ratio R for a fixed value of A^*/H^2. In this example, the chosen total effective area of the openings, A^*, is $0.4\,\mathrm{m}^2$, giving $A^*/H^2 = 0.4/7^2 = 0.008$.

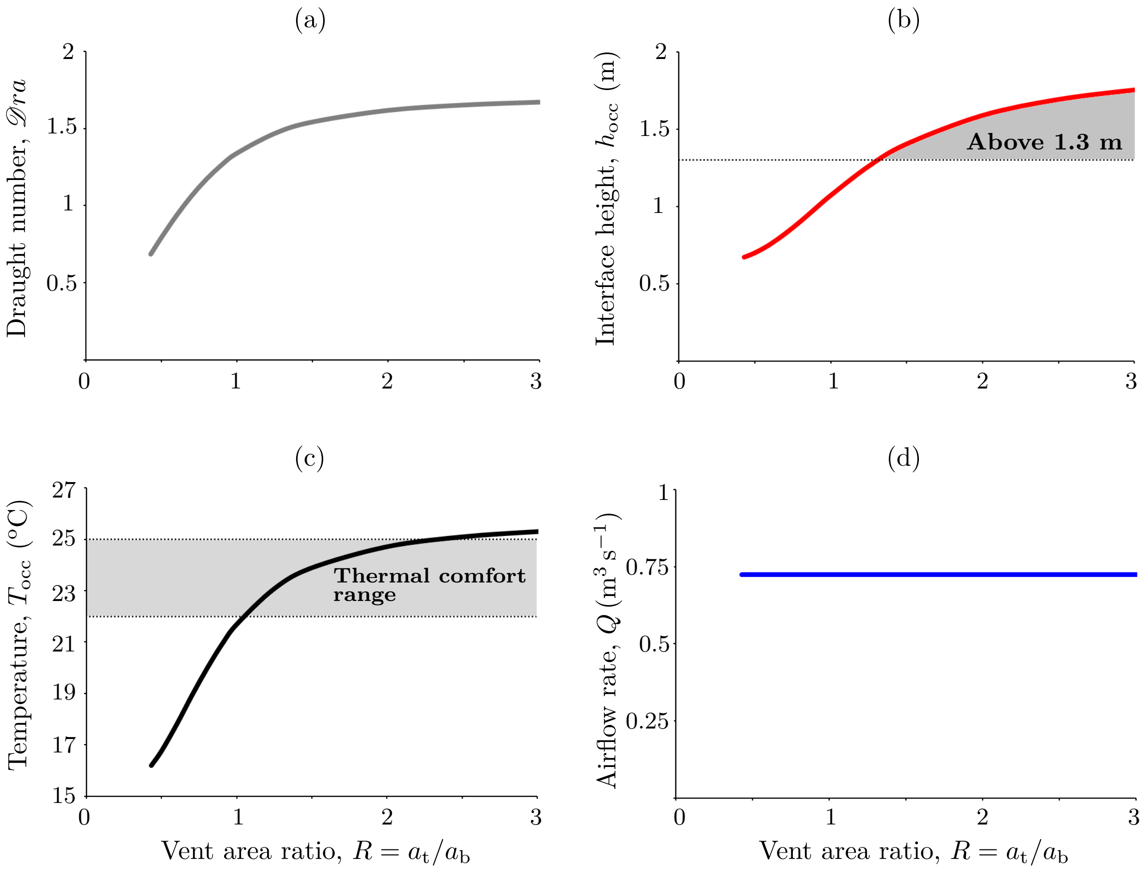


FIGURE 5.10: Plots of (a) the Draught number $\mathscr{D}ra$, (b) the interface height h_{occ} (m), (c) the occupied zone temperature T_{occ} (°C), and (d) the ventilation flow rate Q ($\mathrm{m^3\,s^{-1}}$) as functions of the vent area ratio R for $A^*/H^2 = 0.008$.

Broadly, the plots show that the lower occupied layer increases in depth and in temperature as the vent area ratio R is increased (that is, the total area of the floor-level openings is made smaller relative to the opening area at ceiling level). In contrast, the bulk ventilation flow rate through the classroom remains constant and is unaffected by changes in R.

Q: *Why does the interface height and lower layer temperature increase with increasing vent area ratio?*

A: On decreasing the total area of the floor-level openings relative to the opening area at ceiling level (*i.e.* increasing R), the momentum of the inflowing cool air through the floor-level openings increases; this, in turn, effectively acts to increase the kinetic energy of the inflow to disrupt the otherwise stable interface and turbulently entrain warm air from the upper layer across the interface (Hunt & Coffey, 2010). Consequently, the resulting mixture, with temperature between that of the ambient and the upper layer, arrives in the lower layer at a higher temperature than the outdoor environment. Concurrently, by entraining warm air across the interface, mixing by the inflow erodes the interface further away from the floor, thereby increasing the depth of the lower occupied layer.

Q: ***Why does the ventilation flow rate stay constant?***

A: This is because, for a fixed total effective opening area and heat supply rate, mixing by the inflow does not affect the total amount of heat contained within the room. As a result, the total stack pressure driving the ventilating flow also stays constant.

An interesting feature worth noting is the change in the form of the dependence of the lower layer temperature T_{occ} with the vent area ratio R at high and low Draught numbers (Figures 5.10(a) and 5.10(c)). At high $\mathscr{D}ra$, the dependence of T_{occ} on R is weak for $R > 2$ (the gradient of the curve of T_{occ} is shallow and close to zero). In contrast, at low $\mathscr{D}ra$, there is a strong dependence (almost linear) of T_{occ} on R for $R < 2$. This is because, for small values of R (*i.e.* a large base opening area relative to the area of the top opening), the interface position is in close proximity to the floor-level openings, and so, the distance over which the incoming air has to travel prior to impingement with the interface is reduced. This decrease in the distance travelled by the inflow is associated with an increase in the velocity and therefore kinetic energy of the flow at the interface; these changes, in turn, increases the strength of mixing and therefore the rate at which warm air is brought down to the lower occupied layer. The strong dependence of T_{occ} on R suggests that the lower layer temperature is highly sensitive to variations in the relative areas of the openings, particularly when R is small. This indicates that the control of the indoor thermal environment requires careful control of the relative sizes of the inlet and outlet vents to ensure that the lower layer temperature is maintained within the desired range of temperatures.

We now describe the response of the ventilation of our example classroom to changes in A^* for a given vent area ratio R. For illustrative purposes, we consider $R = 1.5$ in this example. Figure 5.11 shows the effect of A^* (for fixed H) on (a) the Draught number $\mathscr{D}ra$, (b) the interface height h_{occ}, (c) the occupied zone temperature T_{occ}, and (d) the ventilation flow rate Q. In contrast to the previous scenario, Figure 5.11 indicates that there is an increase in the airflow rate through the enclosure and a decrease in the lower layer temperature as A^* is increased.

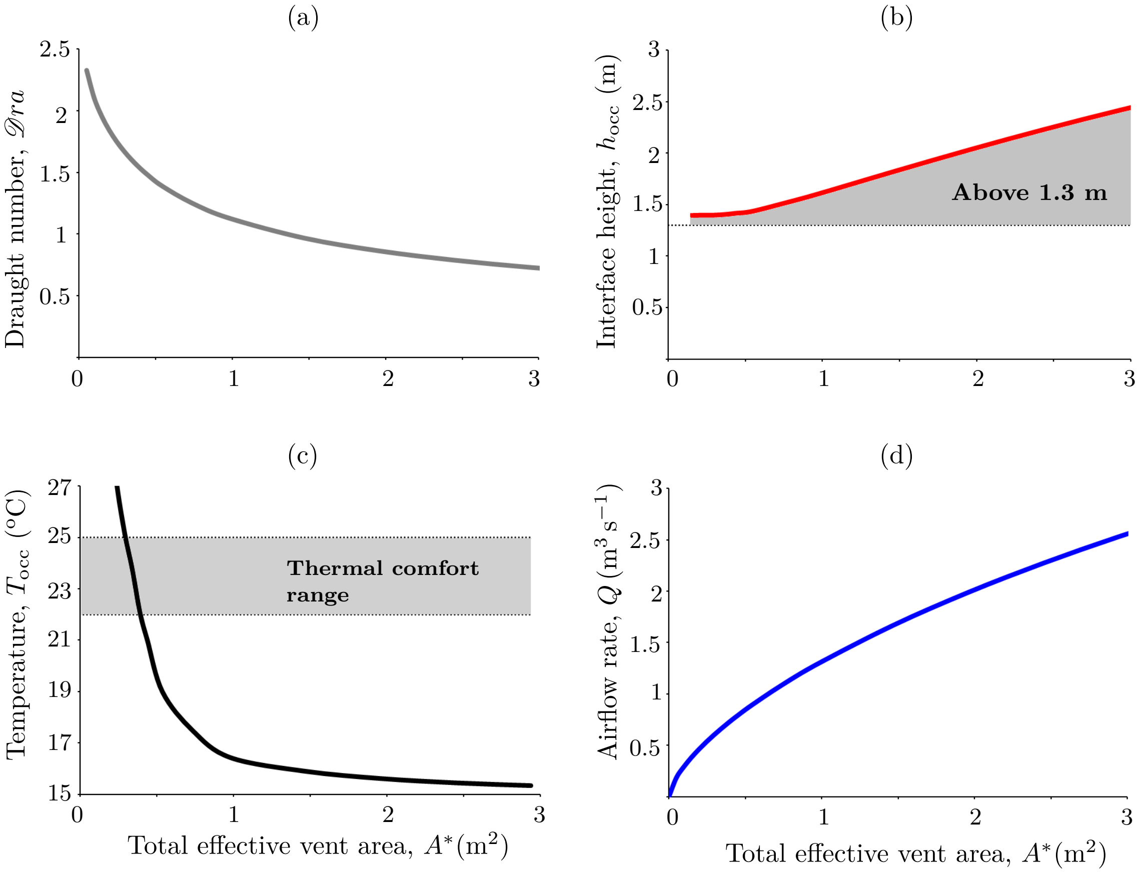


FIGURE 5.11: Plots of (a) the Draught number $\mathscr{D}ra$, (b) the interface height h_{occ} (m), (c) the occupied zone temperature T_{occ} (°C), and (d) the ventilation flow rate Q ($m^3\,s^{-1}$) as functions of the total effective vent area A^* for $R = 1.5$ and $H = 7\,m$.

Q: ***Why does the lower layer temperature decrease when the total effective opening area is increased?***

A: By increasing the total effective opening area, the airflow rate through the room increases; the upper layer decreases in depth and in temperature as it is fed by less buoyant air from the plume. Since the interface is further away from the floor-level openings, the inflowing cool air has to travel over a greater vertical distance through the lower layer prior to reaching the upper layer. This increase in the distance travelled by the inflow is associated with a decrease in its kinetic energy at the interface; there is less kinetic energy available to induce mixing and entrainment of warm air in the upper layer, and thus, the rate at which warm air is transported by the flow across the interface is reduced. Since the temperature of the upper layer decreases as A^* is increased, 'less buoyant' air is carried downwards by the flow, and so, the lower layer temperature decreases. Consequently, the temperature of the upper and lower layers decreases as A^* is increased and the entire room cools.

It is worth pointing out in Figure 5.11(c) that the desired range of comfort temperatures lies only within a narrow range of A^* (approximately between $0.25\,\mathrm{m}^2$ and $0.50\,\mathrm{m}^2$). In practical terms, this means that there is relatively little room for uncertainty in design and reinforces the need for an accurate determination of the effective area of the ventilation openings, and in particular, to reduce errors in estimating the value of the loss coefficients of the openings.

The general effects of A^* and R on passive warming described above are summarised in Figure 5.12, which illustrates how the lower layer depth and temperature both increase as the vent area ratio is increased, while an increase in the total effective area of the openings leads to an increased ventilation flow rate and a reduction in the overall temperature within the room.

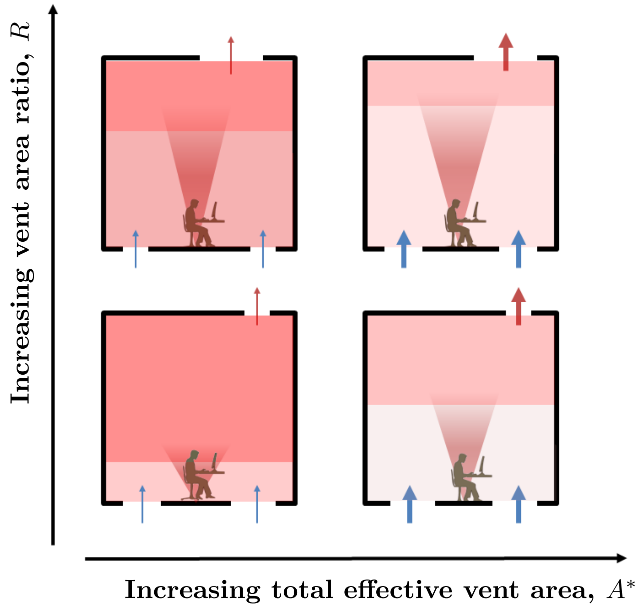


FIGURE 5.12: Schematic illustrating the effect of the vent area ratio R and the total effective vent area A^* on the indoor temperature stratification and bulk airflow rate through the room. Small values of R and A^* produce the shallowest lower layer and smallest ventilation flow rate. Large values of R produce the warmest lower layer, while large values of A^* generate the greatest airflow rate but the coolest lower layer. The intensity of the red shading in the schematics provides a qualitative indication of the temperature of the layer; the darker the shading, the 'hotter' the layer. The thickness of the flow arrows drawn at the openings indicates the magnitude of the airflow rate through the room; the thicker the arrow, the greater the ventilation flow rate.

The aforementioned results have implications for the design of ventilation control strategies, particularly for the control of the relative areas of the openings. Provided the total effective opening area is unaltered, it is possible to independently control the depth and temperature of the lower occupied layer, by adjusting the relative areas of the upper and lower openings only, without affecting the ventilation flow rate through the room. Conversely, for the passive night purging of a room, excess or unwanted heat accumulated during the working day can be partially[2] 'flushed' from the room by increasing the total effective area of the openings.

4. Apart from A^*/H^2 and R, what other variables influence passive warming?

In the previous example we considered the scenario in which both the external air temperature T_{ext} and heating power W are fixed. In practice, internal heat inputs and outdoor air temperatures are likely to vary over the course of the day. Moreover, the basic building shape and height, while usually dictated by the architect, may be influenced by factors such as the site plan and local planning requirements, for example. In addition to the size of the façade openings, variations in the outdoor air temperature, internal heat inputs and the choice of building geometry can impact the room stratification, indoor air temperature and rates of ventilation, and therefore need to be accounted for when designing for a passive warming strategy.

As a quick visual summary, Figure 5.13 illustrates how the ventilation flow rate and indoor temperature of an example room respond to changes in (a) the heating power W of the line source, (b) the outdoor air temperature T_{ext}, (c) the room height H, and (d) the room length L. We stress that these schematics are intended only to highlight, qualitatively, the possible impact of these different variables on passive warming. Each of the four scenarios shown have identical values of A^* and R. Note that in Figure 5.13(d), the heating power *per unit length* of the line source is assumed constant along the length of the room, albeit the *total* heat supply rate to the interior increases as the room length is increased, *e.g.* increasing the number of occupants (with equal per person heat inputs), but the spacing between the occupants remains the same.

Broadly, Figure 5.13 illustrates that for fixed values of A^* and R, an increase in the heating power W results in an increased lower layer depth and temperature, while an increase in the outdoor temperature T_{ext} and room length L leads to a deepening of the upper layer and a shallow lower layer. Conversely, an increase in the floor-to-ceiling height H leads to an increased interface position and ventilation flow rate.

[2]In practice, it is generally a good idea to keep a layer of relatively warm air at the top of the room in order to drive the ventilating flow.

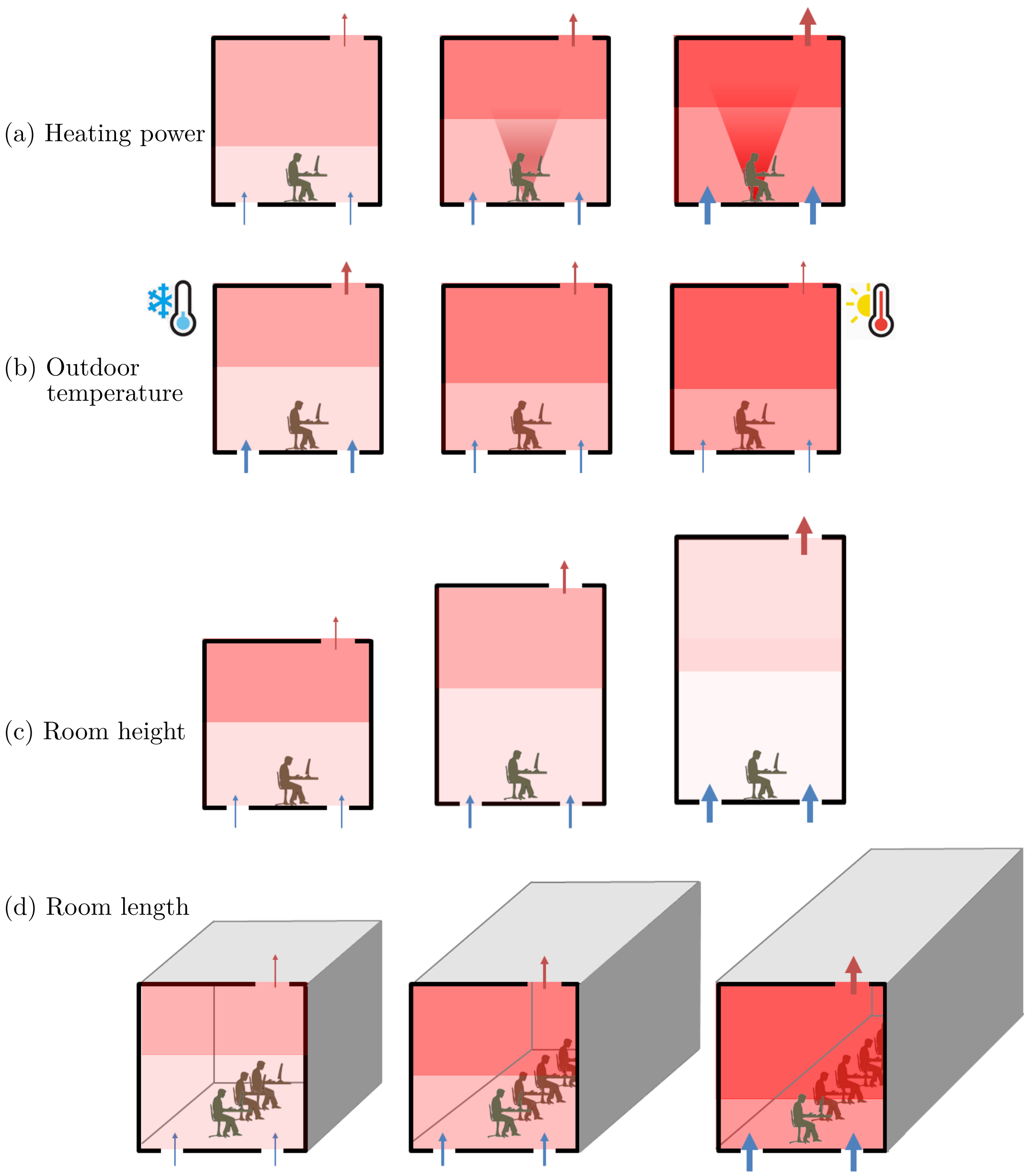


FIGURE 5.13: Schematics of a naturally ventilated room in elevation illustrating how (a) the heat source strength W (for fixed H, L and T_{ext}), (b) the outdoor air temperature T_{ext} (for fixed W, H and L), (c) the room height H (for fixed W, L and T_{ext}), and (d) the room length L (for fixed H, T_{ext} and source strength per unit length) affect the temperature stratification and ventilation flow rate. The total effective vent area A^* and vent area ratio R are identical in all four scenarios. To avoid clutter, mixing by the inflow of cool air in the room is not drawn in the schematics.

5.9 Design guidance for passive warming

We propose a methodology, centred around hand calculations and the use of design charts, to inform the preliminary sizing of openings. We first provide an overview of our approach in §5.9.1 using schematics only. Calculation steps involved in the methodology are summarised in §5.9.2 and design charts used in our methodology are shown in §5.9.3. Finally, in §5.10 a worked example is presented to show how the methodology can be applied in practice.

5.9.1 Overview of our general approach

The three plots in Figure 5.14 summarise our basic approach to determine the suitable areas of the openings and are a 'stripped back' illustration of how the design charts (Figures 5.16 and 5.17 in §5.9.3) are used. These plots relate the dimensionless effective opening area, A^*/H^2, and the vent area ratio, $R = a_\mathrm{t}/a_\mathrm{b}$, to the core design quantities, namely ventilation flow rates, interface heights and occupied zone temperatures.

Figure 5.14(a) is a plot of R (vertical axis) against A^*/H^2 (horizontal axis) showing contours of constant lower layer temperature T_occ. The arrow drawn on the plot points in the direction of increasing temperature, with higher temperature contours at smaller values of A^*/H^2 (*i.e.* from right to left of the plot). The first step is to identify the contour corresponding to the desired occupied zone temperature, say $T_\mathrm{occ} = T^*_\mathrm{occ}$, as illustrated in bold in Figure 5.14(a).

The next step is to identify the pair of A^*/H^2 and R along the line of T^*_occ which will achieve the required ventilation flow rate, say $Q = Q_\mathrm{req}$. Figure 5.14(b) plots contours of constant ventilation flow rate (in blue) and lower layer temperature (in black) on a single set of axes with R on the vertical axis and A^*/H^2 on the horizontal axis. Note how the contours corresponding to T^*_occ and Q_req intersect, as marked by the symbol '•' on the plot. The pair of A^*/H^2 and R needed to achieve the target design requirements can then be determined by finding the intersection of the lines of T^*_occ and Q_req, *i.e.* reading vertically downwards from the intersection to the horizontal axis to determine the required value of A^*/H^2, and reading horizontally across from the intersection to the vertical axis to determine the corresponding value of R.

For the required pair of A^*/H^2 and R, say $A^*/H^2 = \mathrm{X}$ and $R = \mathrm{Y}$, the third step is to determine the position of the interface separating the relatively warm air above and the occupied zone beneath. From a comfort perspective, the height of the interface is a critical design quantity, as it is imperative to ensure that the interface is located above the occupied level, whilst still ensuring that the desired temperature is maintained.

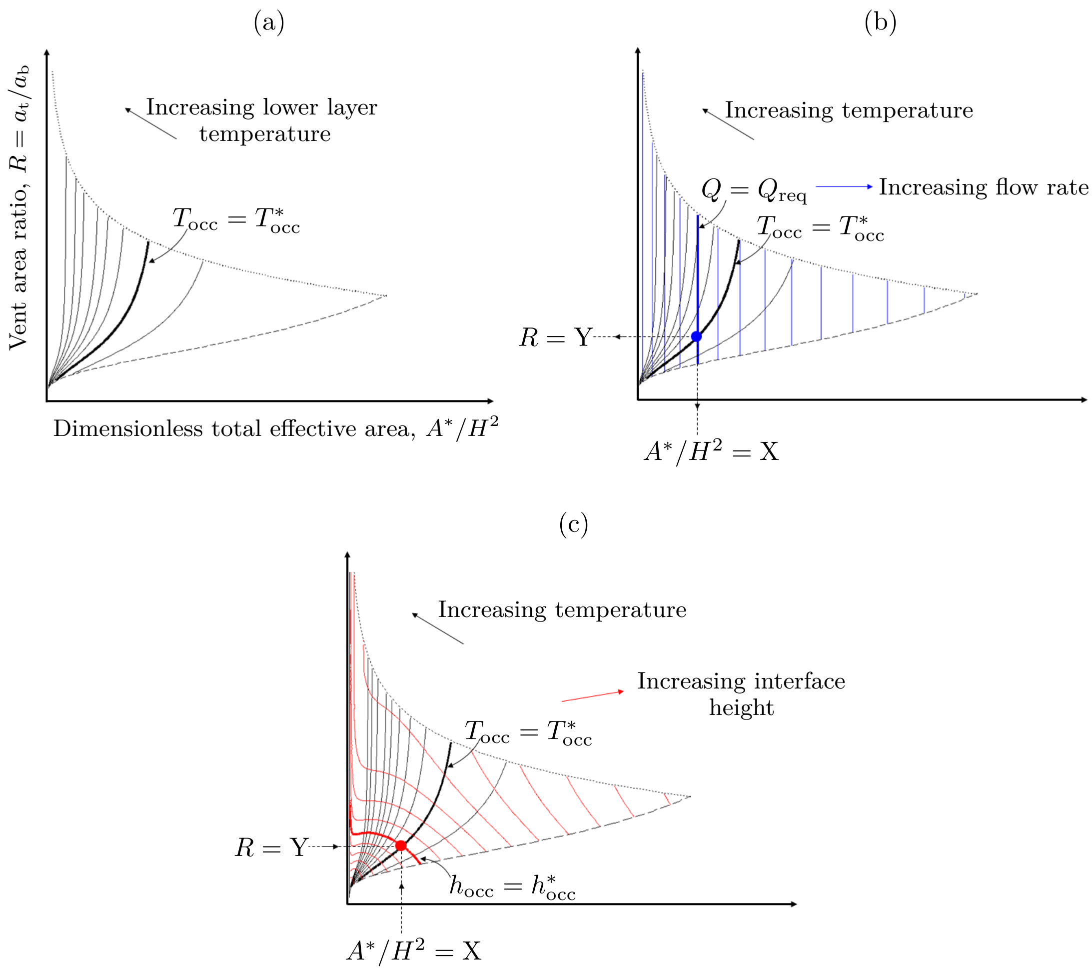


FIGURE 5.14: Annotated design charts showing the relationship between the vent area ratio R (vertical axis), the dimensionless effective vent area A^*/H^2 (horizontal axis), the occupied zone temperature T_{occ}, the airflow rate Q, and the interface height h_{occ}. Contours of constant T_{occ} are shown in black, Q in blue and h_{occ} in red. Dotted and dashed lines denote the critical values of the Direction and Draught numbers, respectively. Note that we have only drawn the contours for the portion of the $\{A^*/H^2, R\}$-space where unidirectional flow and internal mixing occur.

Figure 5.14(c) plots R against A^*/H^2 with superimposed contours of constant interface height h_{occ} (in red) and lower layer temperature T_{occ} (in black). In order to determine the height of the interface, a line is drawn vertically upwards from $A^*/H^2 = \mathrm{X}$ and horizontally across from $R = \mathrm{Y}$ until both lines intersect (as shown at the point marked '•'). The interface height can then be determined by identifying the value of the red contour where the lines of $A^*/H^2 = \mathrm{X}$ and $R = \mathrm{Y}$ meet, *i.e.* at $h_{occ} = h^*_{occ}$. If the interface is below the occupant level, the interface may be raised by increasing the vent area ratio R until h_{occ} satisfies $h_{occ} > h_{head}$, where h_{head} is the head height of occupants. Note, however, that an increase in R will result in an increased lower layer temperature. In order to maintain the occupied zone temperature at the desired value (*i.e.* $T_{occ} = T^*_{occ}$), both the vent area ratio

R *and* the effective vent area A^*/H^2 need to be increased; this, in turn, will result in an increased ventilation flow rate through the enclosure such that $Q > Q_{\mathrm{req}}$.

5.9.2 Summary of design steps

The design procedure to size ventilation openings, based on the approach outlined above, is summarised by the flow chart in Figure 5.15.

The design charts, **'Design Chart A'** and **'Design Chart B'**, used in the methodology are presented in §5.9.3. Note that, unlike the previous plots shown in Figure 5.14, the design charts are now framed in terms of $(A^*/H^2)(L/H)^{-1}$ and R; the contours corresponding to lower layer temperatures, ventilation rates and interface heights are plotted in dimensionless form and are quantities denoted by 'hats' (the dimensionless ventilation flow rate is denoted $\widehat{Q}$, for example). We express these quantities in dimensionless form as their use enable the design charts to be applied to a broad range of situations (*e.g.* different room heights, heat inputs and outdoor air temperatures). As such, the design charts are capable of providing extremely rapid guidance by removing the need to solve a system of coupled non-linear algebraic equations (*i.e.* the governing equations derived in §5.3 of Part I) for every design scenario.

The design procedure to size ventilation openings consists of five calculation steps, as described below. The necessary mathematical equations used in the methodology are obtained from the analysis in §5.3 and are reiterated here using 'architectural' notation and terminologies given in Table 5.3.

Step 1: Based on the desired temperature difference between the occupied zone and the outdoor environment, $\Delta T^* = T^*_{\mathrm{occ}} - T_{\mathrm{ext}}$, calculate the relative temperature of the lower occupied layer in terms of a reduced gravity, g'^*_{occ}:

$$g'^*_{\mathrm{occ}} = g\left(\frac{\Delta T^*}{273 + T_{\mathrm{ext}}}\right)$$

In order to use the design charts, the value of g'^*_{occ} needs to be converted into dimensionless form. The dimensionless relative temperature of the lower layer is given by

$$\widehat{g'^*_{\mathrm{occ}}} = \frac{g'^*_{\mathrm{occ}}}{2.3(B/L)^{2/3}H^{-1}} \quad ; \quad B = \frac{gW}{\rho_{\mathrm{ext}} c_{\mathrm{p}}(273 + T_{\mathrm{ext}})}$$

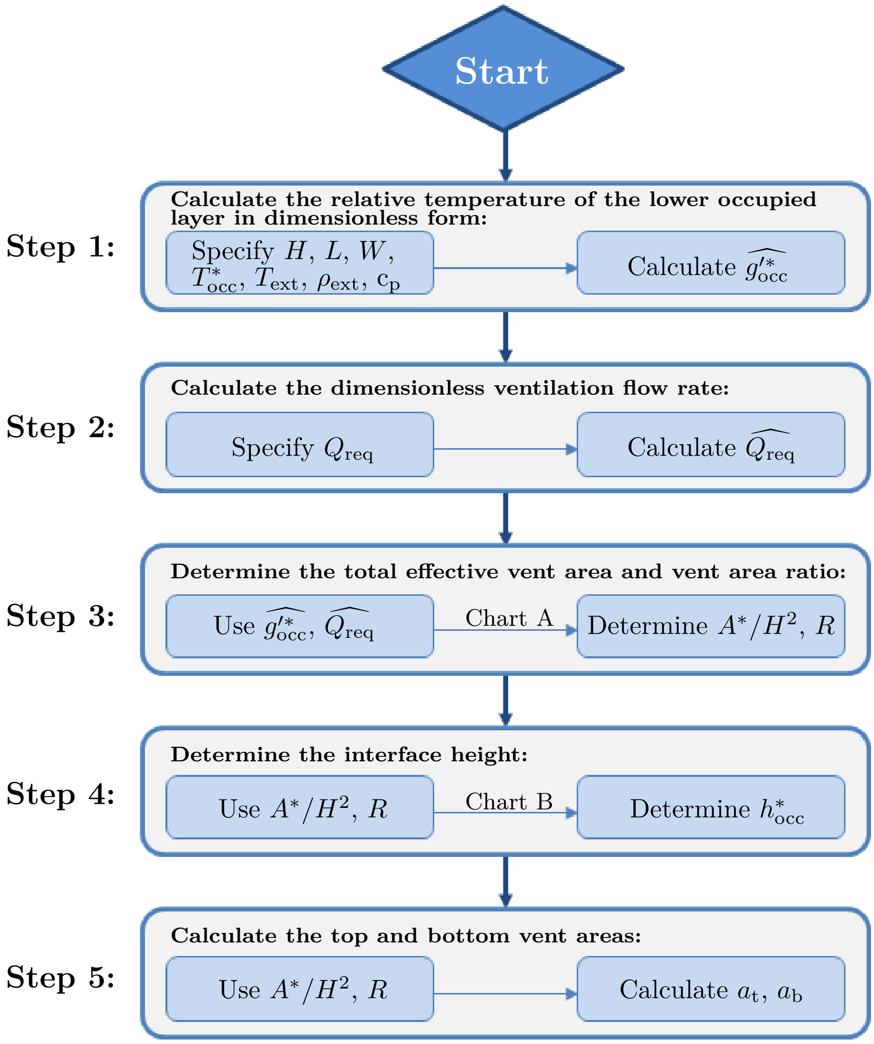


FIGURE 5.15: Flow chart outlining the five key steps to size ventilation openings for passive warming. Each step is discussed in more detail, and key equations are reiterated, in the accompanying text. The design charts, Chart A and Chart B, are presented in Figures 5.16 and 5.17, respectively.

where H and L are the height and length of the room, respectively (see Figure 5.9 for an illustration), and B is the heat supply rate (or heat flux) to the interior and is described in terms of the heating power W (in Watts).

Step 2: Similar to step 1, express the required (or desired) value of the ventilation flow rate, $Q_{\rm req}$, in dimensionless form:

$$\widehat{Q_{\rm req}} = \frac{Q_{\rm req}}{0.43(B/L)^{1/3}HL}$$

Step 3: Using **Design Chart A** (Figure 5.16), find the intersection of the contours corresponding to $\widehat{g'^*_{\mathrm{occ}}}$ (step 1) and $\widehat{Q_{\mathrm{req}}}$ (step 2); read vertically downwards from the intersection to determine the required value of $(A^*/H^2)(L/H)^{-1}$ on the horizontal axis, and then read horizontally across from the intersection to determine the corresponding value of the vent area ratio R on the vertical axis. Next, multiply the value of $(A^*/H^2)(L/H)^{-1}$ by L/H to determine the (dimensionless) effective area of the openings, *i.e.* $A^*/H^2 = (A^*/H^2)(L/H)^{-1} \times L/H$.

Step 4: Using **Design Chart B** (Figure 5.17), draw a vertical line upwards from the selected value of $(A^*/H^2)(L/H)^{-1}$ and a horizontal line across from the value of R until both of these lines intersect. At this intersection, identify the value of $\widehat{h^*_{\mathrm{occ}}}$ (dimensionless interface height) on the red contour line. Next, convert $\widehat{h^*_{\mathrm{occ}}}$ into a physical height by multiplying the value of $\widehat{h^*_{\mathrm{occ}}}$ by the room height, *i.e.* $h^*_{\mathrm{occ}} = \widehat{h^*_{\mathrm{occ}}} \times H$. Ensure that the level of the interface is above the head height of occupants.

Step 5: For the chosen pair of A^*/H^2 and R, calculate the physical areas of the ceiling-level opening, a_{t}, and the combined area of the two floor-level openings, a_{b}, respectively:

$$a_{\mathrm{t}} = \frac{1}{0.6\sqrt{2}} \left(\frac{A^*}{H^2}\right) (R^2+1)^{1/2} H^2 \quad \text{and}$$

$$a_{\mathrm{b}} = \frac{1}{0.6\sqrt{2}} \left(\frac{A^*}{H^2}\right) \left(\frac{1}{R^2}+1\right)^{1/2} H^2$$

5.9.3 Design charts

The derived equations describing the relationship between internal mixing and the core design quantities, namely the lower layer temperature (5.22), ventilation flow rate (5.23), and interface height (5.24) were solved simultaneously using a numerical computational tool, MATLAB 2014a, to produce the dimensionless design charts (Chart A and Chart B in Figures 5.16 and 5.17). The design charts are framed in terms of $(A^*/H^2)(L/H)^{-1}$ on the horizontal axis and R on the vertical axis. Contour lines shown on the charts represent dimensionless ventilation flow rates (blue lines), $\widehat{Q}$, relative lower layer temperatures (black lines), $\widehat{g'_{\mathrm{occ}}}$, and interface heights (red lines), $\widehat{h_{\mathrm{occ}}}$.

For convenience and clarity, Table 5.4 provides a quick summary of the key properties of the design charts, specifically the dimensionless quantities plotted, the contour interval chosen, and at which step of the methodology each design chart is used. Regarding the particular choice of contour spacing, we wanted to use a spacing that could strike a balance between 'legibility' (*i.e.* the contours are suitably spaced apart so that they can be clearly distinguished) and 'applicability' (*i.e.* the contours are sufficiently close together so that the required values can be read off easily from the chart).

	Design Chart	
Design quantity	**A**	**B**
Relative temperature, $\widehat{g'_{\text{occ}}}$	Intervals of 1.0	Intervals of 1.0
Airflow rate, $\widehat{Q}$	Intervals of 0.015	
Interface height, $\widehat{h_{\text{occ}}}$		Intervals of 0.01
Design step	Step 3	Step 4

TABLE 5.4: Summary of the key properties of the design charts, such as the contour interval chosen and the design quantity plotted (shaded in grey).

5.10 Application to an example room

To provide a better feel for how the design charts may be applied in practice, we revisit the example classroom described earlier in §5.8 (see Figure 5.9). The design requirements for the classroom are summarised in Table 5.5. Following the design procedure outlined in §5.9.2, each calculation step (from 1 to 5) are shown in detail below and the results are given to two significant figures. For clarity, the key results from each calculation step is summarised in Table 5.6.

Design conditions	
Net floor area	$49\,\text{m}^2$
Room height, H	$7\,\text{m}$
Room length, L	$7\,\text{m}$
Estimated number of occupants	15
Total heat input, W	$14\,\text{kW}$
Outdoor temperature, T_{ext}	15°C
Design requirements	
Seated head height	$1.3\,\text{m}$
Desired occupied zone temperature, T^*_{occ}	22°C
Minimum per person air supply rate	$10\,\text{L}\,\text{s}^{-1}$

TABLE 5.5: Summary of the design conditions and specific requirements for the naturally ventilated classroom.

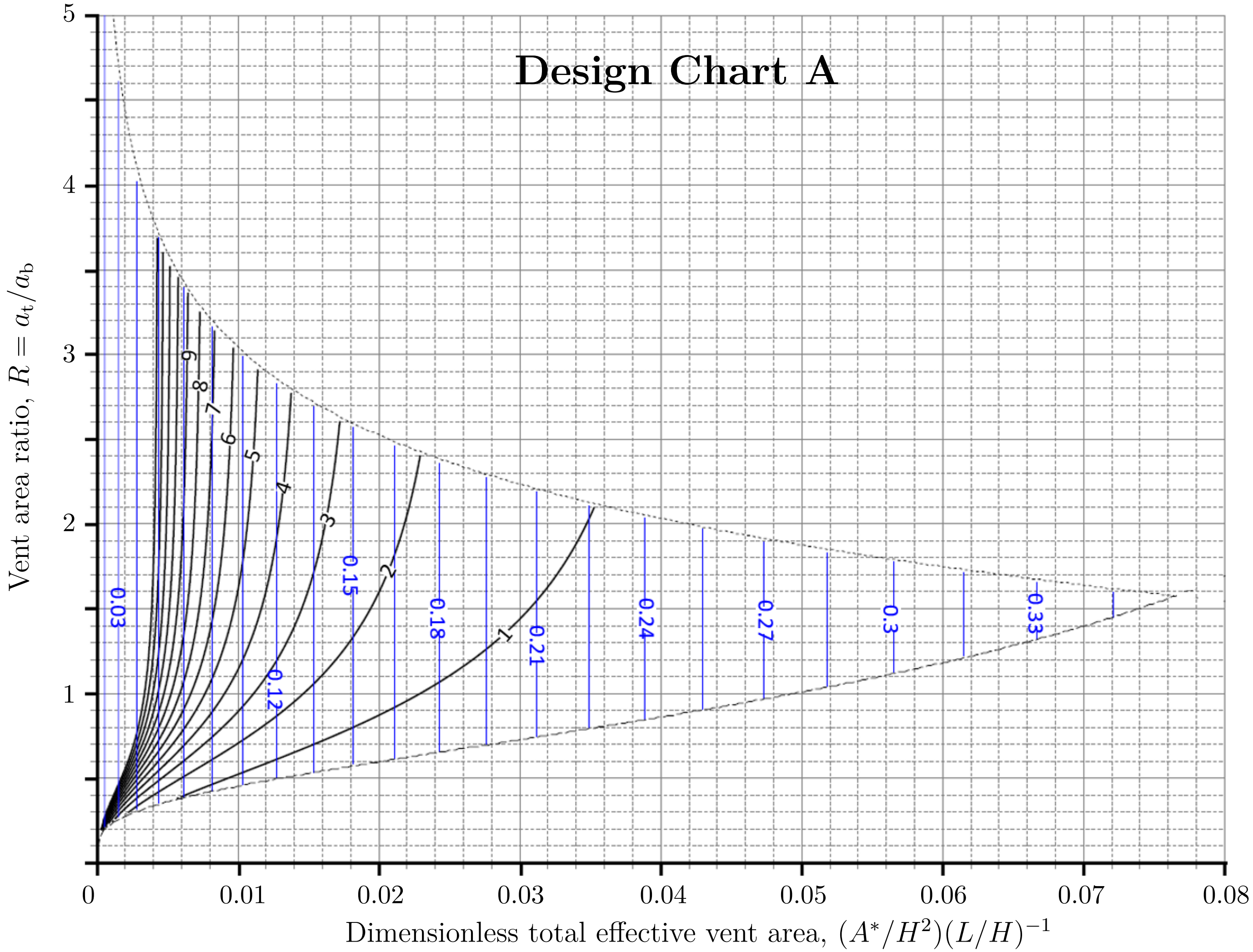


FIGURE 5.16: Design Chart A showing the relationship between R (vertical axis) and $(A^*/H^2)(L/H)^{-1}$ (horizontal axis), and the primary dimensionless quantities $\widehat{Q}$ (blue contours) and $\widehat{g'_{occ}}$ (black contours).

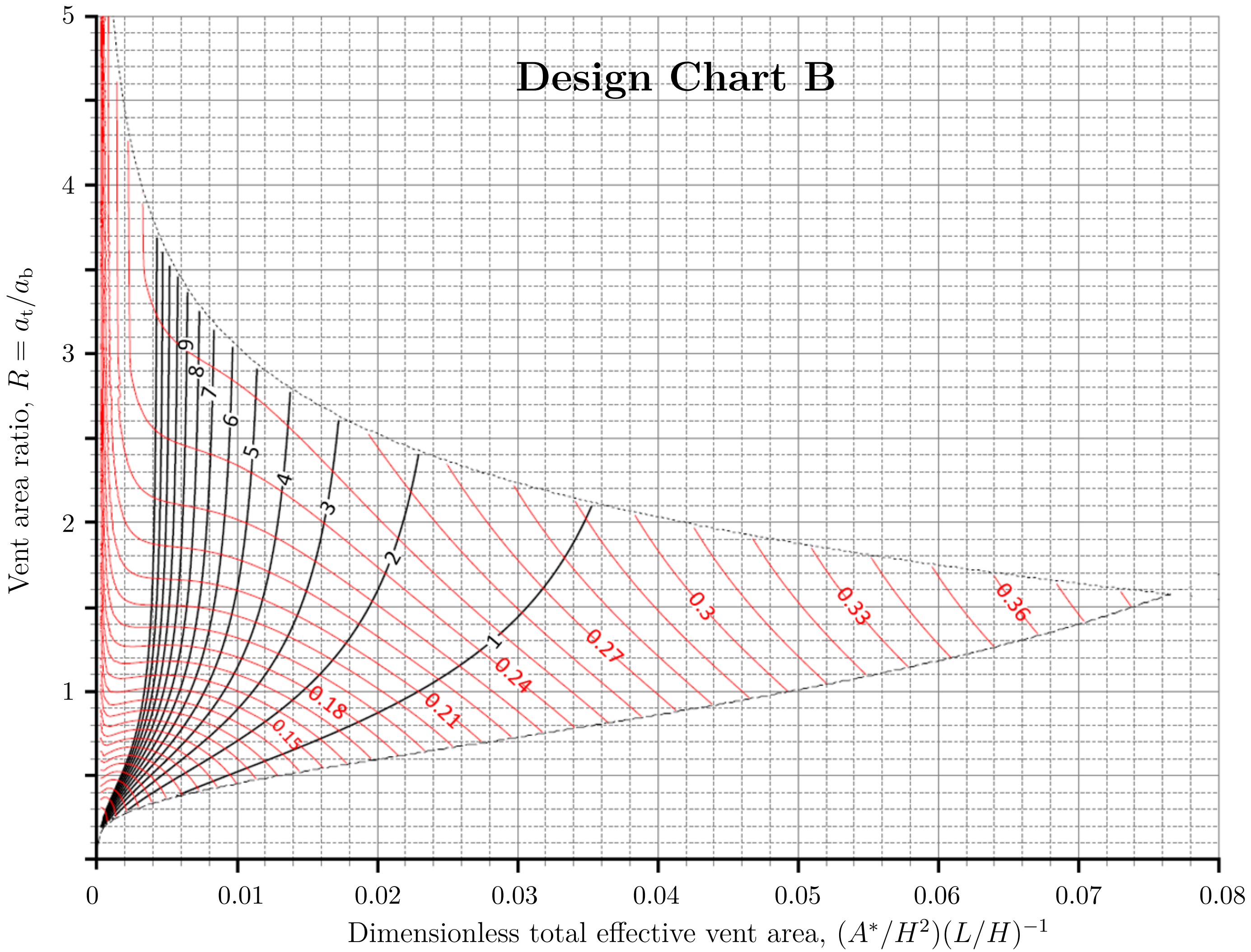


FIGURE 5.17: Design Chart B showing the relationship between R (vertical axis) and $(A^*/H^2)(L/H)^{-1}$ (horizontal axis), and the primary dimensionless quantities $\widehat{h_{\rm occ}}$ (red contours) and $\widehat{g'_{\rm occ}}$ (black contours).

Step 1: For $T_{\text{ext}} = 15^{\text{o}}$C and $T_{\text{occ}} = 22^{\text{o}}$C, the desired temperature difference relative to the outdoor environment is

$$\begin{aligned} g'^{*}_{\text{occ}} &= g\left(\frac{T^{*}_{\text{occ}} - T_{\text{ext}}}{273 + T_{\text{ext}}}\right) \\ &= 9.81 \times \left(\frac{22 - 15}{273 + 15}\right) \\ &= 0.24\,\text{m}\,\text{s}^{-2} \end{aligned}$$

For outdoor air at 15^{o}C, the air density $\rho_{\text{ext}} = 1.2\,\text{kg}\,\text{m}^{-3}$ and specific heat capacity $\text{c}_{\text{p}} = 1007\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$ (Cimbala & Çengel, 2008). Taking $W = 14\,\text{kW}$, the total heat supply rate to the interior is

$$\begin{aligned} B &= \frac{gW}{\rho_{\text{ext}}\text{c}_{\text{p}}(273 + T_{\text{ext}})} \\ &= \frac{9.81 \times 14 \times 1000}{1.2 \times 1007 \times (273 + 15)} \\ &= 0.39\,\text{m}^4\,\text{s}^{-3} \end{aligned}$$

The dimensionless relative temperature of the occupied zone is therefore

$$\begin{aligned} \widehat{g'^{*}_{\text{occ}}} &= \frac{g'^{*}_{\text{occ}}}{2.3(B/L)^{2/3}H^{-1}} \\ &= \frac{0.24}{2.3 \times (0.39/7)^{2/3} \times (1/7)} \\ &= 5.0 \end{aligned}$$

Step 2: The recommended per person fresh air supply rate for a typical classroom is $10\,\text{L}\,\text{s}^{-1}$ (CIBSE, 2006). At full capacity, the classroom is occupied by 15 students (assumed to be seated shoulder-to-shoulder in the centre and along the length of the room). The minimum fresh air supply rate for 15 students, Q_{min}, is $0.15\,\text{m}^3\,\text{s}^{-1}$ (*i.e.* $Q_{\text{min}} = 15 \times 10/1000$).

From Design Chart A, we can see that the largest possible value of $\widehat{Q}$, at which $\widehat{Q}$ intersects with the contour corresponding to $\widehat{g'^{*}_{\text{occ}}} = 5.0$, is approximately 0.11 (see Figure 5.18 for an illustration). This gives a maximum ventilation flow rate of

$$\begin{aligned} Q &= \widehat{Q} \times [0.43(B/L)^{1/3}HL] \\ &= 0.11 \times [0.43 \times (0.39/7)^{1/3} \times 7 \times 7] \\ &= 0.89\,\text{m}^3\,\text{s}^{-1} \end{aligned}$$

which is approximately six times the recommended minimum air supply rate. To ensure that the ventilation flow rate through the classroom exceeds the recommended minimum value, we consider the case in which the design ventilation rate $Q_{\text{req}} = 0.89\,\text{m}^3\,\text{s}^{-1}$ ($\widehat{Q_{\text{req}}} = 0.11$).

Step 3: Using **Design Chart A**, identify the point at which the contours corresponding to $\widehat{g'^{*}_{\text{occ}}} = 5.0$ and $\widehat{Q_{\text{req}}} = 0.11$ intersect. Note that the contour corresponding to $\widehat{Q_{\text{req}}} = 0.11$ lies roughly midway between $\widehat{Q} = 0.105$ and $\widehat{Q} = 0.12$ (since contours of $\widehat{Q}$ in Design Chart A are plotted in intervals of 0.015). In this case, the intersection of the contours of $\widehat{g'^{*}_{\text{occ}}} = 5.0$ and $\widehat{Q_{\text{req}}} = 0.11$ can only be inferred by eye, and the values of $(A^*/H^2)(L/H)^{-1}$ and R corresponding to this intersection point are estimated to be, respectively,

$$(A^*/H^2)(L/H)^{-1} = 0.011 \quad \text{and} \quad R = 2.5$$

Figure 5.18 illustrates how Design Chart A is used to determine the required pair of $(A^*/H^2)(L/H)^{-1}$ and R. For this specific example, each contour line of $\widehat{g'_{\text{occ}}}$ in the chart represents approximately a 1.4°C increment in temperature, while each line of $\widehat{Q}$ corresponds to approximately a $0.12\,\text{m}^3\,\text{s}^{-1}$ increment in airflow rate.

Step 4: Using **Design Chart B**, the dimensionless height of the interface is approximately

$$\widehat{h^{*}_{\text{occ}}} = 0.245$$

which is found by drawing a line vertically upwards from $(A^*/H^2)(L/H)^{-1} = 0.011$ and then horizontally across from $R = 2.5$ until both lines intersect, as illustrated in Figure 5.19. Note that, since the intersection point lies roughly midway between the contours of $\widehat{h_{\text{occ}}} = 0.24$ and $\widehat{h_{\text{occ}}} = 0.25$, the value of $\widehat{h^{*}_{\text{occ}}}$ is estimated only by eye. For the classroom with floor-to-ceiling height $H = 7\,\text{m}$, the physical height of the interface thus is approximately

$$\begin{aligned} h^{*}_{\text{occ}} &= 0.245 \times 7 \\ &= 1.7\,\text{m} \end{aligned}$$

which is about 0.4 m above the head height of occupants.

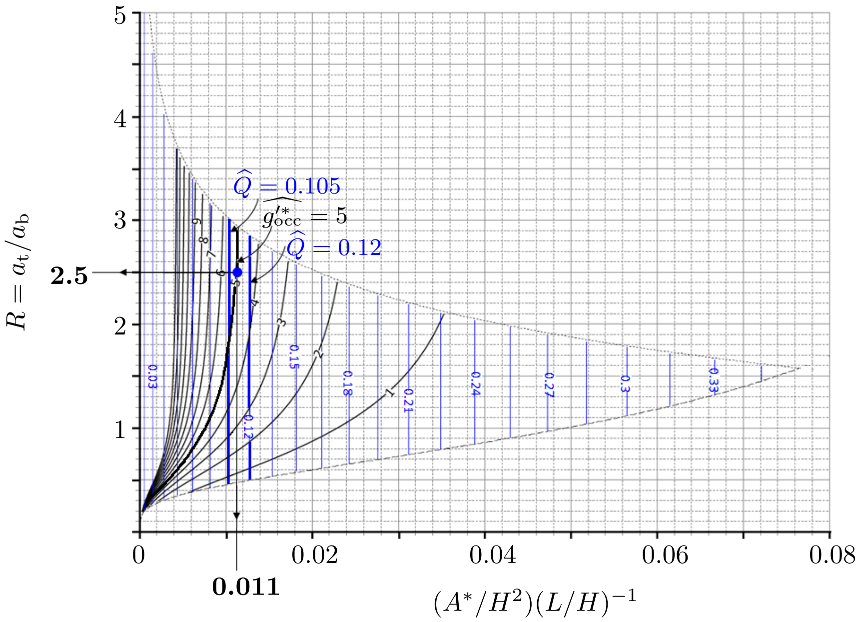


FIGURE 5.18: Illustrative example showing how Design Chart A is used to determine the required pair of $(A^*/H^2)(L/H)^{-1}$ and R. The point at which the contours corresponding to $\widehat{Q_{\rm req}} = 0.11$ ($Q_{\rm req} = 0.89\,{\rm m^3\,s^{-1}}$) and $\widehat{g'^*_{\rm occ}} = 5$ ($T^*_{\rm occ} = 22^{\rm o}$C) intersect is marked at the point '•' on the plot.

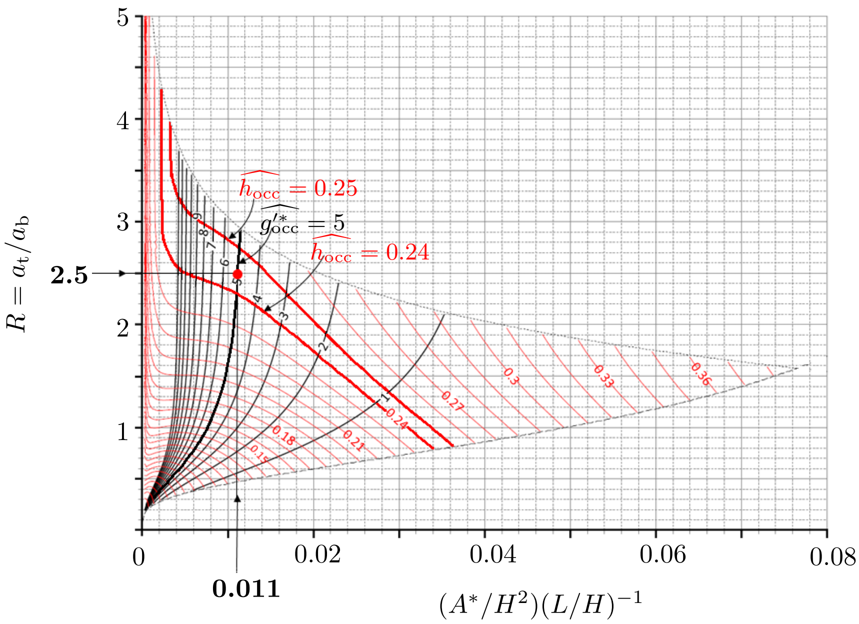


FIGURE 5.19: Illustrative example showing how Design Chart B is used to find the value of $\widehat{h^*_{\rm occ}}$ for $(A^*/H^2)(L/H)^{-1} = 0.011$ and $R = 2.5$. The symbol '•' on the plot marks the point at which the vertical line (corresponding to $(A^*/H^2)(L/H)^{-1} = 0.011$ on the horizontal axis) and the horizontal line (corresponding to $R = 2.5$ on the vertical axis) intersect. This intersection lies roughly midpoint between the contours corresponding to $\widehat{h_{\rm occ}} = 0.24$ ($h_{\rm occ} = 1.68\,$m) and $\widehat{h_{\rm occ}} = 0.25$ ($h_{\rm occ} = 1.75\,$m) on the plot.

Step 5: For $L = 7\,\mathrm{m}$ and $H = 7\,\mathrm{m}$, the dimensionless effective area of the openings $A^*/H^2 = 0.011 \times (7/7)^{-1} = 0.011$. Therefore, the area of the opening at the ceiling level is

$$\begin{aligned} a_\mathrm{t} &= \frac{1}{0.6\sqrt{2}}\left(\frac{A^*}{H^2}\right)(R^2+1)^{1/2}H^2 \\ &= \frac{1}{0.6\times\sqrt{2}} \times (0.011) \times (2.5^2+1)^{1/2} \times 7^2 \\ &= 1.7\,\mathrm{m}^2 \end{aligned}$$

and the corresponding total area of the two floor-level openings is

$$\begin{aligned} a_\mathrm{b} &= \frac{1}{0.6\sqrt{2}}\left(\frac{A^*}{H^2}\right)\left(\frac{1}{R^2}+1\right)^{1/2}H^2 \\ &= \frac{1}{0.6\times\sqrt{2}} \times (0.011) \times \left(\frac{1}{2.5^2}+1\right)^{1/2} \times 7^2 \\ &= 0.68\,\mathrm{m}^2 \end{aligned}$$

The above steps (from 1 to 5) can be repeated for a range of indoor and outdoor air temperatures, heat source strengths and room geometries. As an illustrative example, Table 5.6 shows a comparison between the opening areas required to provide an occupied zone temperature of 20°C, 22°C and 24°C when $T_\mathrm{ext} = 15$°C. In each of the three scenarios, $H = 7\,\mathrm{m}$, $L = 7\,\mathrm{m}$, and the total heat supply rate, W, is 14 kW (or, equivalently, $B = 0.39\,\mathrm{m}^4\,\mathrm{s}^{-3}$). Quantitative predictions of the interface height and ventilation flow rate for each design scenario are also shown in the table.

Symbol	**Occupied zone temperature**		
T_occ (°C)	**20**	**22**	**24**
A^*/H^2	0.011	0.011	0.009
A^* (m^2)	0.54	0.54	0.44
R	1.4	2.5	2.5
a_t (m^2)	1.1	1.7	1.4
a_b (m^2)	0.78	0.68	0.56
Q ($\mathrm{m}^3\,\mathrm{s}^{-1}$)	0.89	0.89	0.78
h_occ (m)	1.5	1.7	1.7

TABLE 5.6: Quantitative predictions of the design opening areas for three different occupied zone temperatures. Values have been calculated for the naturally ventilated classroom with $H = 7\,\mathrm{m}$, $L = 7\,\mathrm{m}$ and $W = 14\,\mathrm{kW}$.

For the example shown, note that it is not possible to provide an occupied zone temperature of 24°C without decreasing the total effective area of the openings (from $A^* = 0.54\,\mathrm{m}^2$ to $A^* = 0.44\,\mathrm{m}^2$). This will subsequently lead to a decrease in the ventilation flow rate through the room (from $Q = 0.89\,\mathrm{m}^3\,\mathrm{s}^{-1}$ to $Q = 0.78\,\mathrm{m}^3\,\mathrm{s}^{-1}$). However, an airflow rate of $0.78\,\mathrm{m}^3\,\mathrm{s}^{-1}$ still exceeds the minimum recommended value of $0.15\,\mathrm{m}^3\,\mathrm{s}^{-1}$ (for 15 occupants) by a factor of around five.

5.11 Conclusion

Following the core ethos of this thesis, the key results of the analysis of Part I have been interpreted and explained in the context of a natural ventilation design. The primary objective of the work was to draw some qualitative understanding of the ventilation system from our analysis and to convey this understanding in an accessible format to inform preliminary design. By focussing on a specific heat source geometry, stratification pattern and opening arrangement, a relatively simple algorithm, centred around hand calculations and the use of design charts, was developed to facilitate the rapid sizing of ventilation openings to provide passive warming of a room. The algorithm is presented in a step-by-step format and summarised in Figure 5.15.

Unlike the previous chapter, the algorithm proposed herein is based on a 'two-zone' modelling approach in which the indoor environment is divided up into two distinct thermal zones. First, we made the distinction between the lower (typically occupied) layer – where temperatures must be carefully controlled – and an upper (unoccupied) layer above the interface – where generally higher temperatures are permissible. A region of localised mixing by the inflowing cool draught of air at the interface was also included in our two-zone model. By separating the interior up into two thermal zones, we were able to develop a relatively simplified mathematical model in Part I to capture some of the effects of internal mixing on the steady flow and stratification in a ventilated room. Specifically, our two-zone model enabled a more detailed insight into the response of the ventilation system, such as the interface position and the apportioning of the accumulated heat between the upper and lower layers, to changes in the size and relative areas of the openings. Such effects would not have been possible to fully capture if a 'single-zone' (or 'well-mixed') model was instead considered.

In developing our mathematical model and thus design algorithm herein, we have intentionally neglected heat losses through the building fabric, and assumed the façade openings are 'sharp-edged' and not protected by baffles, grilles or other obstacles that affect the nature of airflow through the openings. We have also focussed on one particular heat source geometry and opening arrangement. We could have extended the model to investigate a range of opening arrangements (with multiple, unequal opening areas at floor level, for example), or instead to consider the heat inputs as multiple line sources (rather than a single source), as per the heat generated by multiple rows of occupants in a lecture hall. However, by including the aforementioned effects in the mathematical model, we anticipate that the fluid mechanics involved in the analysis would add significant detail and complexity to the model due, in part, to the increased number of interacting factors and interdependent variables to consider, and thus to solve for. This would undoubtedly complicate the necessary 'step-by-step' calculation process of our algorithm even further, which in turn might lessen its appeal and applicability for use in preliminary design, thereby defeating the core aim of this work.

Whilst architects might wish to use a mathematical model which, in their eyes, represents 'reality' as close as possible, the value of such a model would likely be lost in a labyrinth of detail and complexity, which would only serve to shroud understanding and hamper effective communication. The greater the complexity of the model, the more difficult it may be to extract, interpret and generalise the results into a straightforward and usable design format. Indeed, the model should be detailed enough to capture the essential physics of the ventilation to a sufficient extent and to retain its mathematical rigour. However, even if the model could capture all of the complex effects of the ventilating flow down to every last detail, the underlying question still remains as to whether the results obtained from such a model would be of value to architects. Ultimately, there is then a play-off to be made between the complexity of a model and how relevant or applicable the results may be to architects in support of their design decision-making at the drafting board.

Chapter 6

Conclusion

From the outset, the fundamental aim of this research has been towards bolstering the transfer and delivery of knowledge on natural ventilation from the fluid mechanics literature to an architectural audience. Specifically, the research focussed on developing methods to communicate the fundamental physics (*e.g.* the complex terminologies and mathematical formulae encountered) governing natural ventilation flows into formats that can be readily used by architects in preliminary design. Moreover, new practical solutions, based on the development of robust simplified mathematical models, to commonly experienced problems arising in design have been proposed and ultimately conveyed into rapid and intuitive guidance, which we anticipate will potentially be of benefit to the architectural and building design communities.

The genesis of my own personal interest in low-energy building ventilation, an interest which has evolved into the pursuit for a Ph.D. in the field, began during the course of my undergraduate studies in Imperial College London. Beginning with the UROP (Undergraduate Research Opportunities Programme) project in the summer of 2009 and then my undergraduate final year project in 2010, both projects under the supervision of Professor G.R. Hunt, I became increasingly aware of the polar divide in the types of information on natural ventilation available to architects and technical practitioners. Whilst the physics of natural ventilation are widely documented in the fluid mechanics literature, the bulk of this material is written using a highly specific set of terminologies and mathematical notation. Despite my background in engineering, it was exceedingly challenging to decipher, let alone understand, the morass of new and unfamiliar technical terminologies, notation and concepts used in the scientific research papers. Having experienced first-hand some of the challenges when reading technical material, it became easy to then relate to the difficulty that may be experienced by others outside this field of specialism who, for the first time, attempt to read, or seek guidance from, the engineering/scientific literature.

Conversely, it was surprising to discover that most design guidance literature, which presumably provides the *de facto* core understanding for building ventilation flows, tends to oversimplify and, in some cases, misinterpret complex flow phenomena. One particularly prevalent example lies in the frequent use (or rather, misuse) of 'airflow arrows' in building sketches. These airflow arrows typically depict the anticipated or the desired – as opposed to the actual – direction of airflow through façade openings, with limited appreciation of the underlying physics that govern how air and heat flows through buildings (*e.g.* the relationship between airflow direction and vent area configuration/room stratification is not considered). Arrows depicting 'unidirectional' flow have become ubiquitous, yet the guidance on how to ensure this pattern of flow be achieved in practice is entirely absent. It is only upon closer study, and having gained the necessary background and a basic understanding of ventilating flows, could the misunderstanding be distinguished. The overall picture is therefore one of an extensive, but fragmented, mosaic of literature on natural ventilation. Indeed, the challenges experienced as an engineering student tied in with my own personal interests in low-energy building ventilation have provided the necessary impetus and drive to seek ways towards bridging the information gap between the technical research base and the architectural design literature.

Since the overarching theme of this research has been on 'bridging barriers', it was crucial at the outset to acquire some insight into the historical tradition of architects and engineers, as this has inevitably played a crucial role in shaping how both professions disseminate and share disciplinary knowledge, whether this be in a building design process or through journal publications. From reading a broad range of architectural and engineering articles, it became apparent that the dichotomy between the professions is deeply rooted in their pedagogical upbringing. The proliferation of specialisation of architects and engineers as they advance in their academic and professional careers has meant that both disciplines have become increasingly discordant and may even start viewing one another as 'laypeople'.

Further to this, both disciplines have developed their own unique repertoire of language conventions, methods of problem-solving, design philosophies and value systems, all which compound the barriers to knowledge exchange in practice. It is, however, worth mentioning that as the professional role of the architect and engineer diverged over time, they have also become increasingly dependent upon one another for their disciplinary expertise while working towards common goals in the form of structurally-sound, comfortable and aesthetically-pleasing buildings, *i.e.* satisfying the three Vitruvian principles of 'function' (*Utilitas*), 'structure' (*Firmitas*) and 'beauty' (*Venustas*).

At the start of this thesis, the following question was posed: How can we, as academic researchers in the field of low-energy building ventilation, communicate the key physics of natural ventilation in a viable format that enables architects and engineers to understand and apply them without compromising or undervaluing the well-established technical research base? In an effort to answer this question, we have focussed on developing rapid and intuitive design guidance for natural ventilation that has sought to strike a balance between general applicability and practical relevance, while at the same time still retain sufficient depth and ensure mathematical rigour.

As part of a larger body of enquiry into improving the transfer of technical information from the fluid mechanics literature into architectural design guidance, a survey was conducted on a group of student architects to gain direct insight into the information needs of architects with respect to their designing naturally ventilated buildings. Our survey findings revealed that architects prefer to communicate through drawings and graphical notation due, in part, to the perceived ease of absorbing and recollecting the necessary information. This preference can be traced back to how architects are taught and assessed during their academic training, and is echoed in the preferred types of information they acquire and choose to use. Moreover, there was a strong need expressed for architect-focussed natural ventilation design guidance (*e.g.* with regards to vent sizing), wherein guidance on ventilation should preferably be presented in a visual format using architectural conventions and terminologies wherever possible (*e.g.* including a sketch of a human for scale and ground line in schematics of buildings). We also found that there was an overall culture of respect and trust towards engineers and research academics with expertise in low-energy building ventilation. This finding was particularly noteworthy (and reassuring) given that there is much evidence in the literature to support the view that architects are generally suspicious of those outside their community who, as they see it, are trying to constrain their creativity by imposing rules disguised under the veil of 'design guidance'.

Whilst the responses gathered from our survey cannot be regarded as being truly representative of the viewpoints of all architects, our exploratory study has served as an essential pathway that enabled us to connect with the ostensibly disparate world of architecture. Moreover, it has contributed towards improving our own understanding and appreciation of architects' information needs, and crucially, has influenced the way in which the results (obtained from the development of mathematical models, for example) have been conveyed in this thesis. The responses which emerged from our survey, in particular those regarding architects' vision for ideal presentation formats, offered a number of pointers for the writing/presentation styles for technical researchers (and course developers) that may help streamline the delivery of technically-orientated information to architects. These pointers have been summarised in the form of a 'dissemination checklist' in Table 2.4.

The design guidance developed and presented in this thesis took two forms, both of which, we contend, are key to promoting the transfer and uptake of technical information. The first concerns the use of a simplified mathematical approach as a framework for modelling and conveying the physics of natural ventilation. We focussed on the ventilation of a single room with a simple 'box-like' geometry as a starting point to inform preliminary design. Although our survey findings did reveal that the single box-like enclosure could potentially be perceived by architects as too abstract or removed from a real building (see Figure 2.12), we believe that an understanding of the single space is an essential ingredient for more complex space geometries, such as multi-storey buildings with interconnected rooms and atria. We began with the simplest indoor temperature distribution in which the accumulated heat is distributed uniformly throughout the room. This simplification was not unreasonable, given that heat sources – such as occupants, office equipment, solar gains and so on – within real spaces often occupy a significant portion of the total floor area, which can lead to a 'well-mixed', uniform temperature environment within the room (Hunt *et al.*, 2002; Kaye & Hunt, 2010). Essentially, this simplified approach to modelling natural ventilation flows has enabled a quick and straightforward route to establishing an early stage design, and more importantly, has provided the groundwork of our methodology for conveying technical information on natural ventilation to architects.

As the thesis progressed, further layers of detail were added sequentially to the mathematical model to capture more complex flow effects, such as thermal stratification and internal mixing (draught), on the ventilating flow. Our objective was to build up a hierarchy of mathematical models, based on an incremental extension of accepted fluid mechanic principles, which enable insight into the potential impact of these different effects on the ventilation system. Whilst we focussed only on a limited subset of 'primary' variables – namely ventilation flow rates, indoor air temperatures, heat inputs, building geometry, vent sizes and vent location – we demonstrated that our chosen primary variables were able to capture the key underlying physics of stack ventilation to a sufficient extent to inform preliminary design.

Particularly at the early design stage, Charleson & Pirie (2009) commented that architects prefer to explore their individual designs freely and are concerned that if an engineer is involved too early, that he or she can prematurely stifle their design explorations. We anticipate that our proposed design guidance, hinged on the use of simple hand calculations and visual charts, will enable architects to gain a sense of control over their envisioned ventilation design – a responsibility which, following several decades of a highly compartmented educational system, had been ceded exclusively to the specialist ventilation engineer (§1.1). In terms of basic design the guidelines developed herein can provide the architect with a feel for whether the proposed design is effective – essentially that the vent sizes chosen achieve the desired airflow rate and indoor comfort – whilst simultaneously enabling the engineer to be involved at a time when he/she can still influence architectural design.

The second aspect of the guidance developed in this thesis, which is of equal, if not more, cogency is imparting an intuition for the way in which air and heat flows through a building. This is perhaps a more challenging aspect of the guidance to transmit and it was therefore important to gain an insight into the types of information architects prefer to use and perceive as informative. This form of insight is crucial for technical researchers and practitioners when tailoring their work to be read by architects. Indeed, the findings from our survey have prompted and guided, to a large extent, the mindset adopted throughout this discourse when conveying and presenting technically-orientated information.

Given the different learned approaches of architects and engineers to thinking and problem-solving, finding a way to work together in a practical setting is exceedingly challenging, not least because both disciplines have developed their own specific language conventions and design philosophies reflecting these differences. We believe that better communication between engineers and architects is possible only if both camps are able to share, or, at least, appreciate similar 'systems of thought' and 'systems of symbols and conventions' on this common ground of scientific and architectural knowledge.

Whilst we have made the greatest effort in explaining the core concepts and principles of natural ventilation as succinctly and straightforwardly as possible, in some cases we felt that we were not able to explain the concepts in layman terms such that they give justice to the underlying complexities and subtleties. For example, the expression 'vigour of mixing' was used as an equivalent for the term 'Interfacial Froude number', despite not able to fully encapsulate the intrinsic meaning of the term without having to revert back to its original technical definition. In essence, 'simplifying' complex terminologies encountered in the technical literature can only 'go so far', and minute distinctions between terms can alter meaning and confuse communication. Breaking away from 'traditional' conventions of technical writing may even run the risk of rejection not only by the scientific community, but also by the architectural community simply because we have failed to parse and translate technical concepts demanded or expected by the audience. For example, the term 'heat source strength', which we used to simplify the term 'heat flux' may, in fact, be completely meaningless to the architect.

Further to this, there is a limit on the extent to which the physics describing ventilation flows can be simplified without losing a certain level of mathematical rigour, integrity and credibility. Notwithstanding the fact that the mathematical models presented in each chapter of the thesis have already been intentionally simplified, despite their inherent complexity, due to the underlying simplifying assumptions. For example, we assumed that heat transfers between the building fabric and the air inside the room are negligibly small, the ventilation openings are 'sharp-edged' and not covered by obstacles or grilles, and the loss coefficient characterising the pressure loss experienced by the flow through an opening takes roughly a constant value. The virtue of a simplified mathematical model lies exactly in the process of simplification as it allows one to distil the essential physics that govern the ventilation system into a set of fundamental core components, thereby limiting the number of interdependent variables to consider and thus to solve for. Undeniably, imposing these simplifying assumptions will restrict the range of practical situations to which the mathematical models presented herein, and hence the design guidance proposed, can be successfully applied to 'real world' building ventilation problems.

Overall, the practical contributions of this research as per objectives in §1.3 are as follows:

(i) Exposed a number of potential factors that currently affect, detrimentally, the transfer and impact of technical information from engineering/scientific spheres to end users within the architectural community;

(ii) Developed and proposed a set of straightforward design guidelines that allow for the rapid calculation of the individual opening areas required to achieve desired ventilation flow rates and indoor temperatures; and

(iii) Prompted and guided a set of recommendations regarding the style and format for design guidance that would likely ensure improved uptake of technical information on natural ventilation.

6.1 Potential ways forward

A few prominent ideas, which may be insightful as future work, arose during the course of this research. In this section the wider implications of our research are discussed and some prospective avenues for future research in this interdisciplinary field are proposed.

1. To further our current understanding of the information needs of architects

Our understanding of the needs of architects in a building design process is still in its infancy and there is much scope for further learning about the architectural audience. Architects are predisposed to think in certain ways both as a result of their prior educational training and view of their perceived role in society. As a consequence of their deeply-seated belief systems, architects may hold preconceptions not only of members outside their own field of profession, but also regarding the value of the information they have at hand.

As yet, the design guidance for vent sizing proposed in this thesis has not received any critical evaluation nor feedback from the architectural community. It would be informative to 'test' the applicability of the guidance by exploring whether architects would consider using it in practice, and if so, how they would go about incorporating it in their work.

Moreover, there is a whole swathe of architectural conventions and lexicons, as well as means of conveying information deemed as congenial and 'non-threatening' to their practice, which we have not explored explicitly in this thesis. If communication between engineers and architects is to be improved and maintained in the long run, it is imperative to gain a deeper understanding of architects in their everyday work environment, their problems and constraints, and how their existing means of sharing and assimilating knowledge function. The ultimate question now lies as to whether the initiative and drive for carrying out such studies would be instigated only by the technical research community.

2. To encourage interdisciplinary courses in tertiary education

Billington (1991), Charleson & Pirie (2009) and Olsen & Mac Namara (2014) commented how modern tertiary education fosters a 'silo-mentality' and alienation of professions from one another. Most architectural and engineering programmes rarely provide young professionals with the necessary learning environment to facilitate interdisciplinary collaboration between specialists in distinct areas, skills that are prerequisite to the achievement of an integrated design. While architecture students may be exposed to at least one engineer (*e.g.* in their design studio-based tutorial environment), in my experience as an undergraduate engineering student, I had limited opportunity to interact with architects (students or professionals) nor be exposed to any architectural subjects.

We envision that it would make significant contribution to fostering the nexus between architects and engineers if schools of engineering were to offer courses on the fundamentals of architectural design. For example, interdisciplinary courses which would allow engineering students to work in a team alongside student architects in their design studio projects. In such interdisciplinary courses, we anticipate that engineering students would benefit greatly from gaining a more holistic understanding of the architectural profession, which would undoubtedly prepare students for real world design collaboration in the future.

3. To promote greater interest in technical communication

Another suggestion we would like to put forward is for engineering schools to integrate more formal courses on 'communicating science' into the curricula, albeit without detracting from the scientific rigour of the training programmes. Whilst an opinion, it is important for engineers to be able to communicate ideas and information effectively to disciplines other than engineering alone, and therefore it is integral to impart this skill set and confidence early on in their academic training. For example, the first year undergraduate engineering programme at the University of Cambridge offers a compulsory "Exposition" course on communication (which I had the pleasure to be a part of) in which students are assessed on their ability to deliver and present balanced arguments on a controversial technical topic in a comprehensive and non-trivial manner. While this particular course is emphasised only in the first year, we contend that formal training in technical communication should be carried forward through all years in the undergraduate and graduate curricula; this, in turn, would inculcate the importance of communication in conjunction with technical and research dexterity.

6.2 Closing remarks

The overarching aim of this research was to develop a framework for encouraging the transfer and uptake of knowledge on natural ventilation by practitioners spanning the architectural, buildings physics and wider ventilation design communities; a framework which, to our knowledge, has not yet been made available in the open literature, until now. This aim was successfully achieved by a combined quantitative and qualitative approach. Simplified mathematical models were used to capture and identify the key mechanisms underlying natural ventilation flows, which provided both quantitative and qualitative information needed to inform early stage design. In order to gain a better understanding of the architecture audience with whom we wish to better convey technical information to, a survey on a group of student architects was conducted to enquire the types of information they would like to have at their fingertips with respect to their designing naturally ventilated buildings. By drawing from the responses of the group surveyed, we offered some practical recommendations that may be useful and insightful to those who wish to provide information targeted for an architectural audience.

Evidently, this work has drawn attention to the importance of the presentation (visual and written) of research findings, and that it can have a significant bearing on whether work is read, comprehended and used by architects. However, the particular focus on presentation alone may be of questionable value since it is founded on two underlying premises. First, it is assumed that if the information is written in ideal 'exemplary' formats with the 'correct' visual characteristics, architects can access it and, thus, will choose to apply it to their own building designs. Second, it is assumed that if architects do apply it, their designs would consequentially improve.

While necessary, 'good' presentation *per se* is not sufficient to overcome existing barriers to the uptake of technical information by architects. There may be other forces at work beyond aspects of 'presentation' alone which were not explored in this thesis. The choices architects make and how they assimilate information are influenced by their predispositions, which in turn are likely to be deeply rooted in a held set of beliefs instilled by their architectural training and experience (Goodey & Matthew, 1971; Mackinder & Marvin, 1982; Lera *et al.*, 1984). These beliefs can have an overriding effect on architects' perceived value of the information they have at hand. Viewed from this perspective, the presentation of information can be treated not as an isolated factor, but simply as one factor – *inter alia* – affecting the transfer of technical information to the architectural community. It is, perhaps, to these often unexpressed and less 'quantifiable' factors that attention needs to be drawn if further attempts are to be made to bridge communication barriers between both professional fields.

Nevertheless, it is hoped that this research has shed some light on the sheer complexity of the 'communication problem' that exists today between the architectural and engineering communities. We also hope that it has reawakened the interest for furthering research into ways towards improving the communication of natural ventilation to architects and the wider building design spheres. The ever expanding realm of the sciences will bring yet new paradigms to solve associated with naturally ventilated buildings; gaining a deeper systemic understanding of the architectural audience is one important part of the journey. We would like to conclude with a quote from Billington (1991), which aptly permeated the philosophy of this work:

> *"As architecture is an art form, so engineering is established as a parallel art form from which architects can draw inspiration. Once engineering is recognised as an art form, then the architect and engineer can learn from one another. On the one hand, architects can learn about this new art, which represents the highest form that structures can achieve when conceived of aesthetically. On the other hand, engineers can learn from architects' attitudes toward building. They can learn a method of appreciating, understanding, and analysing their own art form from similar methods in architecture. From architecture, engineers can learn how to study structures visually."*

Bibliography

Acred, A. 2014 Natural ventilation in multi-storey buildings: A preliminary design approach. PhD thesis, Department of Civil and Environmental Engineering, Imperial College London, South Kensington, London, United Kingdom.

Acred, A. & Hunt, G.R. 2014*a* A simplified mathematical approach for modelling stack ventilation in multi-compartment buildings. *Building and Environment* **71**, 121–130.

Acred, A. & Hunt, G.R. 2014*b* Stack ventilation in multi-storey atrium buildings: A dimensionless design approach. *Building and Environment* **72**, 44–52.

Adler, E.S. & Clark, R. 2014 *An Invitation to Social Research: How It's Done*. Stamford, CT: Cengage Learning.

Altomonte, S. 2009 Environmental education for sustainable architecture. *Review of European Studies* **1** (2), 12–21.

Andersen, K.T. 1995 Theoretical considerations on natural ventilation by thermal buoyancy. *ASHRAE Transactions* **101**, 1103–1117.

Archdaily 2011 Okanagan College Centre of Excellence in Sustainable Building Technologies and Renewable Energy Conservation. [Online]. Available from: http://www.archdaily.com/173726/okanagan-college-centre-of-excellence-in-sustainable-building-technologies-and-renewable-energy-conservation-cei/.

Architectural Association Inc. 2017 Professional Practice Studies. [Online]. Available from: http://www.aaschool.ac.uk/STUDY/UNDERGRADUATE/?name=comppp.

Ashford, C. 2011 The Delinquent Arrows. *CIBSE Natural Ventilation News* **Issue 04** (July), 1–2.

ASHRAE 2010 *Standard 55: Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Asprino, A., Broadbent, G.H. & Powell, J.A. 1981 A critical examination of design failures in buildings and their relation to design processes. In *Design: Science: Method* (ed. R. Jacques & J.A. Powell). Guildford, United Kingdom: Westbury House.

ASSIMAKOPOULOS, V.D., STATHOPOULOU, O.I., HALIOS, C. & HELMIS, C.G. 2008 Numerical Investigation of Indoor Environmental Conditions in an Office. *International Journal of Ventilation* **6** (4), 315–326.

AXLEY, J. 1998 Introduction to the design of natural ventilation systems using loop equations. In *Proceedings of the 19th AIVC Conference – Ventilation Technologies in Urban Areas*, pp. 47–56. Air Infiltration and Ventilation Centre, Oslo, Norway.

AYNSLEY, R.M., MELBOURNE, W. & VICKERY, B.J. 1977 *Architectural aerodynamics*. London, United Kingdom: Applied Science Publishers Ltd.

BAINES, W.D. 1975 Entrainment by a plume or jet at a density interface. *Journal of Fluid Mechanics* **68** (2), 309–320.

BAINES, W.D. 1983 A technique for the direct measurement of volume flux of a plume. *Journal of Fluid Mechanics* **132**, 247–256.

BAINES, W.D. & TURNER, J.S. 1969 Turbulent buoyant convection from a source in a confined region. *Journal of Fluid Mechanics* **37**, 51–80.

BAKER, N. & LINDEN, P.F. 1991 Physical models of air flows: A new design tool. In *Atrium Buildings Architecture and Engineering* (ed. F. Mills), pp. 13–22. Welwyn, United Kingdom: CICC Publications.

BAKER, N. & STEEMERS, K. 2003 *Energy and Environment in Architecture: A Technical Design Guide*. London, United Kingdom: E & FN Spon.

BANHAM, R. 1960 *Theory and Design in the First Machine Age*. Cambridge, MA: MIT Press, Ltd.

BATCHELOR, G.K. 1954 Heat convection and buoyancy effects in fluids. *Quarterly Journal of the Royal Meteorological Society* **80** (345), 339–358.

BATCHELOR, G.K. 1967 *An Introduction to Fluid Dynamics*. Cambridge, United Kingdom: Cambridge University Press.

BENAIM, R. 2002 Engineering architecture: The art of engineering structures from the Pantheon to the Jubilee Line. *Ingenia* **11**, 6–12.

BILLINGTON, D. 1991 The New Art of Engineering. In *Bridging the Gap: Rethinking the Relationship of Architect and Engineer; The Proceedings of the Building Arts Forum/New York Symposium held in April of 1989 at the Guggenheim Museum* (ed. D. Gans, E. English, E. Simpson, A. Webster, C. Gorczyca & T. Lefcochilos), pp. 3–21. New York, NY: Van Nostrand Reinhold.

BIRT, B. & NEWSHAM, G.R. 2009 Post-occupancy evaluation of energy and indoor environment quality in green buildings: A review. In *Proceedings of the 3rd International Conference on Smart and Sustainable Built Environments*, pp. 1–7. Delft, the Netherlands.

Bower, D.J., Caulfield, C.P., Fitzgerald, S.D. & Woods, A.W. 2008 Transient ventilation dynamics following a change in strength of a point source of heat. *Journal of Fluid Mechanics* **614**, 15–37.

van den Bremer, T.S. & Hunt, G.R. 2014 Two-dimensional planar plumes and fountains. *Journal of Fluid Mechanics* **750**, 210–244.

BSI 1991 *British Standard 5925: Code of practice for ventilation principles and designing for natural ventilation*. London, United Kingdom: British Standards Institute.

Burge, P.S. 2004 Sick building syndrome. *Occupational and Environmental Medicine* **61** (2), 185–190.

Burnette, C.H. 1979 *Making information useful to architects: An analysis and compendium of practical forms for the delivery of information*. AIA Corporation Research and The National Bureau of Standards.

Castro, I.P. & Graham, J.M.R. 1999 Numerical wind engineering: The way ahead? *Proceedings of the Institution of Civil Engineers Structures & Buildings* **134** (3), 275–277.

Charleson, A.W. & Pirie, S. 2009 An investigation of structural engineer-architect collaboration. *SESOC Journal (New Zealand)* **22** (1), 97–104.

Chen, C.J. & Rodi, W. 1980 *Vertical Turbulent Buoyant Jets: A Review of Experimental Data*. Oxford, NY: Pergamon Press.

Chen, Q. 2009 Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment* **44** (4), 848–858.

Chenvidyakarn, T. & Woods, A.W. 2008 On underfloor air-conditioning of a room containing a distributed heat source and a localised heat source. *Energy and Buildings* **40** (7), 1220–1227.

Chiu, Y.H. & Etheridge, D.W. 2007 External flow effects on the discharge coefficients of two types of ventilation opening. *Journal of Wind Engineering and Industrial Aerodynamics* **95** (4), 225–252.

Christenson, M., Manz, H. & Gyalistras, D. 2006 Climate warming impact on degree-days and building energy demand in Switzerland. *Energy Conversion and Management* **47** (6), 671–686.

CIBSE 2005 *Applications Manual AM10: Natural ventilation in non-domestic buildings*. London, United Kingdom: The Chartered Institution of Building Services Engineers.

CIBSE 2006 *Guide A: Environmental design*. London, United Kingdom: The Chartered Institution of Building Services Engineers.

Cimbala, J.M. & Çengel, Y.A. 2008 *Essentials of fluid mechanics: Fundamentals and applications*. London, OH: McGraw Hill Higher Education.

Coffey, C.J. & Hunt, G.R. 2004*a* The effect of draughts on the steady temperature distribution in a naturally ventilated enclosure. In *Proceedings of ROOMVENT 2004 the 9th International Conference on Air Distribution in Rooms* (ed. M.C. Gameiro Da Silva). Coimbra, Portugal: University of Coimbra.

Coffey, C.J. & Hunt, G.R. 2004*b* On the night purging of naturally ventilated enclosures-the effect of the relative area of openings. In *Proceedings of ROOMVENT 2004 the 9th International Conference on Air Distribution in Rooms* (ed. M.C. Gameiro Da Silva). Coimbra, Portugal: University of Coimbra.

Coffey, C.J. & Hunt, G.R. 2007 Ventilation effectiveness measures based on heat removal: Part 2. Application to natural ventilation flows. *Building and Environment* **42** (6), 2249–2262.

Coffey, C.J. & Hunt, G.R. 2010 The unidirectional emptying box. *Journal of Fluid Mechanics* **660**, 456–474.

Collins, E. 2014 *Architects and research-based knowledge: A literature review*. London, United Kingdom: RIBA Research and Development.

Committee on Climate Change 2013 Chapter 3: Progress reducing emissions from buildings. In *Meeting Carbon Budgets – 2013 Progress Report to Parliament*, pp. 109–137. London, United Kingdom.

Coomaraswamy, I.A. & Caulfield, C.P. 2011 Time-dependent ventilation flows driven by opposing wind and buoyancy. *Journal of Fluid Mechanics* **672**, 33–59.

Cooper, I. 1982*a* Comfort and energy conservation: A need for reconciliation? *Energy and Buildings* **5** (2), 83–87.

Cooper, I. 1982*b* Comfort theory and practice: Barriers to the conservation of energy by building occupants. *Applied Energy* **11** (4), 243–288.

Cooper, I. & Crisp, V.H.C. 1984 Barriers to the Exploitation of Daylighting in Building Design: UK Experience. *Energy and Buildings* **6** (2), 127–132.

Cooper, P. & Linden, P.F. 1996 Natural ventilation of an enclosure containing two buoyancy sources. *Journal of Fluid Mechanics* **311**, 153–176.

Cunningham, D. & Stewart, J. 2012 Perceptions and practices: A survey of professional engineers and architects. *International Scholarly Research Network* **2012**, 1–10.

de Dear, R.J. & Brager, G.S. 2002 Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55. *Energy and Buildings* **34** (6), 549–561.

Deuble, M.P. & de Dear, R.J. 2012 Green occupants for green buildings: The missing link? *Building and Environment* **56**, 21–27.

Eicker, U. 2009 *Low Energy Cooling for Sustainable Buildings*. London, United Kingdom: John Wiley & Sons, Ltd.

Ellis, M.W. & Mathews, E.H. 2001 A new simplified thermal design tool for architects. *Building and Environment* **36** (9), 1009–1021.

Ellison, T.H. & Turner, J.S. 1959 Turbulent entrainment in stratified flows. *Journal of Fluid Mechanics* **6** (3), 423–448.

Epstein, M. 1988 Buoyancy-driven exchange flow through small openings in horizontal partitions. *Journal of Heat Transfer* **110** (4a), 885–893.

Etheridge, D.W. 2011 *Natural ventilation of buildings: Theory, measurement and design*. London, United Kingdom: John Wiley & Sons, Ltd.

Etheridge, D.W. & Sandberg, M. 1996 *Building ventilation: Theory and measurement*. Chichester, United Kingdom: John Wiley & Sons Ltd.

European Commission 2015 *Renewable Energy Report*. Brussels, Belgium: Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

Fanger, P.O. & Christensen, N.K. 1986 Perception of draught in ventilated spaces. *Ergonomics* **29** (2), 215–235.

Fanger, P.O., Melikov, A.K., Hanzawa, H. & Ring, J. 1988 Air turbulence and sensation of draught. *Energy and Buildings* **12**, 21–39.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. & Brooks, N.H. 1979 *Mixing in inland and coastal waters*. San Diego, CA: Academic Press, Inc.

Fitzgerald, S.D. & Woods, A.W. 2007 Dramatic ventilation. *Building Services Journal* **January**, 51–56.

Fitzgerald, S.D. & Woods, A.W. 2010 Transient natural ventilation of a space with localised heating. *Building and Environment* **45** (12), 2778–2789.

Flourentzou, F., Van der Maas, J. & Roulet, C.A. 1998 Natural ventilation for passive cooling: Measurement of discharge coefficients. *Energy and Buildings* **27** (3), 283–292.

Fraenkel, J.R. & Wallen, N.E. 2011 *How to design and evaluate research in education*, 8th edn. New York, NY: McGraw-Hill Education.

Gage, S.A., Hunt, G.R. & Linden, P.F. 2001 Top down ventilation and cooling. *Journal of Architectural and Planning Research* **18** (4), 286–301.

Gann, D. & Salter, A. 2001 Interdisciplinary Education for Design Professionals. In *Interdisciplinary Design in Practice* (ed. R. Spence, S. MacMillian & P. Kirby), pp. 95–104. London, United Kingdom: ICE Publishing.

Ghiaus, C. & Allard, F. 2005 *Natural ventilation in the urban environment: Assessment and design*. London, United Kingdom: Earthscan.

Gladstone, C. & Woods, A.W. 2001 On buoyancy-driven natural ventilation of a room with a heated floor. *Journal of Fluid Mechanics* **441**, 293–314.

Goodey, J. & Matthew, K. 1971 *Architects and information*. York, United Kingdom: University of York Institute of Advanced Architectural Studies.

Griefahn, B., Künemund, C. & Gehring, U. 2002 Evaluation of draught in the workplace. *Ergonomics* **45** (2), 124–135.

Hargis, G., Carey, M., Hernandez, A.K., Hughes, P., Longo, D., Rouiller, S. & Wilde, E. 2004 *Developing Quality Technical Information: A Handbook for Writers and Editors*, 2nd edn. Upper Saddle River, NJ: Prentice Hall.

Hawkes, D. 1996 *The Environmental Tradition: Studies in the Architecture of the Environment*. London, United Kingdom: E & FN Spon.

Hayter, S.J., Torcellini, P.A., Hayter, R.B. & Judkoff, R. 2000 The energy design process for designing and constructing high-performance buildings. In *Proceedings of the 7th REHVA World Congress and Clima 2000*. Naples, Italy: REHVA, AiCARR.

Heiselberg, P. 2004 Natural ventilation design. *International Journal of Ventilation* **2** (4), 295–312.

Heiselberg, P., Svidt, K. & Nielsen, P.V. 2001 Characteristics of airflow from open windows. *Building and Environment* **36** (7), 859–869.

Hensel, H. 1981 *Thermoreception and temperature regulation. Monographs of the Physiological Society No. 38*. London, United Kingdom: Academic Press.

Herbert, G. 1999 Architect-engineer relationships: Overlappings and interactions. *Architectural Science Review* **42** (2), 107–110.

Hinrichs, J.R. & Gatewood, R.D. 1967 Differences in opinion-survey response patterns as a function of different methods of survey administration. *Journal of Applied Psychology* **51** (6), 497–502.

Hitchin, E.R. & Wilson, C.B. 1967 A review of experimental techniques for the investigation of natural ventilation in buildings. *Building Science* **2** (1), 59–82.

Holford, J.M. & Hunt, G.R. 2001 The dependence of the discharge coefficient on density contrast – experimental measurements. In *Proceedings of the 14th Australasian Fluid Mechanics Conference* (ed. B.B. Dally), pp. 123–126. University of Adelaide, Australia.

Holford, J.M. & Woods, A.W. 2007 On the thermal buffering of naturally ventilated buildings through internal thermal mass. *Journal of Fluid Mechanics* **580**, 3–29.

Holm, D. 1993 Building Thermal Analyses: What the Industry Needs: The Architect's Perspective. *Building and Environment* **28** (4), 405–407.

Hudson, L. 1968 *Frames of mind: Ability, perception and self-perception in the arts and sciences*. London, United Kingdom: Methuen Publishing, Ltd.

Hunt, G.R. & Coffey, C.J. 2010 Emptying boxes – classifying transient natural ventilation flows. *Journal of Fluid Mechanics* **646**, 137–168.

Hunt, G.R., Cooper, P. & Linden, P.F. 2001*a* Thermal stratification produced by plumes and jets in enclosed spaces. *Building and Environment* **36** (7), 871–882.

Hunt, G.R. & Holford, J.M. 2000 The discharge coefficient – experimental measurement of a dependence on density contrast. In *Proceedings of the 21st Annual AIVC Conference*, pp. 12–24. Air Infiltration and Ventilation Centre, The Hague, Netherlands,.

Hunt, G.R., Holford, J.M. & Linden, P.F. 2001*b* Natural ventilation by the competing effects of localised and distributed heat sources. In *Proceedings of the 14th Australasian Fluid Mechanics Conference* (ed. B.B. Dally), pp. 545–548. University of Adelaide, Australia.

Hunt, G.R., Holford, J.M. & Linden, P.F. 2002 Characterisation of the flow driven by a finite area heat source in a ventilated enclosure. In *Proceedings of ROOMVENT 2002 the 8th International Conference on Air Distribution in Rooms* (ed. P.V. Nielson & A.K. Melikov), pp. 581–584. Copenhagen, Denmark: Technical University of Denmark and Danvak.

Hunt, G.R. & Kaye, N.B. 2001 Virtual origin correction for lazy turbulent plumes. *Journal of Fluid Mechanics* **435**, 377–396.

Hunt, G.R. & Kaye, N.B. 2006 Pollutant flushing with natural displacement ventilation. *Building and Environment* **41** (9), 1190–1197.

Hunt, G.R. & Linden, P.F. 1998 Time-dependent displacement ventilation caused by variations in internal heat gains: Application to a lecture theatre. In *Proceedings of ROOMVENT 1998 the 6th International Conference on Air Distribution in Rooms* (ed. E. Mundt & T.G. Malmström), pp. 203–210. Stockholm, Sweden: KTH.

Hunt, G.R. & Linden, P.F. 1999 The fluid mechanics of natural ventilation – displacement ventilation by buoyancy-driven flows assisted by wind. *Building and Environment* **34** (6), 707–720.

Hunt, G.R. & Linden, P.F. 2001 Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind. *Journal of Fluid Mechanics* **426**, 355–386.

Hunt, G.R. & Linden, P.F. 2005 Displacement and mixing ventilation driven by opposing wind and buoyancy. *Journal of Fluid Mechanics* **527**, 27–55.

Idelchik, I.E. 1986 *Handbook of hydraulic resistance*, 2nd edn. Washington, DC: Hemisphere Publishing Corp.

Jones, B.M., Cook, M.J., Fitzgerald, S.D. & Iddon, C.R. 2016 A review of ventilation opening area terminology. *Energy and Buildings* **118**, 249–258.

Karava, P., Stathopoulos, T. & Athienitis, A.K. 2004 Wind driven flow through openings – a review of discharge coefficients. *International Journal of Ventilation* **3** (3), 255–266.

Kaye, N.B., Flynn, M.R., Cook, M.J. & Ji, Y. 2010 The role of diffusion on the interface thickness in a ventilated filling box. *Journal of Fluid Mechanics* **652**, 195–205.

Kaye, N.B. & Hunt, G.R. 2004 Time-dependent flows in an emptying filling box. *Journal of Fluid Mechanics* **520**, 135–156.

Kaye, N.B. & Hunt, G.R. 2006 Weak fountains. *Journal of Fluid Mechanics* **558**, 319–328.

Kaye, N.B. & Hunt, G.R. 2007 Heat source modelling and natural ventilation efficiency. *Building and Environment* **42** (4), 1624–1631.

Kaye, N.B. & Hunt, G.R. 2009 An experimental study of large area source turbulent plumes. *International Journal of Heat and Fluid Flow* **30** (6), 1099–1105.

Kaye, N.B. & Hunt, G.R. 2010 The effect of floor heat source area on the induced airflow in a room. *Building and Environment* **45** (4), 839–847.

Kenton, A.G., Fitzgerald, S.D. & Woods, A.W. 2004 Theory and practice of natural ventilation in a theatre. In *Proceedings of the 21th Conference on Passive and Low Energy Architecture*, pp. 19–22. Eindhoven, The Netherlands.

Kotsovinos, N.E. 1975 A study of the entrainment and turbulence in a plane buoyant jet. PhD thesis, California Institute of Technology, Pasadena, CA.

Krausse, B., Cook, M.J. & Lomas, K. 2007 Environmental performance of a naturally ventilated city centre library. *Energy and Buildings* **39** (7), 792–801.

Kukadia, V., Kolokotroni, M., Perera, E., Ajiboye, P., Hesketh, M. & Willan, P. 1998 *Barriers to natural ventilation design of office buildings. National report: Great Britain*. Garston, United Kingdom: Building Research Establishment, Ltd.

Kumagai, M. 1984 Turbulent buoyant convection from a source in a confined two-layered region. *Journal of Fluid Mechanics* **147**, 105–131.

Lam, K.P., Kim, S.H., Satwiko, P., Jennings, J. & Cole, J. 2006 Assessment of the effects of environmental factors on air flow in and around buildings. In *Proceedings of the 23rd International Conference on Passive and Low Energy Architecture* (ed. R. Compagnon, P. Haefeli & W. Weber), pp. 6–8. Geneva, Switzerland.

Lane-Serff, G.F. & Sandbach, S.D. 2012 Emptying non-adiabatic filling boxes: The effects of heat transfers on the fluid dynamics of natural ventilation. *Journal of Fluid Mechanics* **701**, 386–406.

Larice, G.S. 2009 Classifying steady states in emptying-filling boxes. PhD thesis, Department of Civil and Environmental Engineering, Imperial College London, South Kensington, London, United Kingdom.

Lawson, B. 2005 *How Designers Think: The Design Process Demystified*, 4th edn. Oxford, United Kingdom: Taylor & Francis.

LEAMAN, A. & BORDASS, B. 2007 Are users more tolerant of 'green' buildings? *Building Research and Information* **35** (6), 662–673.

LEE, S.-L. & EMMONS, H.W. 1961 A study of natural convection above a line fire. *Journal of Fluid Mechanics* **11** (3), 353–368.

LERA, S., COOPER, I. & POWELL, J.A. 1984 Designers and information. In *Designing for building utilization* (ed. J.A. Powell, I. Cooper & S. Lera), pp. 271–283. London, United Kingdom: E & FN Spon.

LI, Y. & HEISELBERG, P. 2003 Analysis Methods for Natural and Hybrid Ventilation – a Critical Literature Review and Recent Developments. *International Journal of Ventilation* **1** (4), 3–20.

LIN, Y.J.P. & LINDEN, P.F. 2005 The entrainment due to a turbulent fountain at a density interface. *Journal of Fluid Mechanics* **542**, 25–52.

LINDEN, P.F. 1999 The fluid mechanics of natural ventilation. *Annual Review of Fluid Mechanics* **31** (1), 201–238.

LINDEN, P.F. 2000 Convection in the environment. In *Perspectives in fluid dynamics: A collective introduction to current research* (ed. G.K. Batchelor, H.K. Moffatt & M.G. Worster), pp. 289–345. Cambridge, United Kingdom: Cambridge University Press.

LINDEN, P.F. & COOPER, P. 1996 Multiple sources of buoyancy in a naturally ventilated enclosure. *Journal of Fluid Mechanics* **311**, 177–192.

LINDEN, P.F., LANE-SERFF, G.F. & SMEED, D.A. 1990 Emptying filling boxes: The fluid mechanics of natural ventilation. *Journal of Fluid Mechanics* **212**, 309–335.

LISHMAN, B. & WOODS, A.W. 2006 The control of naturally ventilated buildings subject to wind and buoyancy. *Journal of Fluid Mechanics* **557**, 451–471.

LIVERMORE, S.R. & WOODS, A.W. 2006 Natural ventilation of multiple storey buildings: The use of stacks for secondary ventilation. *Building and Environment* **41** (10), 1339–1351.

LOMAS, K.J. 2007 Architectural design of an advanced naturally ventilated building form. *Energy and Buildings* **39** (2), 166–181.

MACKINDER, M. & MARVIN, H. 1982 *Design decision making in architectural practice*. York, United Kingdom: University of York Institute of Advanced Architectural Studies.

MANNING, P. 1995 Environmental Design as a Routine. *Building and Environment* **30** (2), 181–196.

MELIKOV, A.K., HANZAWA, H. & FANGER, P.O 1988 Airflow characteristics in the occupied zone of heated spaces without mechanical ventilation. *ASHRAE Transactions* **94** (1), 52–70.

MORTON, B.R., TAYLOR, G.I. & TURNER, J.S. 1956 Turbulent gravitational convection from maintained and instantaneous sources. In *Proceedings of the Royal Society of London, A*, vol. 234, pp. 1–23. London, United Kingdom: The Royal Society.

Newland, P.l, Powell, J.A. & Creed, C. 1987 Understanding architectural designers' selective information handling. *Design Studies* **8** (1), 2–16.

Norouzi, N., Shabak, M., Embi, M.R.B. & Khan, T.H. 2015 The architect, the client and effective communication in architectural design practice. *Procedia-Social and Behavioral Sciences* **172**, 635–642.

Oke, T.R. 2006 Towards better scientific communication in urban climate. *Theoretical and Applied Climatology* **84**, 179–190.

Olesen, B.W., Schøler, M. & Fanger, P.O. 1979 Discomfort caused by vertical air temperature differences. In *Indoor Climate* (ed. P.O. Fanger & O. Valbjørn), pp. 561–579. Copenhagen, Denmark: Danish Building Research Institute.

Olsen, C. & Mac Namara, S. 2014 *Collaborations in Architecture and Engineering*. New York, NY: Routledge.

Omrani, S., Garcia-Hansen, V., Capra, B. & Drogemuller, R. 2017 Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. *Building and Environment* **116**, 182–194.

Paillat, S. & Kaminski, E. 2014 Entrainment in plane turbulent pure plumes. *Journal of Fluid Mechanics* **755** (R2), 1–11.

Partridge, J.L. & Linden, P.F. 2013 Validity of thermally-driven small-scale ventilated filling box models. *Experiments in Fluids* **54** (11), 1–9.

Passe, U. & Battaglia, F. 2015 *Designing Spaces for Natural Ventilation: An Architect's Guide*. New York, NY: Routledge.

Pera, L. & Gebhart, B. 1975 Laminar plume interactions. *Journal of Fluid Mechanics* **68** (2), 259–271.

Pérez-Lombard, L., Ortiz, J. & Pout, C. 2008 A review on buildings energy consumption information. *Energy and Buildings* **40** (3), 394–398.

Peters, T.F. 1991 Architectural and Engineering Design: Two Forms of Technological Thought on the Borderline Between Empiricism and Science. In *Bridging the Gap: Rethinking the Relationship of Architect and Engineer; The Proceedings of the Building Arts Forum/New York Symposium held in April of 1989 at the Guggenheim Museum* (ed. D. Gans, E. English, E. Simpson, A. Webster, C. Gorczyca & T. Lefcochilos), pp. 23–48. New York, NY: Van Nostrand Reinhold.

PLEA 2015 About PLEA. [Online]. Available from: http://www.plea2015.it/about_plea/.

Radomski, S. 2009 Natural ventilation of enclosures driven by sources of buoyancy at different elevations. PhD thesis, Department of Civil and Environmental Engineering, Imperial College London, South Kensington, London, United Kingdom.

Robertson, A.S., Roberts, K.T. & Burge, P.S. 1990 The effects of a change in ventilation category on sickness absence rates and prevalence of sick building syndrome. *Indoor Air* **1**, 237–242.

Rouse, H., Baines, W.D. & Humphreys, H.W. 1953 Free convection over parallel sources of heat. *Proceedings of the Physical Society. Section B* **66** (5), 393–399.

Rouse, H., Yih, C.-S. & Humphreys, H.W. 1952 Gravitational convection from a boundary source. *Tellus* **4** (3), 201–210.

Russell, P., Durling, D., Griffiths, B. & Crum, G. 1997 Design guidelines... an unacceptable constraint on creativity or good design practice? In *International Conference on Design and Technology Educational Research and Curriculum Development* (ed. J.S. Smith), pp. 140–145. Loughborough University, United Kingdom.

Salingaros, N.A. & Masden II, K.G. 2008 Intelligence-based design: A sustainable foundation for worldwide architectural education. *Archnet-IJAR: International Journal of Architectural Research* **2** (1), 129–188.

Salvadori, M. 1991 Introduction: Architect versus Engineer. In *Bridging the Gap: Rethinking the Relationship of Architect and Engineer; The Proceedings of the Building Arts Forum/New York Symposium held in April of 1989 at the Guggenheim Museum* (ed. D. Gans, E. English, E. Simpson, A. Webster, C. Gorczyca & T. Lefcochilos), pp. xii–xv. New York, NY: Van Nostrand Reinhold.

Sandbach, S.D. & Lane-Serff, G.F. 2011 Transient buoyancy-driven ventilation: Part 2: Modelling heat transfer. *Building and Environment* **46** (8), 1589–1599.

Santamouris, M. & Asimakopoulos, D. 1996 *Passive cooling of buildings*. London, United Kingdom: James & James (Science Publishers) Ltd.

Sayigh, A. 2019 *Sustainable Vernacular Architecture: How the Past Can Enrich the Future*. Cham, Switzerland: Springer International Publishing.

Scopus 2017 About Scopus. Available from: www.info.scopus.com/about.

Scott, D.R. 1967 Education in Architectural Environmental Engineering and Design. In *Proceedings of the Institution of Mechanical Engineers*, *Part 3E*, vol. 182, pp. 161–192. London, United Kingdom: The Institution of Mechanical Engineers.

Seppänen, O. & Fisk, W.J. 2001 Association of ventilation system type with SBS symptoms in office workers. *Indoor Air* **12** (2), 98–112.

Short, A.C. 2017 *The recovery of natural environments in architecture: Air, comfort and climate*. London, United Kingdom: Taylor & Francis.

Short, A.C., Lomas K.J. & Woods, A.W. 2004 Design strategy for low-energy ventilation and cooling within an urban heat island. *Building Research and Information* **32** (3), 187–206.

Shrinivas, A.B. & Hunt, G.R. 2014*a* Transient ventilation dynamics induced by heat sources of unequal strength. *Journal of Fluid Mechanics* **738**, 34–64.

Shrinivas, A.B. & Hunt, G.R. 2014*b* Unconfined turbulent entrainment across density interfaces. *Journal of Fluid Mechanics* **757**, 573–598.

Shrinivas, A.B. & Hunt, G.R. 2015 Confined turbulent entrainment across density interfaces. *Journal of Fluid Mechanics* **779**, 116–143.

Szokolay, S.V. 1994 Science in Architectural Education. In *Proceedings of the 28th International ANZAScA Conference*, pp. 191–194. Geelong, Australia.

Thomas, R. 2006 *Environmental design: An introduction for architects and engineers*. London, United Kingdom: Taylor & Francis.

Till, J. 2005 *What is architectural research? Architectural Research: Three Myths and One Model*. Discussion Paper. London, United Kingdom: RIBA Research and Development.

Todesco, G. 1998 Efficiency through design integration. *ASHRAE Journal* **40** (6), 52–56.

Toftum, J. & Nielsen, R. 1996 Draught sensitivity is influenced by general thermal sensation. *International Journal of Industrial Ergonomics* **18** (4), 295–305.

Torcellini, P.A., Hayter, S.J. & Judkoff, R. 1999 Low-energy building design – the process and a case study. *ASHRAE Transactions* **105**, 802–810.

Turner, J.S. 1969 Buoyant plumes and thermals. *Annual Review of Fluid Mechanics* **1** (1), 29–44.

Turner, J.S. 1986 Turbulent entrainment: The development of the entrainment assumption, and its application to geophysical flows. *Journal of Fluid Mechanics* **173**, 431–471.

Ward, I.C. 2004 *Energy and environmental issues for the practising architect: A guide to help at the initial design stage*. London, United Kingdom: ICE Publishing.

Ward-Smith, A.J. 1980 *Internal fluid flow – the fluid dynamics of flow in pipes and ducts*. Oxford, United Kingdom: Oxford University Press.

Wood, D.S. 2003 A comparison of group-administered and mail-administered surveys of Alaskan village public safety officers. *Policing: An International Journal of Police Strategies & Management* **26** (2), 329–340.

Woods, A.W., Fitzgerald, S.D. & Livermore, S.R. 2009 A comparison of winter pre-heating requirements for natural displacement and natural mixing ventilation. *Energy and Buildings* **41** (12), 1306–1312.

World Health Organization 1983 Indoor air pollutants: Exposure and health effects. *Tech. Rep.* 78. WHO Regional Office for Europe, Copenhagen, Denmark.

Yannas, S. 2003 Towards environmentally-responsive architecture. In *Proceedings of PLEA 2003 the 20th Conference on Passive and Low Energy Architecture* (ed. G.W. Bustamante & B.E. Collados), pp. 1–6. Santiago, Chile: Escuela de Construccion Civil, Pontificia Universidad catolica de Chile.

Yuana, L.-M. & Cox, G. 1996 An experimental study of some line fires. *Fire Safety Journal* **27** (2), 123–139.

Appendix

For reference, herein we present the 25 questions that were asked in our questionnaire.

Questionnaire for architects on natural ventilation

Dear Colleague,

Please use this questionnaire to provide constructive feedback that will help us understand the needs of the architectural community in designing naturally ventilated buildings. Your feedback will offer valuable insight to improve our methods of conveying the physics of airflows in naturally buildings to architects. Thank you for your help.

Theme 1: Personal academic background

1. Do you have A-level or equivalent in

a. Mathematics	☐ Yes ☐ No
b. Physics	☐ Yes ☐ No
c. Science (Chemistry or Biology)	☐ Yes ☐ No
d. General Studies	☐ Yes ☐ No

2. Do you have a higher qualification than A-level in

a. Mathematics	☐ Yes ☐ No
b. Physics	☐ Yes ☐ No
c. Science (Chemistry or Biology)	☐ Yes ☐ No
d. Engineering	☐ Yes ☐ No

Theme 2: Preferred types of resource for natural ventilation design guidance

3. Which of the following journal papers and conference proceedings have you read or are interested in reading?

a. Building and Environment

Have read	☐ Yes ☐ No
Interested to read	☐ Yes ☐ No

b. Energy and Buildings
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
c. Applied Energy
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
d. Journal of Fluid Mechanics
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
e. Ergonomics
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
f. International Journal of Sustainable Built Environment
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
g. Proceedings of PLEA
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No
h. Proceedings of Roomvent
Have read ☐ Yes ☐ No
Interested to read ☐ Yes ☐ No

4. If you were designing a naturally ventilated building, which of the following sources of information would you use as reference for design guidance? (Tick all that apply)
☐ Design codes and building standards
State type/name: ______________________
☐ Previous experience and personal expectation
☐ Case studies of already built designs
☐ Scientific journals
State type/name: ______________________
☐ Architectural journals
State type/name: ______________________
☐ Other, *e.g.* conference proceedings, websites
State type/name: ______________________

5. Would you also consider seeking advice from the following individuals when designing a naturally ventilated building?
a. Expert ventilation engineers
☐ Yes ☐ No
State your reason: ______________________
b. Research academics in low-energy building ventilation
☐ Yes ☐ No
State your reason: ______________________
c. Practising architects in industry
☐ Yes ☐ No
State your reason: ______________________

Theme 3: Understanding of natural ventilation

6. How do you perceive your own knowledge of designing naturally ventilated buildings?
☐ None ☐ Some Thorough

7. Have you read articles on the subject of natural ventilation?
☐ Yes ☐ No
If yes, how many?
☐ 1-2 ☐ 3-5 ☐ 6+
Where did you find these articles? ________________

8. Have you been to any technical seminars, conferences and/or lectures on the subject of natural ventilation in buildings?
☐ Yes ☐ No
If yes, how many?
☐ 1-2 ☐ 3-5 ☐ 6+

9. Are you familiar with the following terms? (Tick all that apply)

☐ Adaptive thermal comfort	☐ Heat flux
☐ Air changes per hour	☐ Mixing flow
☐ Bidirectional flow	☐ Neutral pressure level
☐ Biomimicry	☐ Non-dimensional graph
☐ Buoyancy	☐ Pressure coefficient
☐ Cooling load	☐ Single-sided ventilation
☐ Cross ventilation	☐ Stratification
☐ Discharge coefficient	☐ Streamlines
☐ Displacement flow	☐ Solar chimney
☐ Draught risk	☐ Thermal interface
☐ Effective opening area	☐ Unidirectional flow
☐ Exchange flow	☐ Windcatcher

Theme 4: Natural ventilation design concerns

10. Would you consider designing a building using natural ventilation?
☐ Yes ☐ No
State your reason: ________________

11. Would you consider natural ventilation strategies to be effective for providing indoor comfort during the summer?
☐ Yes ☐ No
State your reason: ________________

12. Do you know how to size and locate openings to achieve

a. Ventilation flow rate you want	☐ Yes ☐ No
b. Comfortable airflow without draught	☐ Yes ☐ No
c. Wind-assisted flow rate	☐ Yes ☐ No

13. As an architect, do you think it is important to answer 'YES' to a, b, and c in question 12?
☐ Yes ☐ No
State your reason: ________________

Theme 5: Sketching airflow paths

14. Figures 1 and 2 are two sketches of almost identical buildings (see below). They each have one high-level vent and two low-level vents placed in the building envelope. The total vent area for both buildings (sum of the upper and lower vent areas) are identical. The external environment is windless and of uniform temperature.

a. The total area of the high-level vent in Figure 1 is made smaller compared to the total area of the low-level vents. Please draw arrows to indicate how you would expect the air to flow through the building in Figure 1.

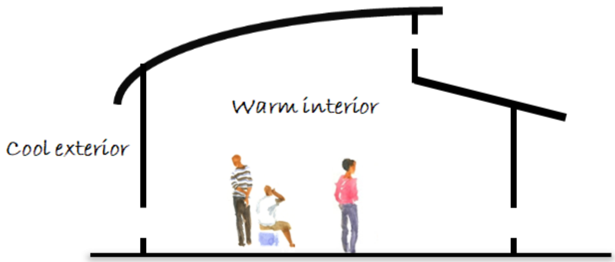


FIGURE 1: Sketch of a building in elevation showing a small upper vent.

b. The total area of the high-level vent in Figure 2 is made very large compared to the total area of the low-level vents. Please draw arrows to indicate how you would expect the air to flow through the building in Figure 2.

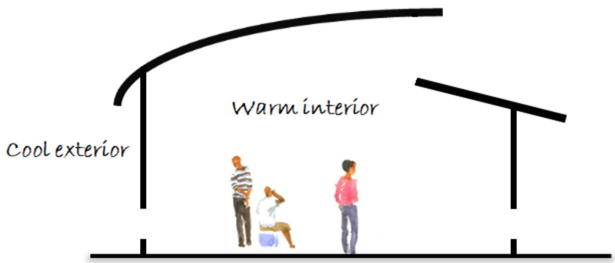


FIGURE 2: Sketch of a building in elevation showing a large upper vent.

15. Figure 3 shows a typical example of a 'box-like' representation of a room as used in the analyses of building ventilation in scientific journals.

a. Is it clear to you why Figure 3 can represent the building in Figure 1 (shown in question 14a.)?
☐ Yes ☐ No
State your reason: ____________________

b. Would you regard the schematic in Figure 3 to be disrespectful of architects' design aspirations?
☐ Yes ☐ No
If yes, how would you like Figure 3 to be visually represented? Provide a sketch below.

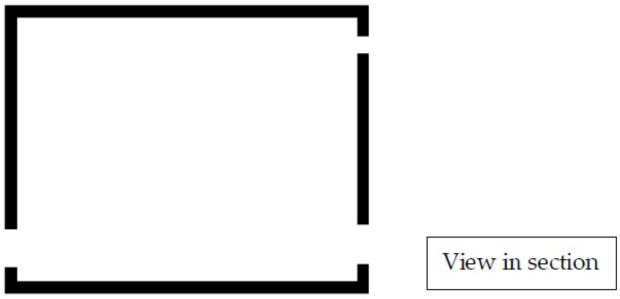


FIGURE 3: Line drawing of a typical 'box-like' ventilated enclosure.

Theme 6: Perceived barriers to natural ventilation design

16. Do you think the quantity of information regarding natural ventilation design is too overwhelming, making it difficult for you as an architect to choose the resources and/or options to use?
☐ Yes ☐ No

17. Do you think the quality of information regarding natural ventilation design is not tailored to the specific needs of architects?
☐ Yes ☐ No

18. Do you think ventilation requirements set by the building regulations and standards are too stringent?
☐ Yes ☐ No
If 'YES', do you think the strict ventilation requirements, set by the building regulations and standards, make it difficult for you as an architect to pursue a natural ventilation design option?
☐ Yes ☐ No

19. Do you perceive natural ventilation as unpredictable and unreliable as it may not meet ventilation and thermal comfort requirements?
☐ Yes ☐ No

20. Do you perceive inner city pollution and noise as barriers to natural ventilation design?
☐ Yes ☐ No

21. Do you think designing a naturally ventilated building restricts your freedom and creativity as an architect?
☐ Yes ☐ No
State your reason: ____________________

Theme 7: Expected future use

22. In the next 5-10 years would you like to see more buildings using natural ventilation as a low-energy strategy?
☐ Yes ☐ No
State your reason: ____________________

Theme 8: Desirable design guidance for architects

23. If a design guide was to be written specifically for architects on natural ventilation...
a. What subjects would you want to read about or have included? (Tick all that apply)
☐ How to size openings for natural ventilation
☐ How to design a building that uses night purge (*i.e.* flushing of warm air from a building/space at night)
☐ How to optimise the use of thermal mass and wind effects
☐ How to size and locate openings to make the best use of wind and stack effects
☐ Other
State subject: ____________________

b. Which of the following presentation styles would you think is ideal? (Tick all that apply)
☐ Diagrams, pictures and descriptions that impart visual information
☐ Mathematical equations and calculation examples to show how these formulae are used in practice
☐ Design graphs and data sheets; specific parameters can be read off the graphs to acquire the information that is needed in a natural ventilation design
☐ Checklists to help recognise necessary design tasks and decisions, *etc.*

c. How detailed would you prefer the design guide to be? (Choose one option)
☐ A short and concise guide with instructions on precisely how to design, *e.g.* simple steps on how to size openings
OR
☐ A lengthy guide in which the instructions are supplemented with detailed reasoning and arguments for the instructions developed

State the reason for your choice in (c): ____________________

24. Where would you like to see the design guide published? (Tick all that apply)

☐ In a series of research papers published in international journals
Please state type/name: ____________________
☐ In RIBA books
☐ In architectural digest(s)
Please state type/name: ____________________
☐ In a stand alone book, *e.g.* 'Natural Ventilation for Architects'
☐ Other
Please state type/name: ____________________

25. Any additional comments?