The impact of using Closed Cavity Façades (CCF) on buildings' thermal and visual performance

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Abstract. Glazing is a critical buildings element as it is the most vulnerable envelope part to heat gain and heat loss accounting for around 50% of a building's energy consumption. However, conventional glazing technologies have relatively low-performance characteristics which cause significant heat losses during winter and undesired heat gain in summer. In this regard, this study investigates the thermal and visual performance of various design configurations of a novel glazing technology, named Closed Cavity Façade (CCF), in comparison with traditional glazing technologies. Several CCF configurations were examined using Energy Plus and IDA ICE and compared to the baseline Double Glazing Unit (DGU) (traditional or thermochromic). MATELab, an office-like test facility at the University of Cambridge was used as the model for the simulations, which was beforehand experimentally validated. The results showed extensive benefits of CCFs compared to DGU systems, in terms of thermal performance and comfort. A 22-41% or 21-37% decrease in annual total energy consumption, compared to traditional DGU or thermochromic respectively, are identified along with a positive effect on thermal comfort with a significant reduction in radiant discomfort. Further investigation showed that glass coatings and solar shading device's characteristics play an important role in achieving further performance improvements.

Keywords
Closed cavity, façade, adaptive, dynamic, double-skin, energy efficiency, thermal comfort, visual comfort.

1. Introduction

Buildings are at the pivotal center of our lives. We spend, on average, 87-90% of our time in buildings [1]. Just as human skin is an all-important barrier and thermal regulator of the human body, the building "skin", as envisioned here, is the first critical element in defining goals for building energy performance and occupants' comfort. Buildings and the building construction sector combined are responsible for 36% of global total end-use energy whereas, in some developed countries this sector is responsible for up to 40% of the total energy consumption [2]. Particularly, the building sector in the EU is the largest single energy consumer absorbing 40% of final energy, while about 75% of buildings are energy inefficient [3]. On the 17th of April 2018, the European Parliament gave its final approval on the revised Energy Performance of Buildings Directive. Through this policy, the EU aims to make new and existing buildings smarter and more energy-efficient, and ultimately to cut CO_2 emissions by at least 40% by 2030 while each State Member must follow the path towards a low and zero-emission building stock by 2050 [3].

The building envelope, and in particular, the glazed openings play a significant role in the building energy consumption. In this regard, about 50% of the energy loss in buildings is attributed to glazing [4, 5]. Therefore, the glazed openings require detailed design and proper selection to provide the highest possible thermal and visual comfort with the lowest possible operational energy demand. It is a fact that in recent years, the window performance has been improved significantly through different window and glazing technologies and the use of several types of coatings, which in general make windows more energy-efficient [6]. However, conventional glazing technologies have relatively poor performance characteristics which cause significant heat losses during winter and undesired heat gain in summer. Hence, during the last two decades, sustainable building design is rapidly moving towards a more holistic design approach, aiming to design innovative high-performance façade systems able to provide high thermal insulation and react to outdoor environment and occupants' requirements to reduce building energy demands and enhance thermal and visual comfort [6, 7]. Such an innovative adaptive façade technology, the Closed Cavity Façade (CCF) has been studied in this work emphasising its thermal, visual and comfort performance, for various types of climates, compared to the traditional double-glazing unit (DGU) as well as to a DGU with thermochromic outer pane and gap filled with Argon.

2. From Double Skin Façade (DSF) to Closed Cavity Façade (CCF)

In contemporary glass office buildings, with window-to-wall ratio (WWR) often around 80%, aiming to maximize daylight and viewing outside, innovative façade systems compared to traditional double-glazed are required to reduce energy demands and meet occupants' comfort requirements imposed by the increasingly stringent codes. A milestone, during the last decade of the previous century, was the development of the Double-Skin-Façade (DSF) which was used mainly in commercial and high-rise buildings. It consists of three distinct layers: interior glazed system, ventilated air cavity, and exterior glazed system. Despite the numerous advantages of DSFs, a few limitations, such as the loss of useful building space and the higher necessary investment, maintenance and cleaning costs associated with DSFs, impede the deployment of them in a greater number of buildings and led to the search for other solutions. A solution for extremely demanding building envelopes with the best properties for insulation and sun protection was still missing until the end of the first decade of this century where a new idea for a DSF type, called Closed Cavity Façade (CCF), was devised. It consists of double or triple glazing on the inner layer and single glazing on the outer (figure 1), forming a cavity with an integrated shading device in between. CCFs present different functional and operational advantages as compared to DSFs, such as preventing accumulation and settlement of dust and particles in the cavity, reducing maintenance cost, eliminating the complexity of the airflow control, and increasing the service life of components inside the cavity [8] etc. Rather than ventilating the double skin, the CCF panels are sealed and equipped with a pressurized supply system of filtered and dehumidified air which supplies dry air in the sealed cavity to control cavity pressure, suppress condensation and avoid heat build-up inside the cavity.

Compared to a conventional externally or internally ventilated DSF, which typically requires around 600 mm distance between glass skins for maintenance, the theoretical thickness of a CCF is 130-150 mm whereas in practice this is approximately 200-250 mm [8]. This significant advantage of the CCF results in less required useful building space for the façade while allowing its prefabrication and consequentially reducing the manufacturing and installation cost.

Since CCF is a relatively recent development in the market of glazing façade technology, there are only a few research papers that investigate the main features, performance, benefits, and limitations of this façade system. Particularly, there is a lack of studies that systematically investigate the performance of different configurations of CCFs in all types of climates. Thus, the main objective of this work is to investigate the thermal, visual, and occupants' comfort performance of various configurations of CCFs in different types of climates.

3. Method

To address the main question of this study, 'how to enhance buildings thermal and comfort performance using CCFs', several CCF configurations, geometries and materials were investigated and compared to the baseline, a conventional DGU or a DGU with thermochromic outer pane and gap filled with Argon. In this regard, various simulation tools (WINDOW 7.7, Energy Plus 8.9.0 and IDA ICE 4.8 SP2) were used to build-up the CCFs configurations and simulate their indoor climate and energy performance for various climates using, as a model for the simulations, the MATELab, an office-like test facility at the University of Cambridge. A detailed description of the methodological steps that were followed is presented below.

3.1 Build-up of CCF configurations

To investigate the performance of CCFs for various climates, a set of different configurations has been built-up considering various types of glass panes, with or without coatings applied, and two types of integrated Venetian blinds. The glass pane of the outer skin and the outer pane of the double inner skin are of 4mm thickness whereas, the innermost pane is tempered of 6mm thickness due to safety considerations. The various CCF configurations are grouped into three groups namely CCFD 1, CCFD 2 and CCFD 3 which are schematically shown in figure 1.

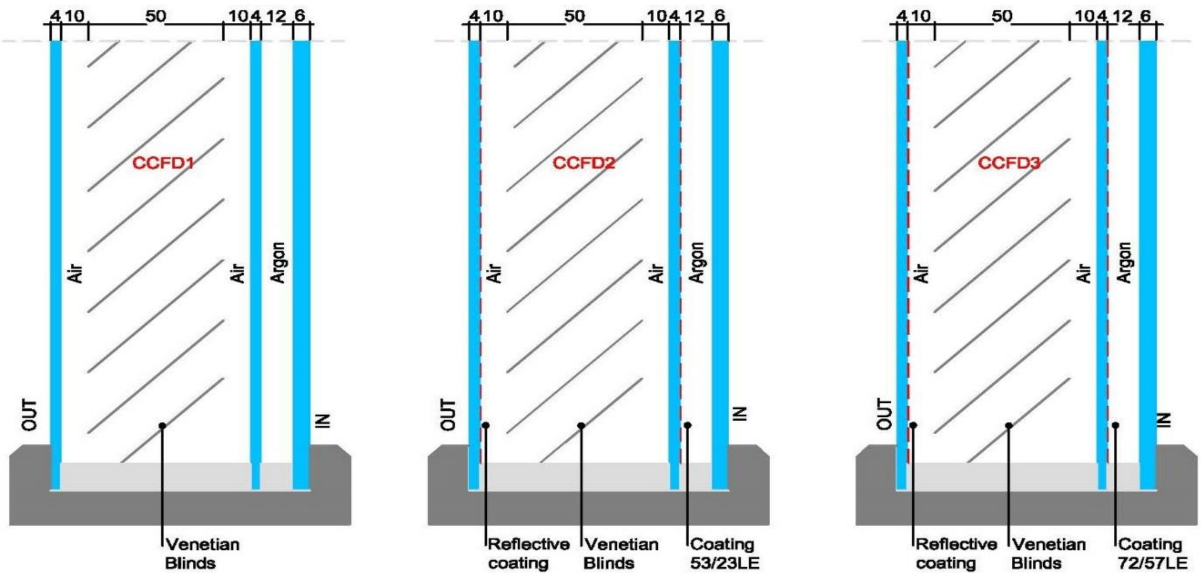

Figure 1. Schematic diagrams of the three groups of CCFs configurations simulated.

Each group includes three configurations: without integrated Venetian blinds, with white horizontal blinds at 45^{o} slat angle (VB1) and the last one integrates wooden coloured horizontal blinds at 45^{o} (VB2). The glass panes of the systems of the first group do not have any applied coatings whereas, for the second group a reflective coating reducing the solar radiation entering the CCF cavity and a high-performance coating 53/23 LE (T_{vis}/T_{sol}) are applied on surfaces No. 2 and No. 4, respectively. Lastly, the systems of the third group are similar to that of the second group with the only difference that the high-performance coating applied on surface No. 4 is of the type 72/57 LE. The build-up of the CCF configurations has been performed and their performance values (U-value, g-value, solar transmittance $T_{sol,}$ visible solar transmittance $T_{vis,}$ emittance of outermost surface E1, and emittance of innermost surface E2), presented in table 1, have been calculated using the software WINDOW 7.7. For the assessment of the CCF configurations in comparison with the baseline DGU (traditional or thermochromic), the values of table 1 are inserted into the Energy Plus and IDA ICE simulation packages considering that the blinds are fully retracted when the incident radiation level on the façade is less than 250 W/m^2 while when this threshold is reached the blinds automatically are fully deployed.

Table 1. Performance values of CCF glazing configurations simulated.

Glazing	U-value [W/m^{2}K]	g-value [-]	T_{sol} [-]	T_{vis} [-]	E1 [-]	E2 [-]
DGU-Baseline	2.631	0.727	0.637	0.781	0.840	0.840
DGU-Thermochromic	2.461	0.548	0.442	0.391	0.840	0.840
CCFD1-w/oVB	1.672	0.653	0.531	0.701	0.840	0.840
CCFD1-VB1	1.240	0.259	0.123	0.169	0.840	0.840
CCFD1-VB2	1.247	0.286	0.039	0.045	0.840	0.840
CCFD2-w/oVB	0.971	0.156	0.115	0.343	0.021	0.840
CCFD2-VB1	0.780	0.070	0.026	0.077	0.021	0.840
CCFD2-VB2	0.783	0.070	0.007	0.022	0.021	0.840
CCFD3-w/oVB	1.255	0.219	0.165	0.460	0.021	0.840
CCFD3-VB1	1.021	0.086	0.038	0.103	0.021	0.840
CCFD3-VB2	1.026	0.081	0.029	0.011	0.021	0.840

3.2 Locations and climate classes

The locations selected to be used for this comparative study comprise cities of different weather characteristics that have building markets with significant potential for high-rise office buildings, where CCFs can be implemented. Eight cities were selected aiming to investigate the performance of the CCF technology for different Köppen climate classes. Table 2 shows the maximum and minimum daily temperatures and global radiation for each climate from which the significant differences in terms of temperature are highlighted.

Table 2. Key climatic data for the selected locations (retrieved from Energy Plus and Meteonorm websites).

Location	Climate class (Köppen)	Climate characteristic name	Maximum daily temperature (ºC)	Minimum daily temperature (ºC)	Maximum daily global radiation (kWh/m^2)	Minimum daily global radiation (kWh/m^2)
Rio de Janeiro	Aw	Tropical savanna	35.8	15.1	9.1	1.3
Dubai	Bwh	Dry Desert Hot	46.1	11.2	7.5	1.8
Sydney	Cfa	Temperate Humid	37.0	5.0	9.4	1.2
New York	Cfa	Temperate Humid	35.8	-13.0	8.8	0.4
London	Cfb	Temperate Oceanic	28.8	-5.0	8.8	0.1
Toronto	Dfa	Continental hot-summer humid	34.5	-20.0	8.9	0.2
Beijing	Dwa	Continental Monsoon-influenced	39.1	-15.0	7.1	0.8
Helsinki	Dfb	Continental warm- summer humid	30.1	-22.0	8.8	0.0

3.3 Modelling and performance simulation of the CCF configurations

Indoor climate and energy modelling was performed in Energy Plus 8.9.0 and IDA ICE 4.8 SP2 building simulation tools, two of the most advanced building performance analysis software, which can assess, for instance, the energy demand (cooling, heating, ventilating and lighting), solar gains and temperatures (space and surfaces), visual and comfort indices, etc. considering façade performance, integrated blinds characteristics and activation settings, HVAC system set-points, lighting, occupancy and equipment schedules, etc. The one-thermal zone model consists of the MATELab (Mobile Adaptive Technologies Experimental Lab), a novel full-scale outdoor test cell in Cambridge (UK).

MATELab has overall dimensions of 6.4x5.4x3.4 m and approximately 35 m^2 floor area. It can host up to three occupants and it has three glazed façades on the south (S1, S2), east (E1, E2, E3) and west (W1, W2, W3) whereas the north façade is an opaque wall. Its glazed façades can be easily changed or covered with opaque insulated panels to test alternative façade technologies [9]. MATELab's envelope is highly insulated with external profiled and sealed polyurethane panels to provide high thermal efficiency and airtightness, minimising thermal bridges and air infiltration. All the artificial services in MATELab (lighting, heating, cooling and ventilation) have been designed to ensure comfortable conditions and a high level of indoor air quality (IAQ) for occupants. Figure 2 shows the real MATELab experimental facility, its 3-D CAD drawing and the model in IDA ICE software.

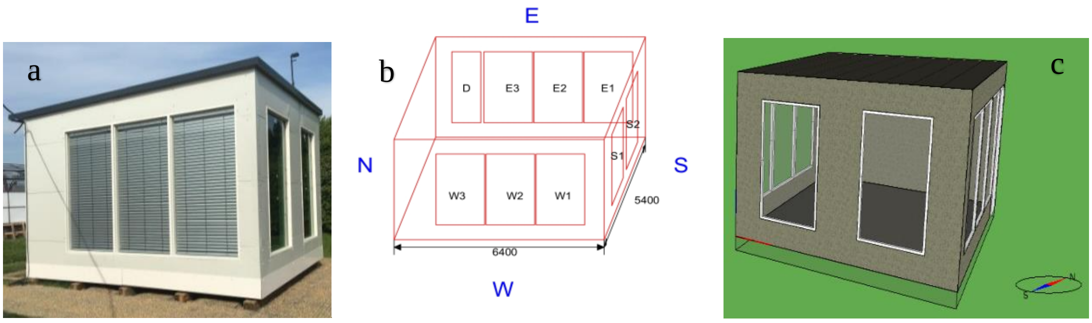

Figure 2. (a) The real MATELab experimental facility, (b) The 3-D CAD drawing and (c) The model in IDA ICE.

The whole model consists of a single zone office, occupied by two people on a weekday working schedule from 08:00-17:00 whereas for all other days (weekends & holidays) the office is unoccupied. Each occupant is modelled as an internal load of 120 W (CIBSE Guide A - Environmental Design (2015)) and it is assumed that each occupant uses electronic equipment (PC, printer etc.) which corresponds to 50 W/person, operating only during office working hours. The lighting system consists of dimmable LED lamps regulating the illuminance level to at least 500 lux in the office zone (CIBSE Guide LG7 - Offices (2015)). The nominal lighting power is set to 12 W/m^2. Lighting control is continuous meaning that the overhead lights dim continuously and linearly from maximum to minimum light output as the daylight illuminance varies.

The HVAC system is assumed to have an unlimited capacity for heating and cooling (ideal loads air system). According to CIBSE Guide A - Environmental Design 2015, the HVAC heating set-point is set to 20 ^{o}C for the occupied hours (08:00-17:00) and 14 ^{o}C during the rest of the unoccupied time. The cooling set-point is set to 24 ^{o}C and 30 ^{o}C respectively. The ventilation is mechanical, set to 14 lt/s/person during occupied hours and 1.4 lt/s/person during the unoccupied time. The infiltration was assumed to be of a constant value of 0.3 air changes/hour throughout the year.

The Venetian blinds incorporated in the CCFs are controlled via a binary control logic allowing the Venetian blinds to be deployed only whenever the external incident radiation on the façade exceeds the threshold of 250 W/m^2. The specific optical and thermal characteristics of CCF configurations were imported into the model from table 1. The indoor climate and energy models were created for eight different location-climate types described in table 2.

4. Results and discussions

The indoor climate and energy performance analysis for each combination type of façade-location focused on the following:

- From the energy efficiency point of view: (i) the total annual energy consumption (heating, cooling, ventilating, lighting) in kWh and (ii) the total annual energy demand per unit of floor area in kWh/m^2
- From the thermal comfort point of view: (i) the percentage of total occupant hours with thermal dissatisfaction, (ii) the percentage of hours when the operative temperature is above 27°C, (iii) the Fanger's comfort indices and (iv) the thermal comfort according to EN 15251
- From the visual comfort point of view: (i) the Daylight Factor (%) and (ii) the illuminance (lux), both at a working plane 0.5 m away from the perimeter and 0.8 m above floor level.

Interpretation of the above results revealed that the most efficient CCF configuration is the CCFD2-VB1. The quantified percentage improvement (100*(DGU-CCF)/DGU) of each of the above performance metrics of the CCF, compared to the traditional DGU, for each location, is calculated and displayed in figure 3. The improvement achieved, for the total energy consumption lies in the range 21.8% (Helsinki)-40.7% (Sydney), increasing from continental to temperate climates. This improvement is mainly due to the benefit achieved in terms of g-value from the integrated Venetian blinds in the cavity (table 1 shows a g-value of 0.070 for CCF with white blinds and 53/23 LE coating). Therefore, the CCF, compared to the DGU, is more efficient in reducing solar gain through the façade, which is the main contributor to energy consumption in cooling-dominated climates where the improvements achieved using CCFs are mainly related to the reduction in the cooling load. For instance, the CCF compared to the DGU in Dubai achieves a decrease in heating load of only 4.3 kWh/m^2 whereas the achieved cooling load decrease is 79.8 kWh/m^2.

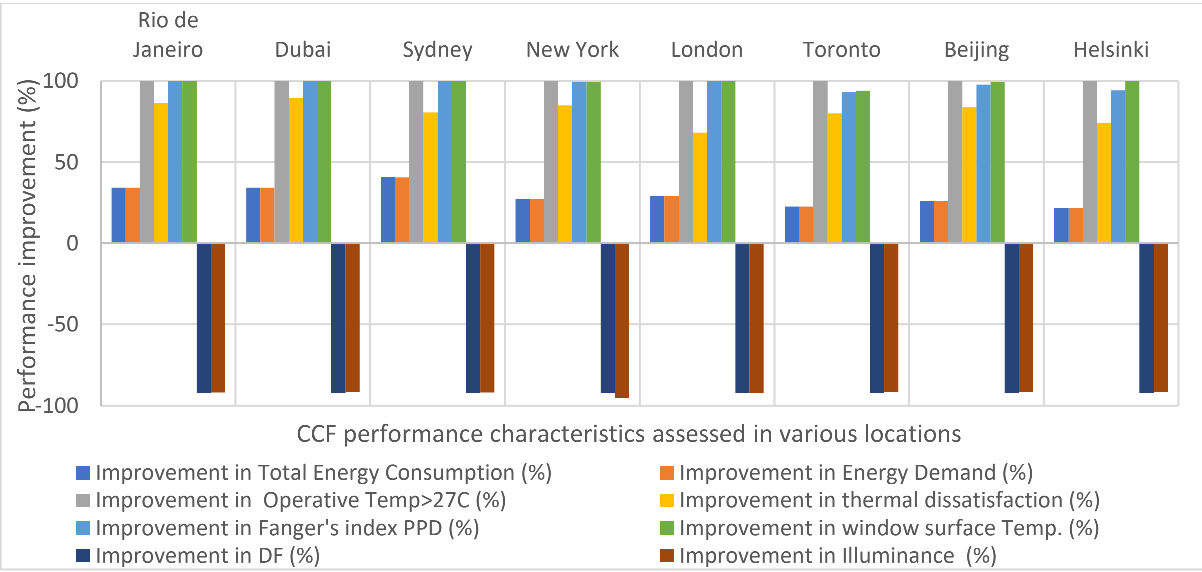

Figure 3. Performance improvements (%) of CCF compared to conventional DGU.

Comparing the effect of the blinds' colour on the reduction of the energy consumption results that the lighter coloured blinds show better performance (1-4% higher improvement) compared to blinds with a darker colour. Also, the use of different coatings has a slight impact on the CCF performance.

For example, the CCFD2 with the 53/23 LE displays slightly better performance (2.2-4.8% higher improvement) compared to the CCFD3 with the 72/57 LE coating.

From the thermal comfort point of view, the comparative study between CCF and traditional DGU confirmed the expected benefits of the CCF as presented in figure 3. In this regard, the improvement in total occupant hours with thermal dissatisfaction when using a CCF was in the range 68.2% (London)-89.6% (Dubai) increasing from continental to temperate and hot climates. Additionally, the improvement in the percentage of hours with the operative temperature above 27°C is 100% which means that using a CCF, for all the climates studied, the operative temperature never exceeds the threshold of 27 °C whereas, in the case of the DGU the percentage of hours with the operative temperature above 27°C lies in the range 27% (London)-88% (Dubai). The impact of using a CCF was also examined considering the thermal comfort according to EN 15251. The result was that for the dry desert hot climate of Dubai for example, the number of occupancy hours with unacceptable comfort with a DGU is 2031 compared to only 15 hours when using a CCF. Furthermore, considering Fanger's comfort indices, predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV), the benefits of using CCF compared to traditional DGU was reconfirmed. When a CCF is used, the PPD never exceeds the value of 11% whereas, in the case of a DGU, it reaches values of up to 98%. Additionally, considering a PMV comfort threshold between -0.5 and 0.5, figure 4 shows that the CCF never exceeds this threshold while the DGU is possible to reach the value of 5.

A factor that significantly affects the occupants' comfort, particularly those sitting adjacent to windows, is the surfaces' temperatures developed during the occupancy hours. In this regard, for example, the surface temperatures of all the windows of the model were examined, for a typical summer day in Dubai, resulting in that when a conventional DGU is used the windows' surfaces reach the value of 47 °C compared to the significantly lower value of 32 °C in the case of using a CCF.

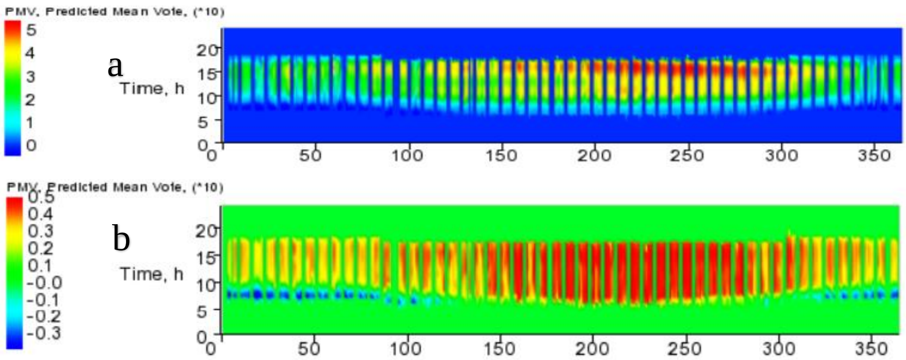

Figure 4. Fanger's index PMV in dry desert hot climate of Dubai (a) for DGU and (b) for CCF.

From the visual comfort point of view, two performance metrics were examined, the Daylight Factor (DF) and the illuminance, both measured on a working plane 0.5 m away from the perimeter and 0.8 m above floor level. In figure 3, the comparative results of using CCF or conventional DGU are illustrated, for all the investigated locations-climates. The DF, when the CCF is used, is significantly reduced by up to 92% for all climates. The illuminance was also reduced by a significant amount lying in the range of 91.5-95.5% in the case of CCF. Despite this disadvantage of the CCF, it was observed that, except for the Temperate Humid and Temperate Oceanic climates (New York and London), the illuminance level achieved using the CCF lies above or marginally near the required threshold of 500 lux for office spaces.

Following the same methodology, an additional study was performed for the same climatic classes comparing the CCF configurations with a thermochromic double glazing unit consisting of an outer 7 mm thermochromic pane, 12 mm gap filled with Argon and a 6 mm inner clear floating pane.

Interpretation of the simulation results revealed that the improvements achieved by CCF compared to the thermochromic glazing as baseline are slightly lower than those achieved when the reference glazing is the conventional DGU. For instance, the improvement achieved by the CCF for the total energy consumption lies in the range 21.2% (Helsinki)-37.3% (Sydney) when the baseline is the thermochromig glazing instead of 21.8%-40.7% with conventional DGU. From the thermal comfort point of view, the improvement in total occupant hours with thermal dissatisfaction when using a CCF was in the range 53.3% (London)-87.5% (Dubai) when the reference is the thermochromic instead of 68.2%-89.6% when the baseline is the traditional DGU. Considering the thermal comfort according to EN 15251, the result was that for the dry desert hot climate of Dubai for example, the number of occupancy hours with unacceptable comfort with a thermochromic DGU is 1917 compared to only 15 hours when using a CCF. From the visual comfort point of view, the comparative results of using CCF or thermochromic DGU showed that the DF, when the CCF is used, is reduced by up to 82.9% for all climates whereas, the illuminance was reduced by a significant amount lying in the range of 82.3-82.6% compared to 91.5-95.5% when the baseline is the conventional DGU.

5. Conclusions and future work

The current study examines the impact on buildings' energy performance and occupants' thermal and visual comfort level using a novel façade named Closed Cavity Façade (CCF). A baseline DGU (conventional or thermochromic) and nine different configurations of CCF were simulated in IDA ICE and Energy Plus building simulation tools, in eight different locations-climates. The performance analyses carried out, for the eighty-eight combinations of CCF configuration-climate, results in extensive benefits in terms of energy performance and comfort, of using a CCF compared to the DGU (conventional or thermochromic). All the CCF configurations, and in all the climates investigated, led to significant improvement of energy consumption in the range of 22-41% compared to the conventional DGU or 21-37% compared to thermochromic DGU used as the baseline. This is mainly attributed to the improved thermal transmittance and g-value because of integrating Venetian blinds in the cavity and of applying suitable glass coatings. A higher energy improvement is observed in cooling-dominated locations since the CCF significantly reduces the solar gain through the façade, which is the main contributor to energy consumption. Furthermore, this study shows that the suitable selection of the components of a CCF system (colour of blinds, glazing coatings etc.) plays an essential role in the level of improvement of its energy and comfort performance. Another significant benefit of the use of CCF is the improvement of the users' comfort, achieving values of Fanger's comfort indices, PPD and PMV, less than 11% and in the range -0.5-0.5, respectively. Despite its plethora of advantages, the CCF reduces visual comfort by remarkably decreasing the DF and illuminance level in the space. This occurs due to the reduced value of its T_{vis} normally being around 0.1. However, for many climates, such as Tropical and Continental, the proper selection of CCF components is possible to result in acceptable illuminance levels (500lux).

This study, in addition to the conclusions it reached, brought to light new research questions such as investigation of overheating in the CCF cavity, transient performance analysis of CCF using CFD, performance analysis of CCF using different blinds control strategies and slat angles, comparative performance analysis of CCF with triple inner skin and a triple glazing unit (TGU) as baseline for various climates.

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