Extending the applicability of the adaptive comfort model to the control of air-conditioning systems

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Abstract:

Extensive studies have been done on adaptive thermal comfort for naturally ventilated buildings. However, further studies of the adaptive comfort model are needed to develop a control method for buildings with the air-conditioning systems. This study aims to extend the application of the adaptive comfort model by developing an adaptive comfort control (ACC) for air-conditioning systems. Special attention is given to testing the acceptability of the ACC to the occupants of the office buildings. Two extensive longitudinal field studies were carried out that involved 807 office workers and a total of 13,523 individual comfort votes were collected. This study reveals that it is possible to develop statistically and substantively significant adaptive comfort models for the cooling operation of air-conditioned buildings. This field study provides scientific evidence that the adaptive comfort model can be used to control an air-conditioning system without sacrificing occupants' thermal comfort. Further field studies on air-conditioned buildings are warranted to quantify the energy use implications of the ACC.

Keywords: Adaptive comfort; Control; Air-conditioning; Adaptive opportunity; Field study.

1. Introduction

Buildings are one of the largest energy end-use sectors, responsible for 32% of total global energy consumption [1] and 60% of global electricity consumption [2]. Greenhouse gas (GHG) emissions from the building sector have been increasing continuously since 1970 and reached 9.18 billion metric tonnes of carbon dioxide equivalent (tCO2e) in 2010, representing 19% of global GHG emissions [3]. Without active efforts to reduce building energy use, global energy consumption in buildings is expected to double by 2050 through rapid urbanization, economic development, and increased demands for comfort [4]. Thus, it is critical to understand how buildings use energy for comfort, in order to reduce GHG emissions from the building sector.

One fundamental function of a building is to provide a comfortable indoor climate for its occupants, and a large amount of energy is used in the process of creating such environments [5,6]. Globally, space conditioning to meet thermal comfort requirements accounted for 34–40% of the final energy consumption in both residential and commercial buildings in 2010 [4]. In the European Union, space conditioning is the largest energy end use in the building sector, representing 69% of residential energy consumption and 45% of commercial energy use in 2010 [7]. Thus, it is evident that maintaining thermal comfort is a key factor in how buildings use energy and consequently in GHG emissions from buildings.

Research on thermal comfort has taken two approaches — the heat balance model and the adaptive model. The heat balance model, developed by Fanger [8], is based on a series of climate chamber studies that investigate both the conditions for thermal equilibrium between a human body and its surroundings and the thermal perception of building occupants in a wide range of environmental conditions with four environmental elements (air temperature, radiant temperature, humidity, and air velocity) and two personal factors (insulation level of clothing and metabolic rate). Fanger’s seminal work, on the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) models, have been adopted widely in standards such as International Standard Organization (ISO) 7730 [9], European Standard EN 15251 [10], and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55 [11].

On the one hand, many studies have examined the validity of the PMV model through climate chambers and field studies. Several climate chamber studies confirmed that the predicted thermal responses from the PMV model on the ASHRAE comfort scale were similar to the actual mean vote (AMV) of human subjects for thermally neutral conditions. Doherty and Arens [12] showed that the PMV model accurately predicted the thermal sensation of resting subjects in a climate chamber when the effective temperature was between 26°C and 30°C. Parsons [13] found that the difference between PMV and AMV values was less than 0.5 of a 7-point ASHRAE comfort scale for neural conditions. Zhang and Zhao [14] found that the PMV model was valid only in steady and uniform thermal conditions.

On the other hand, many field studies have found large discrepancies between PMV values and the actual thermal sensations of people in everyday thermal environments in real buildings where people use various adaptive measures to attain thermal comfort [15,16,17]. Humphreys and Nicol [18] found that the PMV model differed noticeably from the AMV value for both air-conditioned and naturally ventilated buildings using the ASHRAE thermal comfort database prepared by de Dear and Brager [19]. Using the same ASHRAE database, De Dear and Brager [20] showed that the PMV model was unreliable in predicting the thermal responses of people in naturally ventilated buildings. Field studies to test the applicability of the PMV model to young children [21,22] and university students [23,24] found that modifications were required to the original PMV model to reduce the discrepancy between predicted and actual thermal sensations.

In response to those field studies showing the inaccurate prediction of the PMV model, several researchers tried to improve the original PMV model. Fanger and Totfum [25] proposed an ‘expectancy factor’ to extend the application of the PMV model to naturally ventilated buildings.

Alfano et al. [26] also developed an expectancy factor to apply the original PMV for Mediterranean schools. Humphreys and Nicol [18] revised the PMV model using the ASHRAE thermal comfort database to reduce the bias between predicted and actual thermal sensations. Yao et al. [27] proposed an adaptive PMV model that included an adaptive coefficient to represent the adaptive factors of people in real buildings. Recently, Kim et al. [28] developed two types of adaptive PMV models using the methods proposed by Humphreys and Nicol [18] and Yao et al. [27].

The adaptive comfort model of thermal comfort was introduced in the 1970s based on field studies of people in buildings that found that comfort temperatures were not fixed, but changed with outdoor temperatures [29]. The adaptive comfort model is best characterized by the work of Nicol and Humphreys [30,31] and de Dear and Brager [19,20] and has mainly focused on naturally ventilated buildings [32]. The adaptive comfort model in ASHRAE 55 [11] was intended to determine acceptable thermal conditions in naturally ventilated buildings, and the adaptive model in EN 15251 [10] specified comfort temperatures for free-running buildings. Several other researchers developed adaptive comfort models for naturally ventilated residential buildings [33,34,35,36]. Ye et al. developed an adaptive model for residential buildings with natural ventilation in Shanghai [36], and Wong et al. [33] and Indraganti [35] highlighted the importance of adaptive behaviour of occupants in residential buildings.

The adaptive comfort model for office buildings with natural ventilation and hybrid ventilation has been also actively investigated [37,38,39]. Daghigh et al. [37] revealed that predictions from the adaptive comfort model in ASHRAE 55 were in line with the actual thermal comfort sensations of people in naturally ventilated offices. Yang and Zhang [38] developed an adaptive model for naturally ventilated office buildings and showed that people in naturally ventilated buildings were more tolerant of higher temperatures than people in air-conditioned buildings. Field studies in Shenzhen, China [39], and Sydney, Australia [40], found that the thermal perceptions of occupants in a mixed-mode building were successfully represented by the adaptive comfort model when the natural ventilation mode was in use.

The adaptive comfort model commonly uses the monthly mean temperature as the index for outdoor temperature, although comfort temperatures change within a month as the outdoor temperature varies [41]. In particular, there were only a few field studies developing an adaptive comfort model for air-conditioned buildings with an outdoor running mean temperature instead of the monthly mean temperature. This is because field studies for air-conditioned buildings focused on the test of the accuracy of PMV index [15]. McCartney and Nicol [42] developed adaptive comfort models for air-conditioned buildings in Europe, while Yun et al. [43] proposed the adaptive comfort model for the office buildings with air-conditioning systems in Seoul, Korea. Both models used the outdoor running mean temperatures as a predictor so that an air-conditioning control system based on the developed adaptive comfort models could respond to outdoor temperature variations. However, further studies to develop the control method for an air-conditioning system using the adaptive comfort model are needed to test if or to what extent the adaptive comfort model can be used in control systems [42].

Based on the previous research on the adaptive comfort model, this study aims to test its application to the control of air-conditioned buildings by developing an adaptive comfort control (ACC) strategy for air-conditioning systems. We have given special attention to testing the acceptability of the ACC to the occupants of air-conditioned office buildings.

2. Methods

2.1 Data acquisition for the development of the adaptive comfort model

We began by conducting extensive longitudinal field studies on the thermal perceptions of 551 office workers in air-conditioned buildings, along with measurements of indoor and outdoor environmental conditions from July 2009 to February 2010 and from January 2012 to December

2012 to cover a full cycle of the seasons. We used the 11,161 individual comfort votes (11,161 questionnaire sets) collected during those longitudinal field studies to develop an adaptive comfort model for air-conditioned buildings. Survey participants were office workers in four offices in the area of Seoul, South Korea (37° N, 126° E), which has a humid continental climate with hot humid summers and cold dry winters, with strong seasonality (Figure 1). The participants worked in open plan offices with electric air conditioning systems. The first and second offices were equipped with ductless, split heat pumps for heating and cooling and were monitored from July 2009 to February 2010. Direct-expansion air handling units (DX AHU) were used in the third office, and a variable refrigerant flow (VRF) air conditioning system that provided heating and cooling was installed in the fourth office, with energy recovery ventilators to meet fresh air requirements. Individual indoor units in the offices with the ductless, split heat pump and VRF system were controlled by the office workers. The monitoring period for the third and fourth offices was from January 2012 to December 2012. The DX AHU were operated by a central building energy management system (BEMS) that determined all operation parameters, including the opening ratio of the outdoor air damper and setpoint temperatures. Office workers in the office with the DX AHU had remote controllers to adjust indoor units. Only the two offices with the ductless, split heat pumps had operable windows, but the windows were rarely opened by office workers due to external noise and poor outdoor air quality.

We obtained outdoor conditions from external temperature and humidity data loggers, HOBO U23-002 with solar radiation shields, installed on the roofs of the monitored offices. HOBO U23-002 has an accuracy of ± 0.2K for air temperature and ± 2.5% for relative humidity, with a measurement range from – 40°C to 75°C. We used 28 standalone data loggers (HOBO U12-012; accuracy of ± 0.35K for air temperature and ± 2.5% for relative humidity) to measure the indoor air temperatures and humidity levels experienced by participating office workers at 10 minute intervals throughout the whole monitoring period. We positioned the indoor data loggers on the tops of desk partitions 1.1m above the floor near participating office workers to characterize the local indoor environment experienced by the office workers. In addition, we measured globe temperatures using a temperature sensor (HOBO TMC1-HD) with its probe inserted at the centre of a black painted table tennis ball for the monitoring period from January 2012 to December 2012, taking care to avoid exposure to heat sources such as direct solar radiation and the heat dissipating fans of personal computers. The operative temperature that is calculated from air temperature, radiant temperature and air speed was used in the analysis.

Each office worker received a paper folder with comfort questionnaires coded to indicate their location within each building. We collected and replaced the folders every two weeks. The office workers were asked to fill out a questionnaire five times a day (twice in the morning, twice in the afternoon, and once in the evening) during the monitoring period from July 2009 to February 2010. In 2012, we reduced the number of daily questionnaire surveys to one to minimize interruptions at work. Office workers assessed their thermal comfort using the ASHRAE thermal comfort scale ranging from cold (-3) to hot (+3), with neutral (0) in the middle. A question to evaluate thermal preference adopted a five-point scale: ‘Warmer’, ‘Slightly warmer’, ‘No change’, ‘Slightly cooler’, and ‘Cooler’.

2.2 Test of the occupant acceptability of the adaptive comfort control

After we developed our adaptive comfort model using our collected data (described in section 3 below), we applied it to the air-conditioning systems of two offices to test its acceptability to the building occupants. The two offices were those with the DX AHU and the VRF system from our monitoring study because the DX AHU and the VRF system market showed rapid growth in South Korea. We determined the daily setpoint temperatures using our adaptive comfort model just after midnight because the daily optimal comfort temperature in the adaptive comfort model depends on the outdoor daily mean temperature of the previous day and the running mean of the outdoor temperature [10,30,31,32,43]. The BEMS operator controlled the DX AHU using the daily setpoint temperature from the adaptive comfort model, whereas a data management server (DMS) controlled the VRF system. During the monitoring period, the indoor control units were disabled. Building occupants did not know that the air-conditioning systems were being operated following the adaptive comfort model.

The monitoring period for the occupant acceptability testing of the ACC was from August 2013 to September 2013. We collected 2,362 questionnaire sets from 256 office workers during this field study. We used the same questionnaire survey folders we had used during the 2012 monitoring period. The monitoring method for measuring outdoor air temperature, indoor air temperature, globe temperature, and relative humidity remained unchanged from the first field study.

3. Adaptive comfort model for air-conditioned buildings

3.1 Outdoor and indoor conditions

Figure 1 shows the outdoor air temperature distributions during the monitoring period, which represent the typical Korean climate with a clear seasonal variation ($F_{(3,15111)}=49637$, $P < 0.001$). The average outdoor temperature was 14.6°C in spring (standard deviation, SD=4.7°C) and rose to 26.6°C (SD=2.7°C) in summer. The average temperature dropped to 10.6°C in autumn and reached a low of -0.1°C (SD=4.4°C) in winter. The average monthly temperature from 1981 to 2010 was 25.6°C in August and 0.0°C in December [44]. The maximum outdoor temperature during the monitoring period was 34.9°C in summer, and the minimum temperature was -10.3°C, which shows the wide variation in outdoor temperatures during the monitoring period. There were also clear distinctions in outdoor absolute humidity among the seasons ($F_{(3,15111)}=73311$, $P < 0.001$). The mean absolute humidity ranged from 2.2 g/kg (SD = 0.1 g/kg) in winter to 15.1 g/kg (SD = 0.2 g/kg) in summer. Thus, the outdoor conditions during the monitoring period were characterized by a hot humid summer and a cold dry winter.

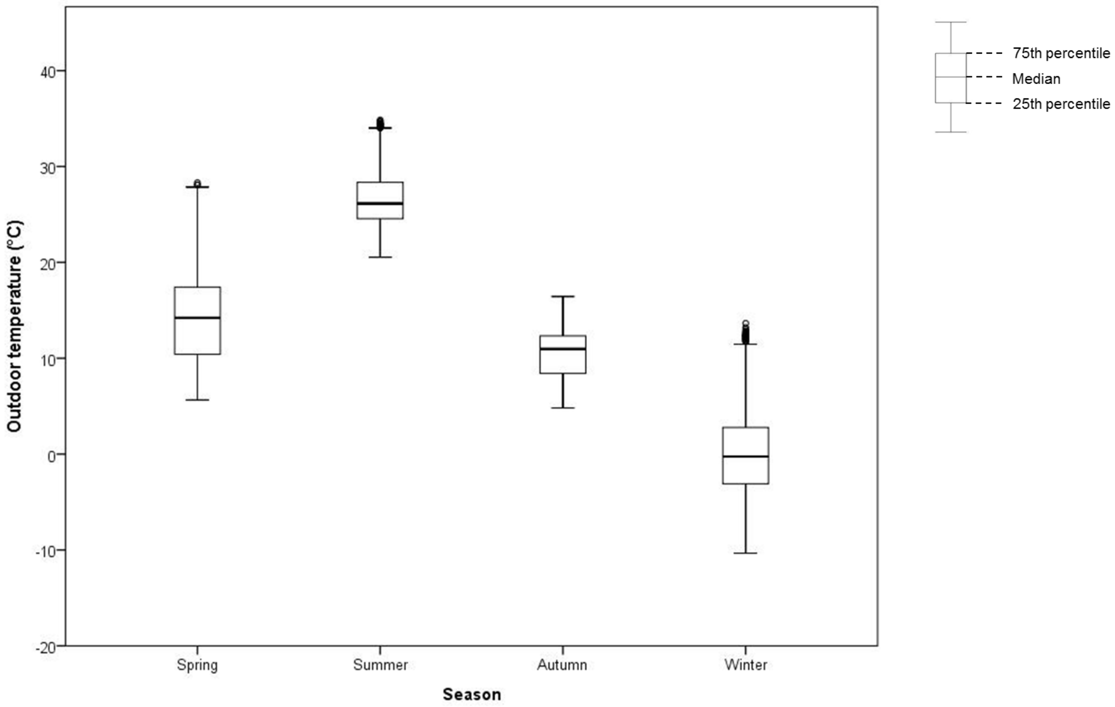

Figure 1. Outdoor air temperature distribution during the monitoring period

Indoor air temperatures recorded from the standalone data loggers ranged from 10.8°C to 34.1°C during the monitoring period (Figure 2). One-way analysis of variance (ANOVA) test is applied to examine whether the seasonal variations during the monitoring period is statistically meaningful. The statistical analysis program, SPSS Statistics version 22, was used in this study. The statistical test in this study was carried out with the statistical analysis program, SPSS Statistics version 22. The variation in indoor temperatures as a function of the seasons was statistically significant ($F_{(3,275745)}$=26192, $P < 0.001$) but less clear than that in outdoor temperatures. The average temperature during the whole monitoring period was 24.5°C (SD=3.3°C), and the interquartile range, the difference between the upper and lower quartiles, was only 3.5°C. The average temperatures in summer and winter were 26.5°C (SD=1.5°C) and 23.0°C (SD=3.7°C), respectively, which suggests that there were adaptive adjustments such as changes in setpoint temperatures.

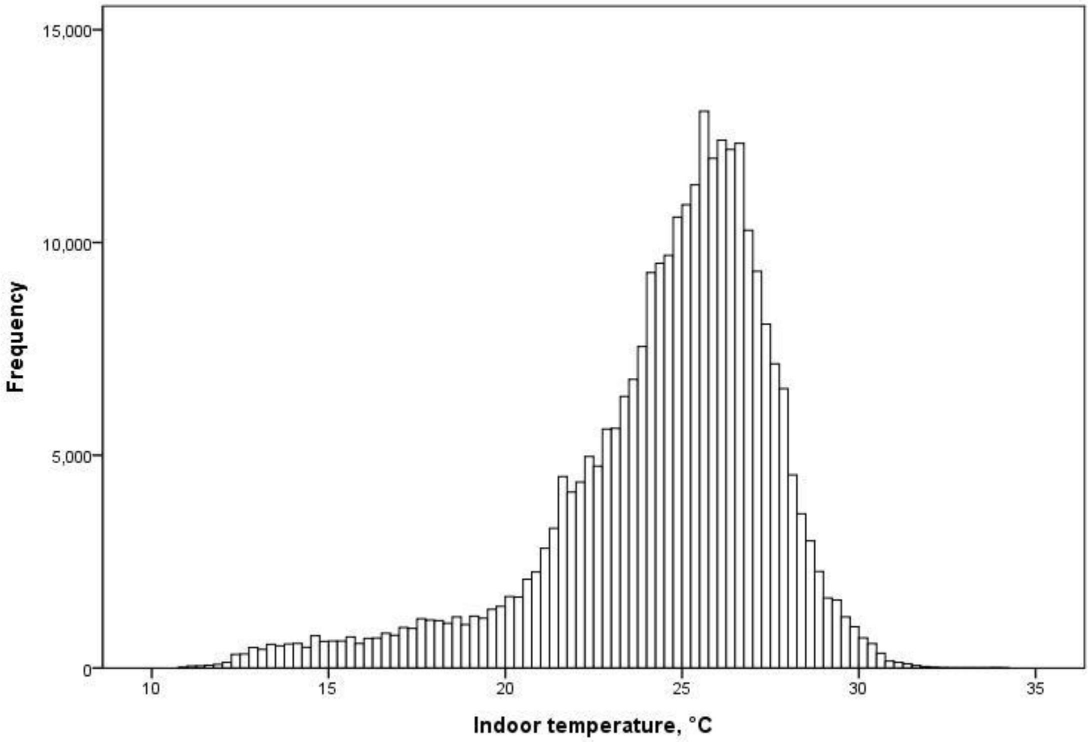

Figure 2. Indoor temperature distribution during the monitoring period

We investigated the change in indoor temperature in relation to variation in outdoor temperatures (Figure 3) and found a positive correlation. As the outdoor temperature increased, so did the indoor temperature. The Pearson correlation coefficient, R, between indoor and outdoor temperatures is 0.466 ($F_{(1,7728)}$)=2139, $P<0.001$). A potential reason for this correlation is that the indoor temperatures in Figure 3 includes periods when buildings were unoccupied and so heating or cooling systems were turned off. Also, Internal and solar heat gains would be a potential reason why indoor temperatures were sometimes higher than outdoor temperatures.

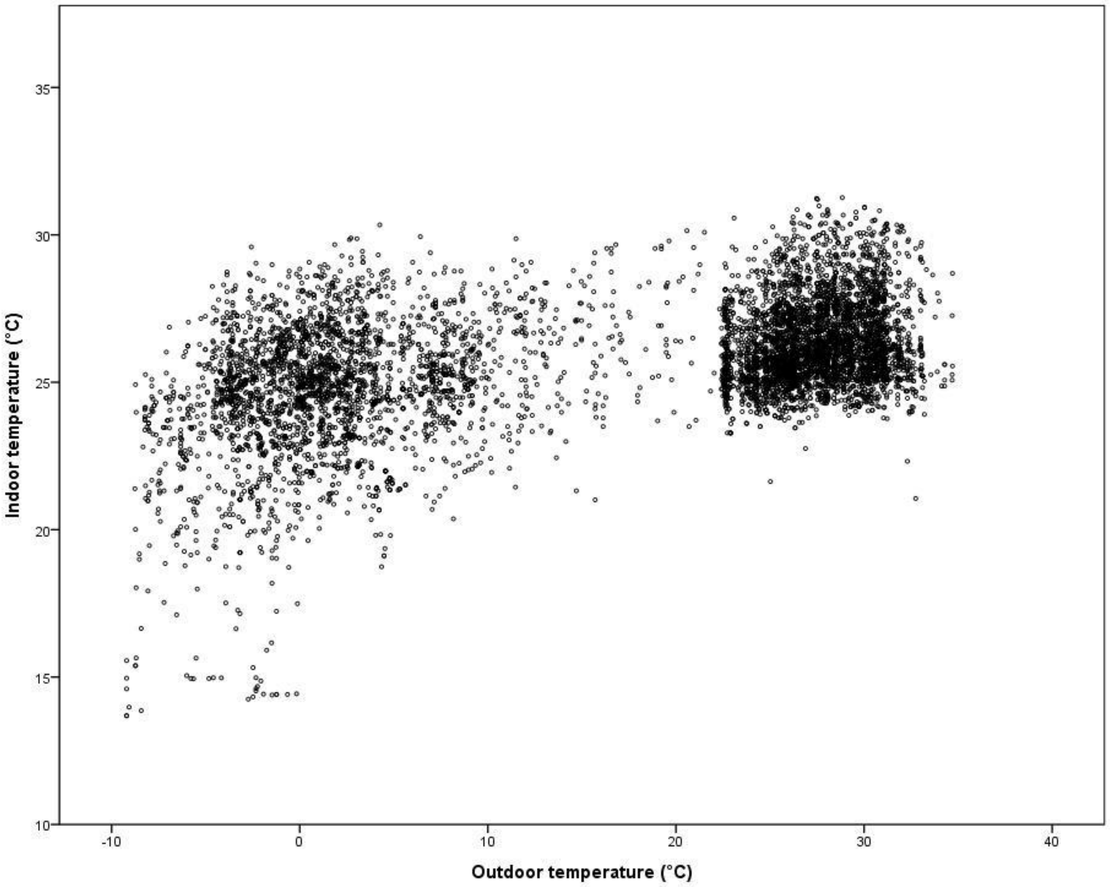

Figure 3. Relationship between outdoor and indoor temperatures

After we revealed the positive relationship between indoor and outdoor temperatures, we investigated a potential relationship between the optimal comfort temperatures of office workers and prevailing outdoor temperatures. The optimal comfort temperature refers to indoor temperature for which building occupants will vote neutral on the ASHRAE scale and is calculated using the comfort vote from office workers investigated using the method by Humphreys and Nicol [42]. The monitored data indicates a statistically significant relationship between the optimal comfort temperature of office workers in air-conditioned buildings and outdoor temperatures (Figure 4). The Pearson correlation coefficient, R, is 0.404 ($F_{(1,7728)}$)=2506, P<0.001). This analysis indicates that the optimal comfort temperature of survey participants in the air-conditioned offices changed with outdoor temperatures, although the cooling and heating setpoint temperatures were not determined by a change in outdoor temperatures.

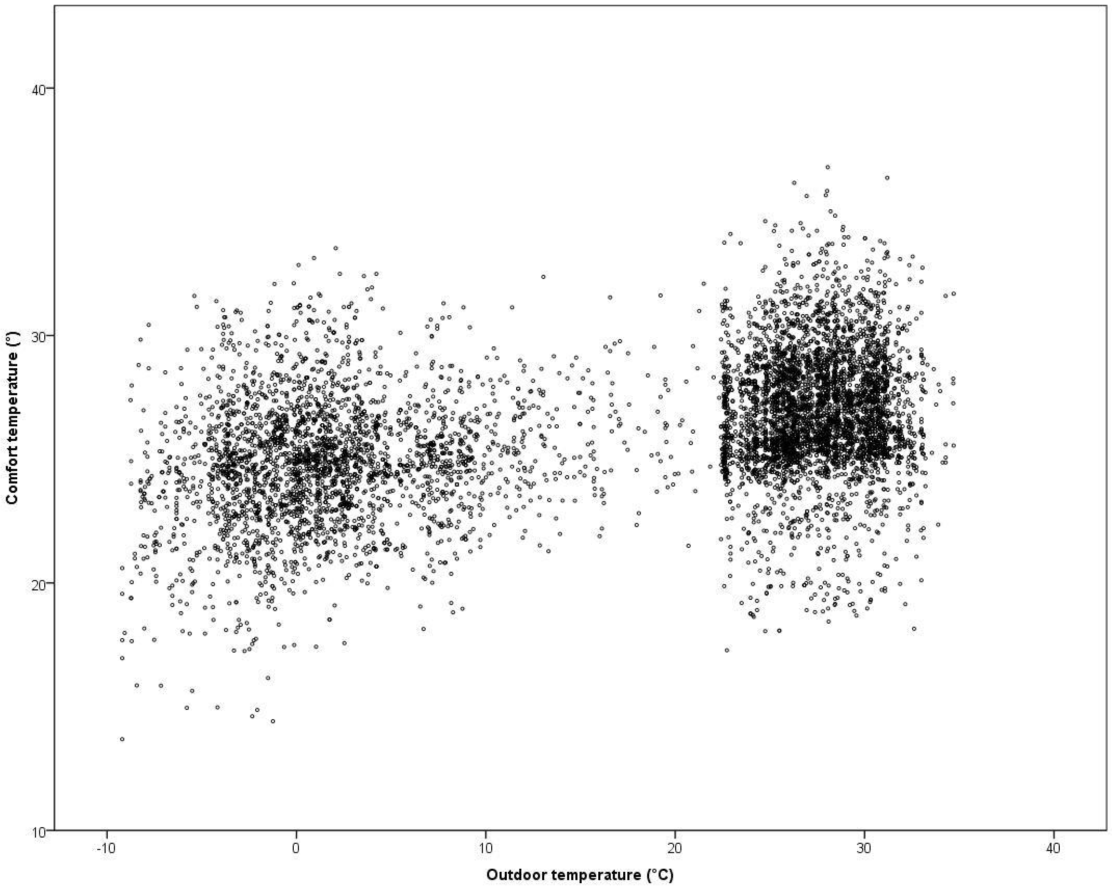

Figure 4. Relationship between outdoor and optimal comfort temperatures

Table 1 compares the indoor temperatures of the interior office zone with those of the perimeter zone, which was directly influenced by the outdoor conditions. We set the depth of the perimeter zone from the external wall as 2.5 times the floor to ceiling height in this study. The results show that the indoor temperatures for the interior and perimeter zones differed from each other. The temperature of the perimeter zone was higher than that of the interior zone in summer, whereas the temperature was higher in the interior zone in winter. The difference between the interior and perimeter zones was most evident in the afternoon. For example, the average temperature difference in spring was 0.8K in the afternoon and only 0.1K in the morning. The temperature difference between the interior and perimeter zones increased as the indoor and outdoor temperature difference became greater. The largest temperature difference, found in winter, was 0.9K in the morning.

Table 1. Mean indoor temperatures for the perimeter and interior zones of the fourth office with the VRF system

Indoor temperature (℃)		Morning (06 AM to 12 PM)		Afternoon (12 PM to 6 PM)		Evening (6 PM to 12 AM)	
		Interior zone	Perimeter zone	Interior zone	Perimeter zone	Interior zone	Perimeter zone
Spring	Mean	25.1	25.2	27.3	28.1	25.3	25.1
	Standard deviation	1.7	2.3	0.8	1.5	1.7	2.1
Summer	Mean	25.8	26.2	26.8	27.4	25.4	25.5
	Standard deviation	1.2	1.6	0.6	1.3	0.9	1.3
Autumn	Mean	25.5	24.9	27.0	26.8	25.6	24.8
	Standard deviation	1.3	1.5	1.1	1.1	1.3	1.5
Winter	Mean	24.0	23.1	27.0	26.1	24.6	23.5
	Standard deviation	2.3	2.5	1.3	1.3	2.4	2.5

We developed our adaptive comfort models for air-conditioned buildings from data obtained from all buildings in the study to predict daily optimal comfort temperatures using a running mean outdoor temperature (Table 2). Our basic equation for the adaptive comfort model is as follows:

$$T_{c(n)} = aT_{rm(n)} + b \qquad \text{Equation (1)}$$

where $T_{c(n)}$ is the optimal comfort temperature for day n, and $T_{rm(n)}$ is the weighted running mean temperature for day n. Nicol and Humphreys [31,32] proposed the running mean temperature to better reflect the effect of past outdoor temperatures and represent the time-dependence of the optimal comfort temperature. The running mean temperature is given by Equation (2):

$$T_{rm(n)} = (1-\alpha)T_{out(n-1)} + \alpha T_{rm(n-1)} \qquad \text{Equation (2)}$$

where $T_{out(n-1)}$ is the mean outdoor temperature for day n-1 and α is a constant between 0 and 1. The constant α determines the responsiveness of the running mean temperature to a change in outdoor temperatures. Previous studies [42,43] found that an α value of 0.8 gave the best fit between running mean temperature and optimal comfort temperature in Europe and Korea. Thus, we set the α value at 0.8 in this study. Research has shown that the strength of the correlation between optimal comfort temperature and outdoor temperature for buildings with mechanical heating or cooling systems changes at an outdoor temperature of 10°C [19,29,30]. The relationship is close when the outdoor temperature is above 10°C; however, outdoor temperature is not a good indicator at or below an outdoor temperature of 10°C. Thus, we have developed separate models for heating and cooling operation modes, and we have assumed that the heating mode would come in to effect at or below an outdoor temperature of 10°C. Table 2 summarizes the adaptive comfort models for the air-conditioned buildings. We used the F-test to examine the statistical significance of an overall model and the T-test to examine the significance of the running mean temperature variable as a predictor in the model, both with a significance level of $P < 0.05$.

F-tests indicate that the adaptive comfort models in Table 2 are statistically significant at the significance level of $P < 0.001$, except for the models of the heating mode. For example, the adaptive comfort model of the heating mode for the interior zone was not statistically or substantively meaningful ($P = 0.222$, $R = 0.031$). The model implies that the optimal comfort temperature should change very little with the outdoor temperature because the coefficient value for the outdoor temperature was only 0.0022. In addition, T-test results show that the outdoor temperature was not a statistically significant predictor of optimal comfort temperature in the heating mode when outdoor temperature was less than 10°C. However, the adaptive comfort models for the cooling mode, when outdoor temperature was equal to or higher than 10°C, were all statistically meaningful at the significance level of $P < 0.001$. Also, the Pearson correlation coefficients for the cooling models indicate that a correlation between the optimal comfort temperature and the running mean outdoor temperature was high, with R values higher than 0.67. According to Cohen [45], an R value higher than 0.5 indicates that the effect size or strength of the relationship is large in social and behavioural research.

Table 2. Adaptive comfort models for air-conditioned buildings as a function of thermal zones

Thermal zone	Operation mode	Coefficient		F test		T test		R
		a	b	F-statistic	P value	T-statistic	P value	
Perimeter & Interior	Cooling	0.238	20.089	5233	< 0.001	72	< 0.001	0.731
	Heating	0.053	23.963	16	< 0.001	4	< 0.001	0.075
Perimeter	Cooling	0.191	21.044	1179	< 0.001	34	< 0.001	0.670
	Heating	0.029	23.973	2	0.107	1.614	0.107	0.047
Interior	Cooling	0.245	19.988	4122	< 0.001	64	< 0.001	0.761
	Heating	0.022	24.101	1	0.222	1	0.222	0.031

4. Occupant acceptability of the adaptive comfort control for the air-conditioning system

After we developed adaptive comfort models for the cooling mode that are statistically and substantively significant, we applied them to the control of air-conditioning systems to test their occupant acceptability. Figure 5 shows the outdoor temperature distribution during the monitoring period from August 2013 to September 2013, which was a typical summer season in South Korea. The outdoor temperature during the second monitoring period ranged from 13.2°C to 34.8°C, with an average temperature of 24.8°C (SD = 3.9°C). The outdoor temperature range stayed within the range we used when developing the adaptive comfort model, so the application of the adaptive comfort model was free from extrapolation.

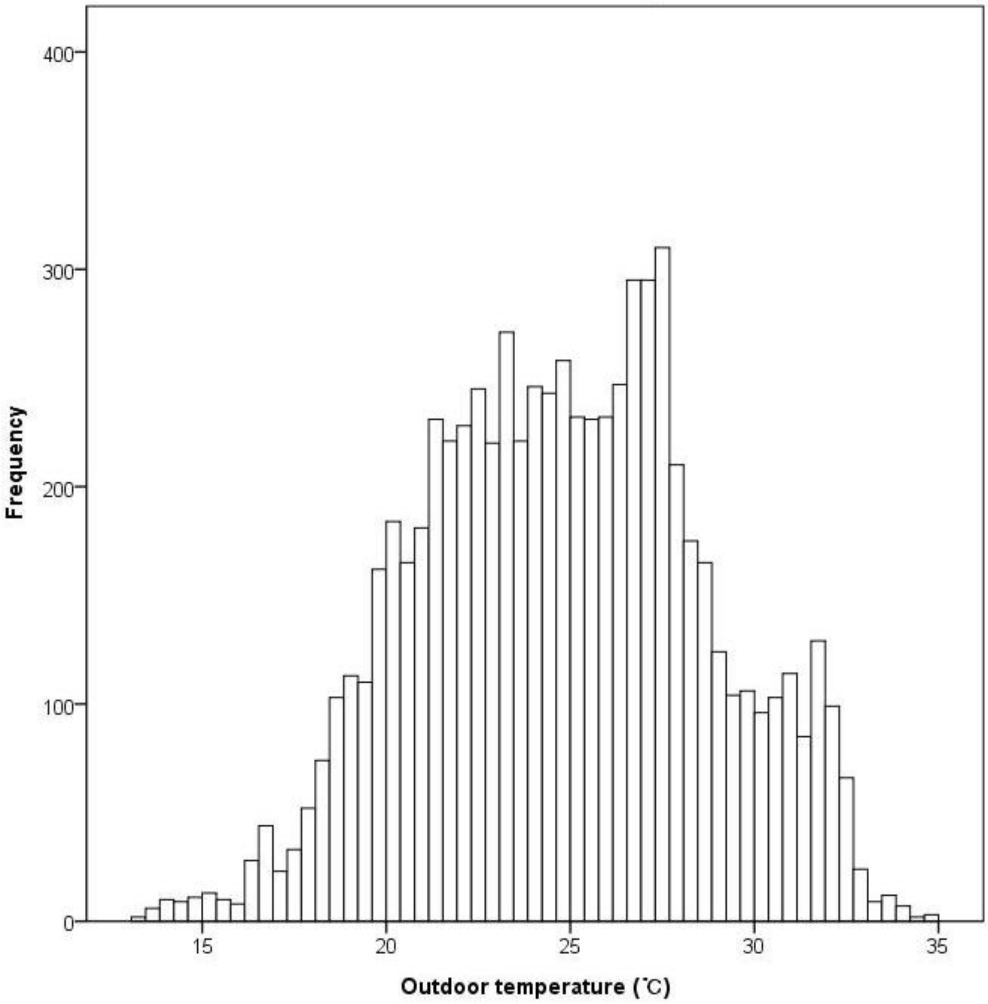

Figure 5. Outdoor temperature distribution during the monitoring period for testing the acceptability of the adaptive comfort control

We determined the setpoint temperatures for the DX AHU and VRF system using our adaptive comfort model (Table 2). We had to use the adaptive comfort model for the whole zone because the air-conditioning systems in the participating offices could not accommodate the distinction between the perimeter and interior zones. Figure 6 illustrates the daily setpoint temperatures for the DX AHU and VRF system in the offices. The setpoint temperatures ranged from 25°C to 28°C. The minimum interval of the temperature settings for the VRF system was 1K. The setpoint temperatures were equal to or greater than 26°C except for September 30th, when the setpoint temperature was 25°C. 48 per cent of the monitoring period was controlled at or higher than 27°C. The setpoint temperatures applied in this study were considerably higher than the thermal comfort conditions recommended by ASHRAE Standard 55 (22°C for summer assuming a relative humidity of 50%, a mean relative velocity lower than 0.15 m/s, and a metabolic rate of 1.2 met) [46]. The existing setpoint temperature for the office with the DX AHU in the cooling period of 2012, before the adaptive comfort control was applied, was set at 23°C. Occupants in an office with the VRF system had remote controllers to change setpoint temperatures of the indoor units in 2012. As a result, occupants freely changed setpoint temperatures. Building facility managers informed us that the setpoint temperatures of the indoor unit in the cooling season of 2012 were in most cases lower than 24 °C and often less than 22°C.

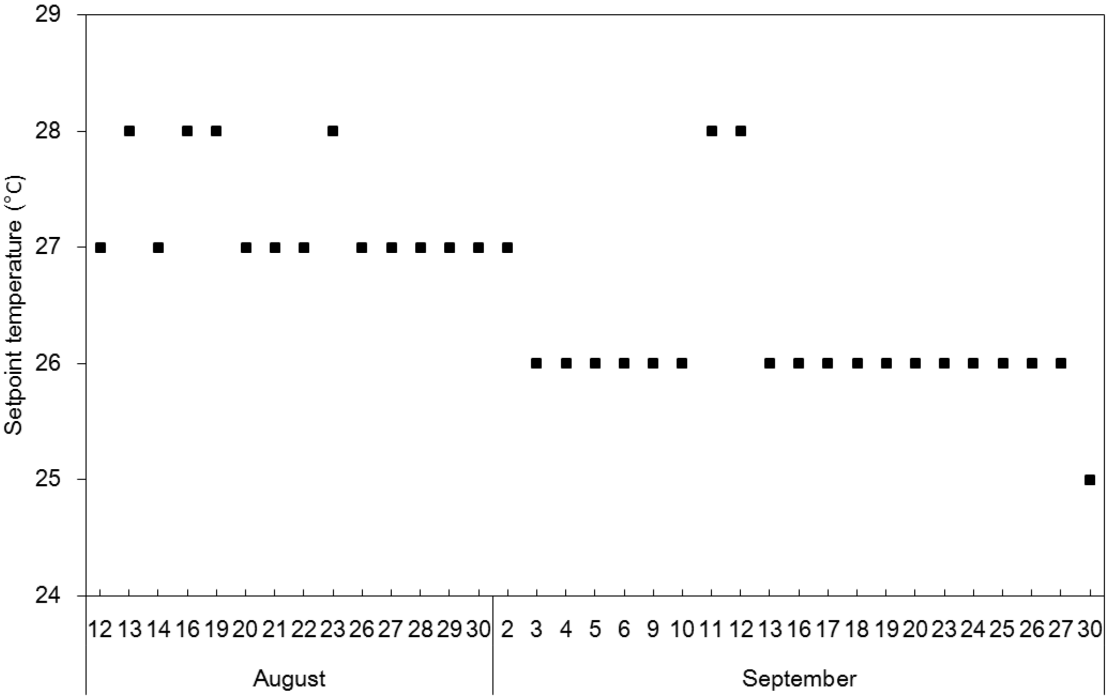

Figure 6. Setpoint temperatures for the DX AHU and VRF system

Figure 7 illustrates the indoor temperature distributions of the investigated offices during the test for occupant acceptability of the adaptive comfort model. The average indoor temperature was 26.6°C (SD = 1.2°C) in the office with the DX AHU and 25.7°C (SD = 0.6°C) in the office with the VRF system. One reason for the higher indoor temperature in the office with the DX AHU was a malfunction of the DX AHU from the afternoon of September 19th to the morning of September 20th. The indoor temperature increased to above 30°C, peaking at 32.4°C in the afternoon of September 19th due to the fault of the DX AHU. Office workers still worked during the period that the DX AHU was not operating; therefore, we included the data from that period in the analysis.

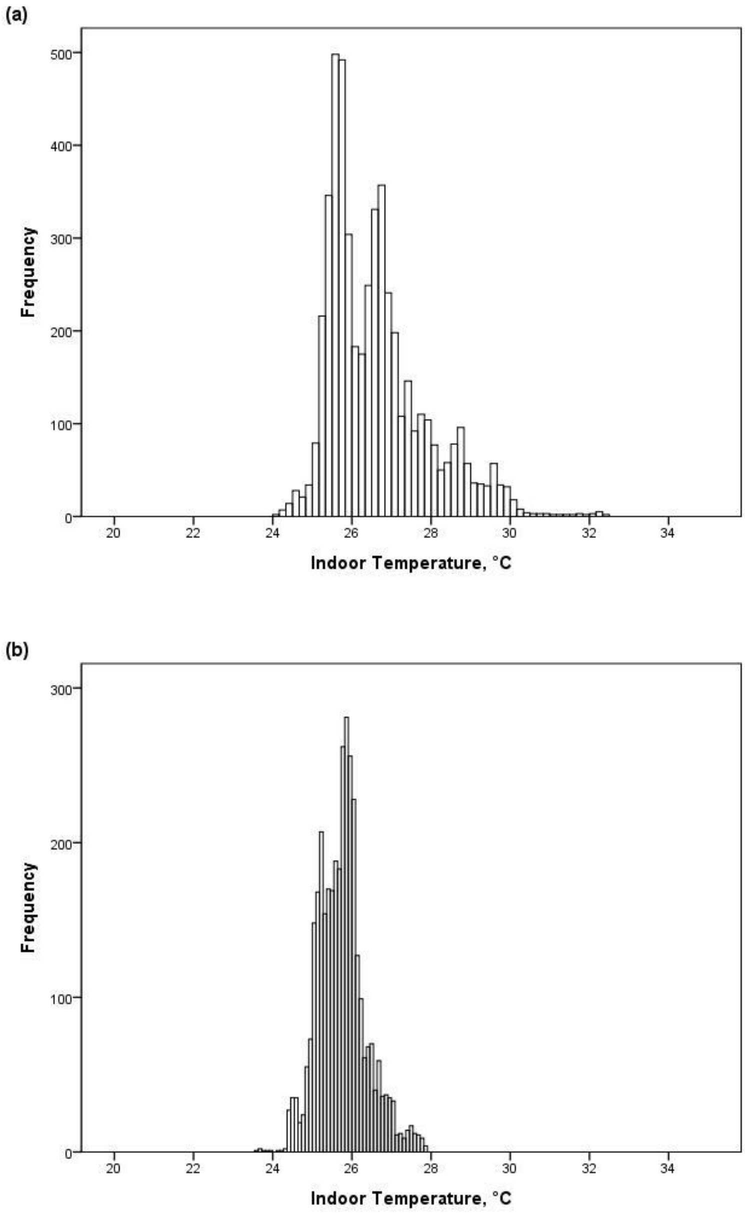

Figure 7. Indoor temperature distributions during the test for occupant acceptability of the adaptive comfort model, (a) Office with DX AHU, (b) Office with VRF system

Figure 8 shows that office workers mostly accepted the indoor thermal conditions set using the adaptive comfort model. Office workers who voted -1, 0, or +1 were assumed to accept their thermal conditions in this study. The percentage of office workers who accepted the thermal conditions was 83% in the office with DX AHU and 87% in the office with the VRF system. Fewer than 1 per cent of the thermal sensation votes were -2 (Cold), and the ratio of the votes above 1 was 15 per cent in the office with the DX AHU and 13 per cent in the office with the VRF system.

The rate of acceptance by office workers reduced from 90% to 83% in the office with the DX AHU and from 94% to 87% in the office with the VRF system. The reduction was relatively small considering the setpoint temperature by the adaptive comfort control was 2K to 5K higher than that of the existing control and also the fact that the occupants of the office with the VRF system lost their controllability over indoor units when the adaptive comfort control was applied. The comfort conditions met existing standards [9,11], though theoretically acceptance rates reduced slightly by an average of 7%.

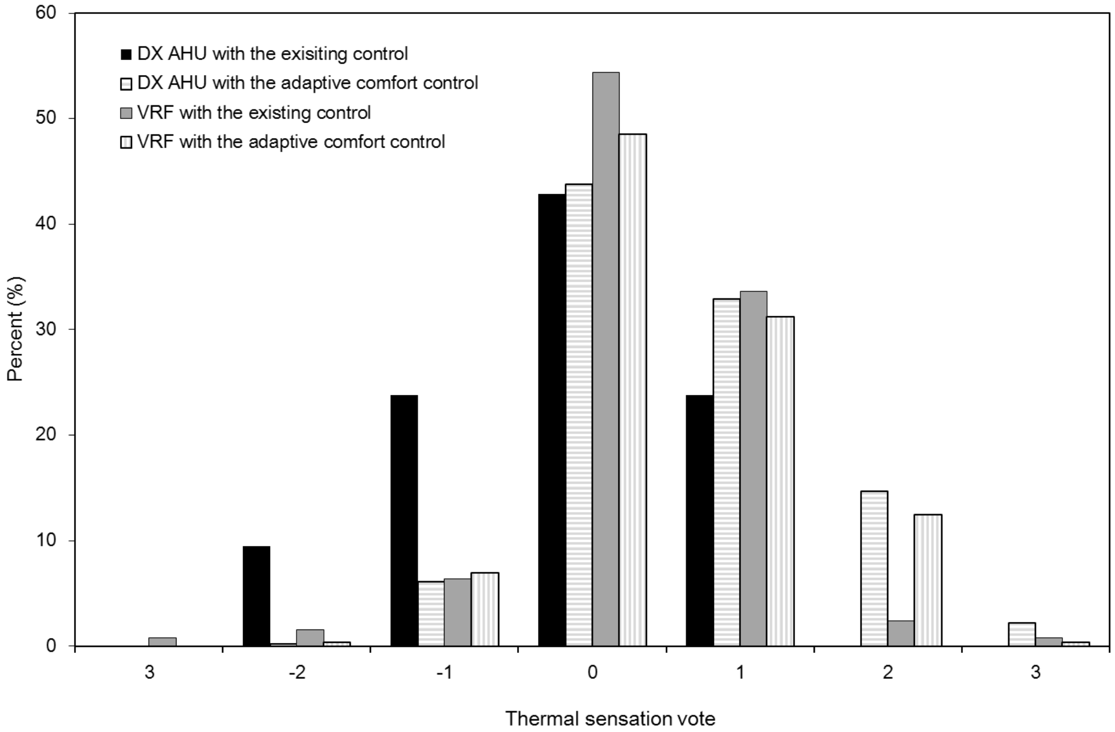

Figure 8. Comparison of thermal sensation votes of office workers when the adaptive comfort control is used with those of the existing control

After we analysed the acceptance ratio of the thermal sensation votes, we examined the office workers' thermal acceptance as a function of indoor temperatures (Figure 9). The monitoring results indicated that the ratio of occupant acceptance of the indoor conditions was greater than 89% until the indoor temperature reached 26°C. The acceptance ratio started to decrease as the indoor temperature rose above 26°C. The acceptance ratio fell to 58% at an indoor temperature of 30°C, and no office workers accepted the thermal condition when the indoor temperature reached 31°C. We also examined the average thermal sensation vote as a function of indoor temperature (Figure 10) and found that it increased as the indoor temperature rose. The thermal sensation vote was -0.33 at an indoor temperature of 23°C and reached 0.98 at an indoor temperature of 28°C. We found a negative relation between the ratio of the thermal acceptance and the average thermal sensation vote of office workers. As the thermal sensation vote increased, the acceptance ratio of office workers decreased. When the mean thermal sensation votes increased from 0.18 at an indoor temperature of 24 °C to 0.98 at an indoor temperature of 28 °C, the acceptance ratio fell by 40%.

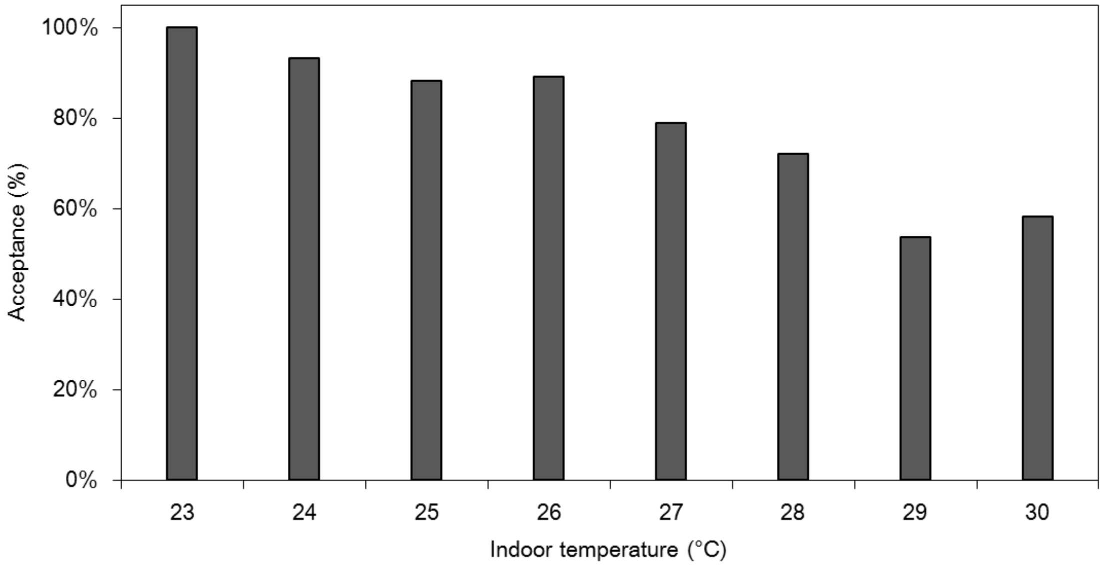

Figure 9. Occupant acceptance of the indoor conditions as a function of indoor temperature

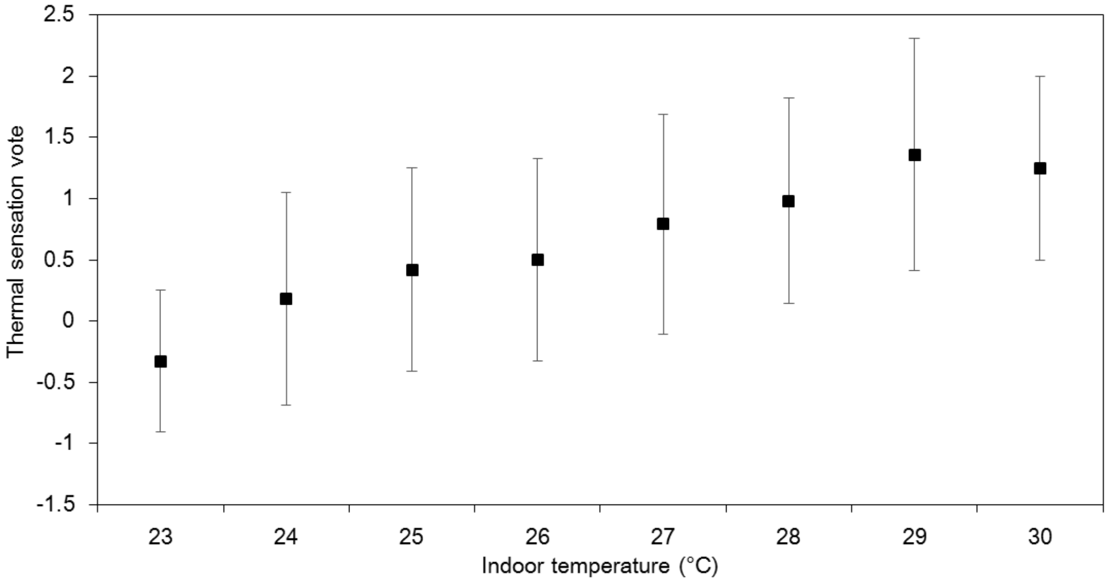

Figure 10. Thermal sensation vote with standard deviation as a function of indoor temperature

5. Discussion and conclusions

For this study, we carried out two field studies to extend the applicability of the adaptive comfort model to the control of air-conditioning systems. With data from the first field study (11,161 sets of individual comfort votes from 551 office workers), we developed an adaptive comfort model for air-conditioned buildings. We conducted the second field study to test the occupant acceptability of our adaptive comfort model, which we applied to the control of the air-conditioning systems in summer. For the second study, we collected 2,362 questionnaire sets from 256 office workers.

Our results provide scientific evidence that there is a statistically significant relationship between outdoor temperatures and optimal comfort temperatures inside air-conditioned office buildings when the cooling is controlled independent of changes in outdoor temperature ($R = 0.404$, $P < 0.001$). Moreover, we showed that it is possible to develop statistically and substantively significant adaptive comfort models for cooling operations in air-conditioned buildings ($R = 0.731$, $P < 0.001$). Previous adaptive comfort models have been intended for application in naturally ventilated buildings [32,33,34,35,36]. For example, the adaptive comfort model in ASHRAE Standard 55 [11] is only for naturally ventilated buildings. Therefore, the outcomes of this study can contribute to extending the application potentials of adaptive comfort theory to air-conditioned buildings.

An R value for the adaptive comfort models developed in this study ranged from 0.670 to 0.761. Further field studies are required to improve the adaptive comfort model, although an R value over 0.5 indicates a strong relationship between independent and dependent variables in behavioural research [5]. In particular, the effects of indoor humidity and current outdoor temperature on thermal comfort sensation should be carefully investigated in order to better predict the thermal comfort evaluation of building occupants. In this study, only outside temperature and humidity were measured. However, further studies should include the measurement of solar radiation because the thermal perception of occupants is also influenced by solar radiation.

We also found that the adaptive potential of people in relation to thermal comfort was limited when outdoor temperatures were less than 10°C. The adaptive comfort models for the heating operation, when outdoor temperatures were below 10°C, were not statistically significant. For example, the adaptive comfort model of the interior zone for the heating operation had an R value of 0.031, and the T test result indicates that outdoor temperatures were not a significant indicator for optimal comfort temperatures. This finding is in line with those of previous studies [19,29,30]. Humphreys [30] showed that optimal comfort temperature did not change with outdoor temperature when the outdoor temperature was below 10°C, which was confirmed by de Dear [19,32] using the ASHRAE thermal comfort database. One potential reason is that buildings in cold environments offer their occupants fewer adaptive opportunities than buildings in warm environments [47].

One important outcome of this study is the occupant acceptability of the adaptive comfort model applied to the control of air-conditioned buildings in summer. Our second field study indicates that the adaptive comfort model could be applied to the control of air-conditioning systems with a slight penalty in thermal comfort of occupants. For example, the percentage of the thermal acceptance (i.e. occupants who voted -1, 0, or +1) reduced from 94% to 87% in the office with DX AHU when the adaptive comfort model developed in this study was applied. Our study indicates that the setpoint temperature should not exceed a maximum of 27°C because the rate of thermal acceptance fell below 80% when the temperature was over 27°C [Figure 10]. Few studies have developed statistically significant adaptive comfort models for air-conditioned buildings [19,42,43]. Moreover, it is rare to test an adaptive comfort model in an air-conditioned building. This study can therefore reduce barriers to the application of adaptive comfort models by providing field evidence that most occupants in summer were satisfied with the indoor thermal conditions in an air-conditioned building with the adaptive comfort control.

The adaptive comfort control we developed in this study has an energy savings potential with a slight theoretical penalty in occupant comfort. The application of the adaptive comfort control in the office with the DX AHU increases the setpoint temperature by 2K to 5K higher than the existing setpoint temperature of 23°C (Figure 6). Previous studies [48,49,50,51] reveal that cooling energy consumption reduces by 6% for every 1K increase in cooling setpoint temperature. We calculate daily cooling energy savings due to the increase in setpoint temperatures of the office with the DX AHU when the adaptive comfort control was used, considering the relationship between cooling energy savings and an increase in setpoint temperature revealed in the previous studies. It is estimated that daily cooling energy savings by the adaptive comfort control would be 22% on average. The acceptance rate of thermal conditions reduced by only 7% but was still over the 80% threshold used to determine comfort (Figure 8). Further field studies on air-conditioned buildings with the adaptive comfort control are warranted to quantify its energy-use implications in more detail.

The adaptive approach to thermal comfort [19,30] is applied in this study. However, Fanger's PMV/PPD model has been a foundation for thermal comfort research and has been widely used in practice. In particular, Fanger's model includes all the major personal and physical variables affecting thermal sensation, which makes the model useful for wide applications [25]. It should be mentioned that the adaptive comfort and the PMV/PPD models are complementary. For example, Humphreys and Nicol [18] proposed a method to improve the PMV model by considering both outside temperature and PMV variables. Recently, Kim et al. [28] developed the adaptive PMV model that considers both the major variables of the PMV model and the variable from the adaptive comfort model as a corrective term. The combination of the factors of the two models is necessary for a comprehensive thermal comfort model.

Acknowledgements

The authors are very grateful to anonymous reviewers for their invaluable comments on our manuscript and like to thank Sun Ho Jo for his assistance. This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (2014R1A1A2054494).

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