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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.
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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

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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 [15–17]. 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 [33–36]. 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 [37–39]. 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 (Fig. 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.

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