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Thermal comfort and indoor air quality in the lecture room with 4-way cassette air-conditioner and mixing ventilation system

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Abstract

We performed the experimental and the numerical studies on thermal comfort (TC) and indoor air quality (IAQ) in the lecture room with cooling loads when the operating conditions are changed. Predicted mean vote (PMV) value and CO_2 concentration of the lecture room were measured and compared to the numerical results. Both of them showed a reasonable agreement with each other and then we applied the numerical model to analyze TC and IAQ for a couple of different operating conditions. From the results we found that the increment of the discharge angle of 4-way cassette air-conditioner makes uniformity of TC worse, but rarely affects IAQ. It turned out that TC and IAQ are hardly affected by the variation of the discharge airflow. Finally TC was merely affected by the increment of the ventilation rate, but when the ventilation rate is more than $800\,m^3/h$, the average CO_2 concentration can be satisfied with the standard limits of Japanese in our case studies.

Keywords: Carbon dioxide (CO_2); Indoor air quality (IAQ); Predicted mean vote (PMV); 4-way cassette air-conditioner; Thermal comfort (TC)

1. Introduction

Indoor environments of rooms are needed to be more thermally comfortable and healthy as the residence time in the building has been gradually increased and the well-being concepts to upgrade the quality of life have dominated our society. Recently, the personal air-conditioning systems have been developed rapidly to satisfy the individual sensation and save the energy, competing with the central ones. For this reason, multi-split air-conditioning systems like a 4-way cassette air-conditioner are widely used with the ventilation systems in Korea. But existing information or academic performance on thermal comfort (TC) and indoor air quality (IAQ) in the school building are especially limited and those have been studied separately by many researchers. In the view of TC, Choi et al. [1] studied on the evaluation of heating-conditioned environment in the classroom through simulations to get the thermal environment of the classroom improving. Kim et al. [2] proposed the new modelling strategy of the mean radiant temperature, which affects predicted mean vote (PMV) value, when the solar radiation is considered. They verified their model at the low velocity condition through comparing experiments and numerical simulations in the seminar room. Wong and Khoo [3] conducted a field study in classrooms in Singapore with ventilations to assess their thermal conditions during the lesson hours and they found that ASHRAE standard 55-92 is not applicable in the free-running buildings in the local climate and Fanger's PMV model was over-estimate the actual thermal sensations with the discrepancy being higher at lower temperatures. Cheong et al. [4] evaluated the TC of air-conditioned lecture theatre in the tropics using objective measurement, CFD analysis and subjective assessment and their recommendations were made to improve TC and reduce the CO_2 concentration. In the view of IAQ, Lee and Chang [5] investigated the indoor and outdoor air quality of the five classrooms at five different schools in Hong Kong and pointed that PM_{10} and CO_2 concentration exceeded the HKIAQ limits due to the high outdoor PM_{10} concentration and inadequate ventilation respectively. Holmberg and

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Chen [6] investigated the air flow characteristics and the 10 μm particles distributions with different ventilation systems in a classroom using computer simulation programs and suggested the better ventilation design guidelines. Daisey et al. [7] reviewed the literature on IAQ, ventilation and health symptoms in schools and showed that ventilation was inadequate in many classrooms, possibly leading to health problems. Apte et al. [8] investigated the associations between indoor CO_2 concentrations and sick building syndromes (SBS) from the analysis of the 1994–1996 BASE study data and showed the regression results between maximum indoor 1 h average CO_2 minus outdoor CO_2 concentrations and SBS were very similar.

However, the simultaneous studies on both TC and IAQ for the school buildings have been limited until now. Therefore we performed the experimental and the numerical studies on TC and IAQ in a lecture room with 4-way cassette air-conditioner to control the indoor climate, and ventilation system to meet indoor regulations during class hours. With variation of three operating conditions such as the discharge angle, the airflow of 4-way cassette air-conditioner, or the ventilation rate we investigated TC and IAQ and analyzed the effects of control parameters on TC and IAQ.

2. Performance criteria

One important objective of the air distribution is to create a comfortable thermal environment with a proper combination of comfort variables [9]. The comfort variables are metabolic rate, clothing, air velocity, air temperature, radiant temperature, draft rate (DR), vertical air temperature difference, radiant temperature asymmetry, and so on [10]. There are a number of TC models available in this area. Among them PMV, DR, and vertical air temperature difference were used in this study as TC criteria. The most common and best-understood model is PMV for TC and the associated percent persons dissatisfied (PPD) [10]. This index considers 6 parameters, which are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity, as the defining conditions for TC. The thermal sensation scale for use in quantifying people's thermal sensation was developed and defined from −3 to +3. The acceptable PMV zone for TC is defined in the range from −0.5 to +0.5. However, this previous model has not included the impact of turbulence intensity on the heat loss on the skin. Fanger et al. [11] pointed out that turbulence of airflow has a significant effect on the sensation draft, and a mathematical model of draft risk including turbulence intensity was developed. This model predicts the percentage of people dissatisfied due to draft as a function of the local air temperature, the local mean air speed, and the local turbulence. The value of DR predicted must be in the limits, 20%, for the acceptable condition [10]. Also the thermal stratification may cause the thermal discomfort. The vertical air temperature difference from the ankle level to the head one has been used to determine the local thermal discomfort. The maximum temperature difference between ankle level and head one must be below 3 °C [10]. TC indices mentioned above are given by

$$\mathrm{PMV} = (0.03\mathrm{e}^{-0.036M} + 0.028) \times [(M - W) - H - E_c - C_{\mathrm{res}} - E_{\mathrm{res}}], \quad (1)$$

$$\mathrm{DR} = [(34 - t_{\mathrm{a}}) \times (u - 0.05)^{0.062}] \times (0.037 \times u \times T_u + 3.14], \quad (2)$$

$$\mathrm{VATD} = t_{\mathrm{head}} - t_{\mathrm{ankle}}, \quad (3)$$

where M is the metabolic rate; W is the external work; H is the dry heat loss; E_c is the evaporative heat exchange at the skin; C_{res} is the respiratory convective heat exchange; E_{res} is the respiratory evaporative heat exchange; t_{a} is the local air temperature, °C; u is the local air speed, m/s; T_u is the local turbulence intensity, %; t_{h} is the head level temperature, °C; and t_{dn} is the head level temperature, °C. Additional details related with the PMV refer to ISO 7730 [12].

On the other hand IAQ is also an important factor for evaluating the performance of the multi-use facilities such as classrooms, offices, terminals, museums, and so on. Many gaseous materials, like VOCs, formaldehyde, NO_x, SO_x, ozone, CO_2, CO, and particulate matters, like dusts, asbestos, microbes, have been often used as indicators for IAQ. But we only used CO_2 concentration as a typical pollutant to estimate IAQ in this study for a couple of causes. The concentrations of VOCs and formaldehyde are mainly affected from the age of the building, building materials, office equipments, human activities, etc. These two gaseous pollutants are exponentially decreased as time goes on and then it is ambiguous to evaluate IAQ using them. Therefore, the regulations against the emission rate of the building materials were recently established and use of materials to emit VOCs or formaldehyde is restricted to improve the IAQ in Korea [13]. In case of formaldehyde, the previous studies also reported that the concentration was sufficiently lower than the standard limits [5,7,14]. In case of the other gaseous contaminants except CO_2 and particulate matters such as PM_{10}, their indoor concentration has been normally measured to be low in Korea [14]. However, the indoor CO_2 concentration was generally measured higher in summer or winter due to the low ventilation rate [8,15]. And it has been used as an indicator for comfort criteria related with other occupant-generated pollutants, particularly bioeffluents [9].

3. Research methods

3.1. Model descriptions

Fig. 1(a) shows the schematic design of a real lecture room which is presently used in one of universities in Korea. This lecture room has 3 windows and 2 doors to