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Potential of stratum ventilation to satisfy differentiated comfort requirements in multi-occupied zones

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ABSTRACT

It is desirable to establish collective air distribution systems to simultaneously accommodate individual preferences for the thermal comfort parameters of different occupants. In the study, the potential of stratum ventilation for providing differentiated thermal parameters in different occupied zones in a shared space according to different thermal comfort requirements is numerically investigated with air supply temperatures from different inlets that are adjusted independently. Eight cases are set up, and the numerically calculated results are analyzed in terms of air velocity, temperature, and PMV distributions with respect to different occupied zones. It is concluded that: (1) the differentiated zonal thermal environment is obtained in two occupied zones facing two different supply air inlets groups to satisfy individual requirements for thermal comfort. The control effect on the occupied zones in the first row exceeds that in the second row; (2) the zonal thermal environment is obtained in the room such that both the general and local thermal comfort levels are satisfied; and (3) the difference in zonal thermal parameters increases by increasing the difference in supply air temperature from different inlets groups and is influenced by the heat source distribution. The study may provide guidance for accommodating individual preferences for the thermal environment with collective air distribution systems.

1. Introduction

Ventilation plays an important role in ensuring the thermal comfort and indoor air quality (IAQ). Traditionally, the collective air distribution systems, such as mixing ventilation and displacement ventilation, are utilized to serve multiple occupants in a shared indoor space. The aim of the air distributions involves achieving a uniform environment in the working space, and this implies that all the occupants are treated as standard individuals [1–5]. However, occupants exhibit different preferences for the thermal environment parameters due to multiple influencing factors such as different activity levels, ages, and physiological and psychological states [6]. There is a need to provide a non-uniform thermal environment (i.e., different desired air parameters at different occupied positions) to address the individual preferences in a shared space [7]. During the last decade, there is a target shift from achieving a uniform collective environment to a non-uniform and personalized thermal environment. Personalized ventilation (PV) represents an existing solution in a direction that is achieved by installing a personalized supply terminal near the occupant in each workstation to independently control the local environment surrounding each occupant [6,8,9]. Numerous studies were conducted to verify the effectiveness of PV in personalized control. Melikov et al. [10] and Khalifa et al. [11] developed the PV terminals and verified their performances. Tham and Pantelic [12] proposed a combined scheme with a PV terminal on the desk and a fan beneath the desk to achieve increased uniform cooling around the body surface. Li et al. [13] investigated the performance of PV combined with the under-floor air distribution (UFAD) system in the hot and humid climate. Pan et al. [14] proposed a novel personalized fan coil unit that was shown to exhibit a faster response in PMV to the load variation compared with traditional air conditioning system. Studies verified that the PV performed well in terms of indoor air quality, thermal comfort, and energy efficiency [10–14]. However, the air ducts and terminals operate in the occupied zone for most of the investigated PV patterns, and this is difficult to realize in some circumstances. Besides, it is necessary to install an additional background ventilation system, and thus the entire system is complex and expensive. A modification was attempted by using the "ductless" PV terminal [15], but this system cannot supply fresh air closely to the occupants, one of the most important advantages of PV. Yang et al. [16] proposed to use a ceiling amounted PV terminal

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to provide the personalized air jet to avoid installing air ducts in the occupied zone. However, this increases the distance between the occupant and supply terminal, and thus increases mixing due to entrainment and possible coupling effect of neighboring supply terminals appears inevitable [7,17]. It is necessary to develop various types of air distributions in addition to PV to satisfy the different requirements for thermal parameters from occupants.

Collective air distributions with a non-uniform environment that focuses on the occupied zone are promising ventilation modes as they balance system simplicity, flexibility, energy efficiency, and cost-effectiveness [18]. Generally, the thermal parameters at different occupied positions or small occupied zones are uniformly designed for collective air distributions, and the supply air parameters including air velocity and temperature are simultaneously regulated. It is possible for these air distributions to obtain different air parameters at different occupied positions or zones based on individual preferences by independently regulating the supply air parameters from different supply inlets [7,17]. A certain distance exists between the supply inlets and the occupants for collective air distributions, and thus the interaction between supply air jets is inevitable. This may influence personalized control effectiveness to a certain extent. Stratum ventilation (SV) was proposed [19] as an energy efficient air distribution to accommodate the requirement for the elevated indoor air temperature in summer. The conditioned air from the air supply inlets is delivered close to the upper part of the occupied zone. Compared with mixing ventilation and displacement ventilation, SV provides the air of younger age and lowers the inhaled contaminant concentration [19,20]. In addition, the increased airflow movement in the breathing zone compensates the deterioration in thermal comfort due to the increased air temperature. Tian et al. [21] and Yao and Lin [22,23] investigated the performance of SV in a single office and a classroom, respectively, and indicated that SV provided an effective solution for the elevated room air temperatures. Cheng and Lin [24–27] examined the effect of air supply parameters including the effect of SV in terms of satisfying occupants in multiple rows, uniformity of the air parameter in the occupied zone, and the mechanism for the interaction between the airflow and human body. Wang and Lin [28] examined the dynamic response characteristic and indicated that SV changed the thermal air parameters from the initial thermal state to a comfortable state at a faster pace when compared with mixing ventilation and displacement ventilation. The primary focus of extant studies on SV involves obtaining a uniform thermal environment in the occupied zone. However, the air supply jets are near the occupants and a fast response mechanism exists for the dynamic change of the thermal state when compared to traditional collective air distributions [28]; therefore, SV is expected to exhibit a potential to obtain the personalized non-uniform environment based on the premise that the air supply parameters from different inlets are independently modulated. In the study, the potential of SV for the personalized non-uniform environment was investigated in a typical classroom with sixteen seats involving numerical cases. Given the limited number of supply inlets, the realizable thermal parameters difference was primarily analyzed at different occupied zones as opposed to different occupied positions.

2. Methodology

2.1. Implementation of differentiated zonal thermal environment by using stratum ventilation

Fig. 1 shows a typical air terminal layout of stratum ventilation in a typical classroom. The supply air inlets (S1 – S4) are located on the front wall, and the return air outlets (R1 – R4) are located on the rear wall. Both the inlets and outlets are at a height of 1.3 m, namely the head level for the sedentary occupants. For the convenience of the analysis, the sixteen seats were divided into four zones (i.e., Zones 1–4) with four seats for each zone as shown in Fig. 1. It is necessary to deliver the supply air from different inlets at different air parameters to achieve the differentiated control for occupants in different zones. For example, a lower air supply temperature from the inlets near Zone 1 and a higher air supply temperature from the inlets near Zone 2 should be independently regulated to simultaneously maintain a slightly cool condition at Zone 1 and a slight warm condition at Zone 2 (Fig. 1). In order to achieve independent control of different groups of inlets, multiple cooling coils may be designed for air temperature control with a cooling coil for each group of inlets. Additionally, the supply airflow rate and direction from different inlets can also be independently modulated to generate differences in thermal parameters in different zones. Multiple dampers or secondary supply fans can be designed to control the supply airflow rate with a damper or fan for each inlets group. In the study, the potential of SV to create differentiated multiple zonal environments was primarily investigated by independently regulating the air supply temperature from different inlets groups.

2.2. Case design

The study was conducted based on a numerical method. The classroom shown in Fig. 1 was adopted as the model room, and the established geometry model is shown in Fig. 2.

The dimension of the classroom was 8.8 m (length) × 6.1 m (width) × 2.4 m (height). There were sixteen seats (numbered as 1–16) distributed in two rows. The classroom was divided into four occupied zones (i.e., Zones 1–4) as shown in Fig. 1. A workstation computer was located at the corner of the classroom. As shown in Fig. 1, all the air supply terminals were divided into two groups, namely Group 1 (S1 and S2) and Group 2 (S3 and S4). The sizes of both the supply air inlet and return air outlet were 0.2 m × 0.2 m. The air change rate was 10 ACH, which is commonly used for stratum ventilation. The corresponding supply air velocity was 2.11 m/s. We assumed that the air supply temperature from both inlets groups was adjusted in the range of 17 °C–26 °C with a maximum temperature difference of 9 °C. Four different scenarios of heat source distribution were designed as listed in Table 1 in which the external wall corresponded to the sidewall next to Zones 1 and 3, and the lamps were at the ceiling. The other walls were treated as adiabatic. The metabolic rate and the clothing insulation for each occupant were set as 1.0 met and 0.57 clo, respectively, to consider the normal activity and clothing level for a sedentary occupant in the summer. The relative humidity in the room was set to 50%.

The designed cases are listed in Table 2 with different combinations of the air supply temperature from two inlets groups and heat source scenarios.

For each sedentary occupant, the air parameters at the heights of 0.1 m (the ankle level), 0.6 m (the waist level), and 1.1 m (the head level) were monitored to reflect the parameter difference relative to the height of the human body. The monitored points were located at a distance of 0.1 m in front of each occupant.

2.3. Numerical approach

The indoor airflow field and temperature field were simulated by Airpak, which is a CFD tool that counts the indoor airflow and temperature distribution characteristics. The RNG k-ε model was used to simulate the indoor turbulent flow. A standard wall function was adopted to model the turbulent flow in the near wall region [29]. The Boussinesq model was adopted to consider the buoyancy effect. The discrete ordinates (DO) model was applied to simulate the radiant heat transfer of the walls [30]. The finite volume method was used to discretize the Reynolds Averaged Navier–Stokes equations and averaged energy and mass conservation equations. The difference scheme was a second-order upwind scheme. The momentum equations were solved on non-uniform staggered grids by using a SIMPLE algorithm [31]. Linear under-relaxation iteration was used to ensure convergence. The inlet was defined as an opening with uniform velocity, and the outlet