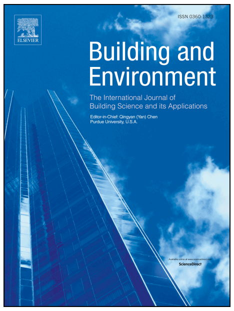

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Subzone Control Method of Stratum Ventilation for Thermal Comfort Improvement

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Abstract

The conventional control method of a collective ventilation (e.g., stratum ventilation) controls the averaged thermal environment in the occupied zone to satisfy the averaged thermal preference of a group of occupants. However, the averaged thermal environment in the occupied zone is not the same as the microclimates of the occupants, because the thermal environment in the occupied zone is not absolutely uniform. Moreover, the averaged thermal preference of the occupants could deviate from the individual thermal preferences, because the occupants could have different individual thermal preferences. This study proposes a subzone control method for stratum ventilation to improve thermal comfort. The proposed method divides the occupied zone into subzones, and controls the microclimates of the subzones to satisfy the thermal preferences of the respective subzones. Experiments in a stratum-ventilated classroom are conducted to model and validate the Predicted Mean Votes (PMVs) of the subzones, with a mean absolute error between 0.05 scale and 0.14 scale. Using the PMV models, the supply air parameters are optimized to minimize the deviation between the PMVs of the subzones and the respective thermal preferences. Case studies show that the proposed method can fulfill the thermal constraints of all subzones for thermal comfort, while the conventional method fails. The proposed method further improves thermal comfort by reducing the deviation of the achieved PMVs of subzones from the preferred ones by 17.6% to 41.5% as compared with the conventional method. The proposed method is also promising for other collective ventilations (e.g., mixing ventilation and displacement ventilation).

Keywords: Thermal comfort improvement; Thermal preferences; Subzones; Control; Stratum ventilation

1. Introduction

Indoor thermal comfort is critical to the occupants' health and productivity [1, 2]. Ventilation is one of the major methods to provide thermal comfort, including personalized ventilation and collective ventilation [3]. While personalized ventilation is oriented for individuals, the collective ventilation is designed for a group of occupants [3]. Although personalized ventilation can provide thermal comfort at low energy penalty, it is limited by the high initial cost and space-invasion in the occupied zone, particularly for rooms with high occupant density [4]. The collective ventilation is widely implemented in practice, e.g., mixing ventilation, displacement ventilation and stratum ventilation [3, 5, 6]. Stratum ventilation supplies cool air horizontally into the breathing zone, with the lowest air temperature and highest air velocity around the head to efficiently provide thermal comfort [7]. Compared with mixing ventilation and displacement ventilation, stratum ventilation was found to save energy of the air conditioning system annually by at least 44% and 25% respectively for the comparable thermal comfort [8]. Moreover, Cheng et al. [9] recommended that the supply air temperature of stratum ventilation should not be below 20°C to minimize draft risk. The high supply air temperature is particularly beneficial for the implementation of the solar air conditioning systems [10, 11].

The conventional control method of the collective ventilation targets at a uniform thermal environment in the occupied zone for a group of occupants [12-14]. Via objective measurements, subjective surveys and numerical simulations, Cheng and Lin [15, 16] confirmed that stratum ventilation could provide thermal comfort for multiple rows of occupants. Zhang et al. [17] modified the Predicted Mean Vote (PMV) model to be a function of the supply airflow rate and indoor air temperature, and the indoor air temperature was optimized to achieve the preferred thermal condition (i.e., preferred PMV value) in the occupied zone with the maximal energy saving of the air conditioning system. The indoor air temperature in the occupied zone can be efficiently computed by the multi-node model [18]. To maintain the indoor air temperature at the optimal value regardless of the disturbance (e.g., the variations of the outdoor weather condition), a dynamic indoor air temperature control method based on heat removal efficiency was proposed and experimentally verified, with the root mean square error not greater than 0.18°C [19]. These studies essentially are based on the assumptions that the thermal environment of the occupied zone is uniform and all the occupants are typical persons in term of thermal comfort [14, 17, 19].

However, the thermal environment of the occupied zone is not absolutely uniform [20] and individual thermal preferences exist among occupants [21]. These limit the thermal comfort performance of the conventional control method of the collective ventilation. Due to the effects of heat sources, turbulence, etc., the thermal parameters (e.g., air temperature and velocity) in the occupied zone cannot be absolutely uniform, which can be evaluated by the air diffuser performance index (ADPI) [15]. Generally, the reference thermal parameters at one point or the averaged values of several points are used to represent the thermal condition of the occupied zone [9, 22, 23]. The supply air parameters are modulated to control the reference thermal parameters only, which essentially ignores the thermal non-uniformity in the occupied zone. As a result, when the reference thermal parameters are maintained at the preferred levels, the actual microclimates of the occupants could deviate from the preferred levels to some degree. On the other hand, the differentiated thermal preferences among individuals are well recognized, which mainly result from physiological differences, cultural differences and behavioral differences [21, 24]. Based on ASHRAE thermal comfort database, Humphreys and Nicol [25] found that the standard deviation of the individual thermal preferences was around one scale in the 7-point thermal sensation scale, indicating a difference of 3°C in the preferred air temperature [21]. The conventional control method targets at the mean value of the individual thermal preferences. It inevitably deteriorates the thermal comfort of some occupants, given the fact that the individual thermal preference difference is significant [13]. The widely used thermal comfort model, PMV-PPD, echoes the deficiency of the conventional control method that even under the optimal condition, at least 5% occupants would feel dissatisfied with the thermal environment [26]. Subjective surveys of stratum ventilation also confirmed the deficiency of the conventional control method [27, 28]. Even with proper control, the percentage of occupants feeling thermal comfort was generally from 80% to 90%, leaving the remaining occupants suffering from thermal discomfort [27, 28].

This study proposes a subzone control method. The proposed method can solve the above-mentioned problems of the conventional method to improve thermal comfort. The proposed method will be explained in Section 2, and case studies on a stratum-ventilated classroom will be conducted to demonstrate the effectiveness of the proposed method (Section 3). The applications of the proposed method will be further discussed in Section 4.

2. Methodology

2.1 Proposed subzone control method

The thermal constraint is defined by the thermal comfort zone (e.g., PMV within ±0.75 according to EN 15251-2007 [29]). Failing the thermal constraint indicates thermal discomfort [26]. Thus, for thermal comfort control, the first requirement is to fulfill the thermal constraint. Within the thermal comfort zone, some thermal conditions (e.g., PMV=0) are perceived to be more comfortable than the others (e.g., PMV=0.75) [24]. The thermal preference is defined as the most comfortable thermal condition (e.g., PMV=0 according to EN 15251-2007 [29]). Thus, when the thermal constraint is fulfilled, thermal comfort can be further improved by reducing the deviation between the achieved thermal condition and the thermal preference [9].

As shown in Figure 1, the main idea of the subzone control method is to divide the occupied zone into subzones, and controls the thermal conditions of the subzones to firstly the fulfill the respective thermal constraints and to secondly be as close as possible to the respective thermal preferences. One subzone can include one or more occupants (which will be further discussed in Section 4). For example, for the stratum-ventilated classroom in Figure 2, the conventional method determines the supply air parameters to control the averaged air temperature and velocity of the eight sampling points M1-M8 to fulfill the averaged thermal constraint of the sixteen occupants and maximally satisfy their averaged thermal preference [19]. The proposed method can divide the occupied zone into Subzones A-D, and control the thermal condition of each and every subzone (e.g., the averaged air temperature and velocity of the sampling points M1 and M2 for Subzone A) to fulfill the respective thermal constraint (e.g., the averaged thermal constraint of Occupants 1-4 for Subzone A) and to maximally satisfy the respective thermal preference (e.g., the averaged thermal preference of Occupants 1-4 for Subzone A). The proposed method can improve thermal comfort by two ways when compared with the conventional method. On the one hand, the proposed method can fulfill the thermal constraint of each subzone for thermal comfort, while the conventional method might fail. The averaged thermal condition of the subzones is not the real thermal conditions of the subzones due to the non-uniformity of the thermal environment (Section 1). Thus, the conventional method cannot guarantee that the thermal condition of each subzone fulfills the respective thermal constraint. On the other hand, the proposed method further improves thermal comfort by reducing the deviation of the achieved thermal conditions of the subzones from the respective thermal preferences. The averaged thermal preference of the subzones is not the real thermal preferences of the subzones when different individual thermal preferences exist (Section 1). Thus, the conventional method cannot ensure that the deviation of the achieved thermal conditions of the subzones from the respective thermal preferences is minimized.

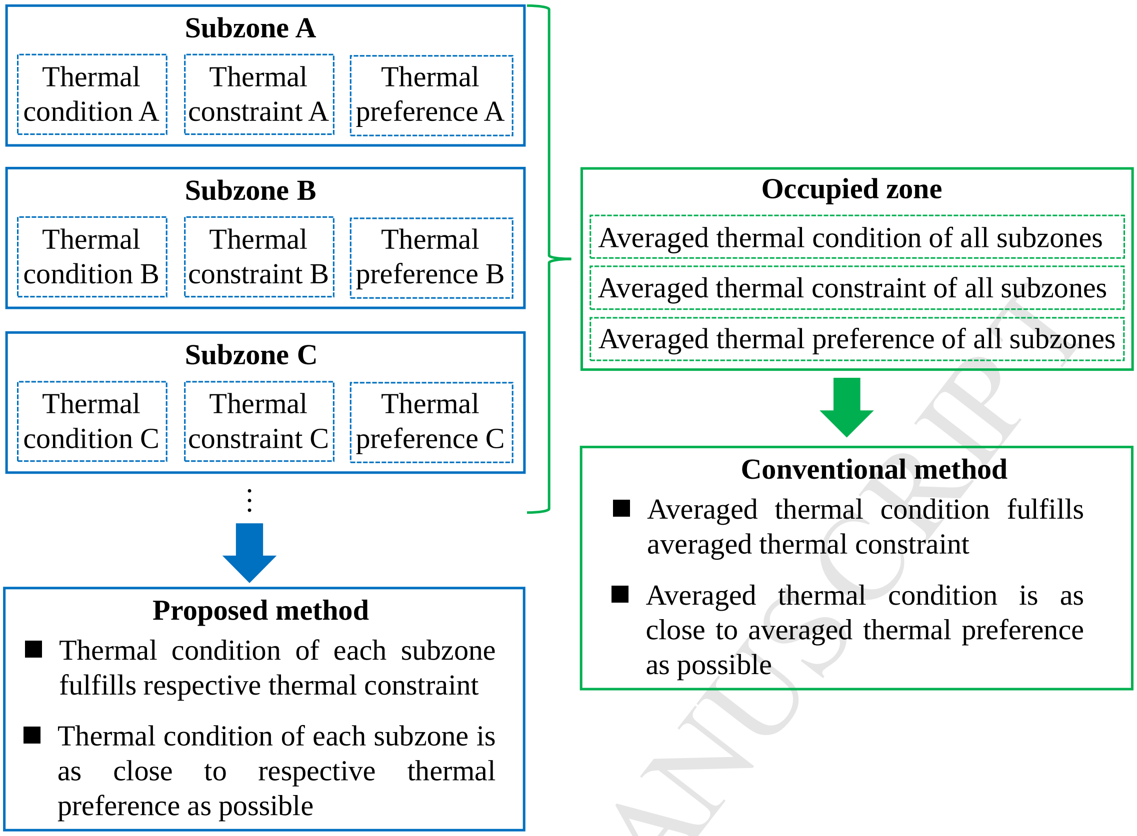
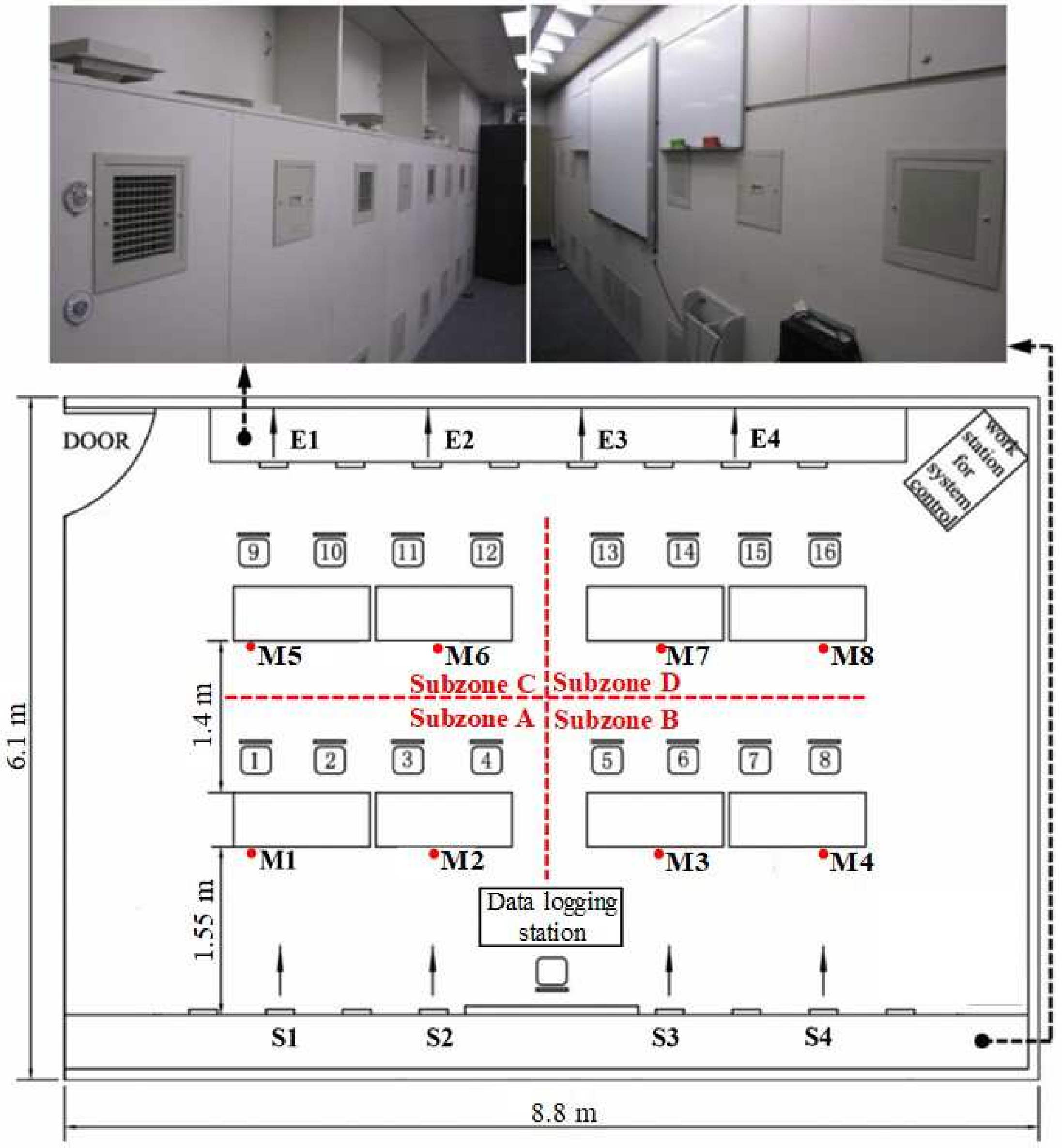


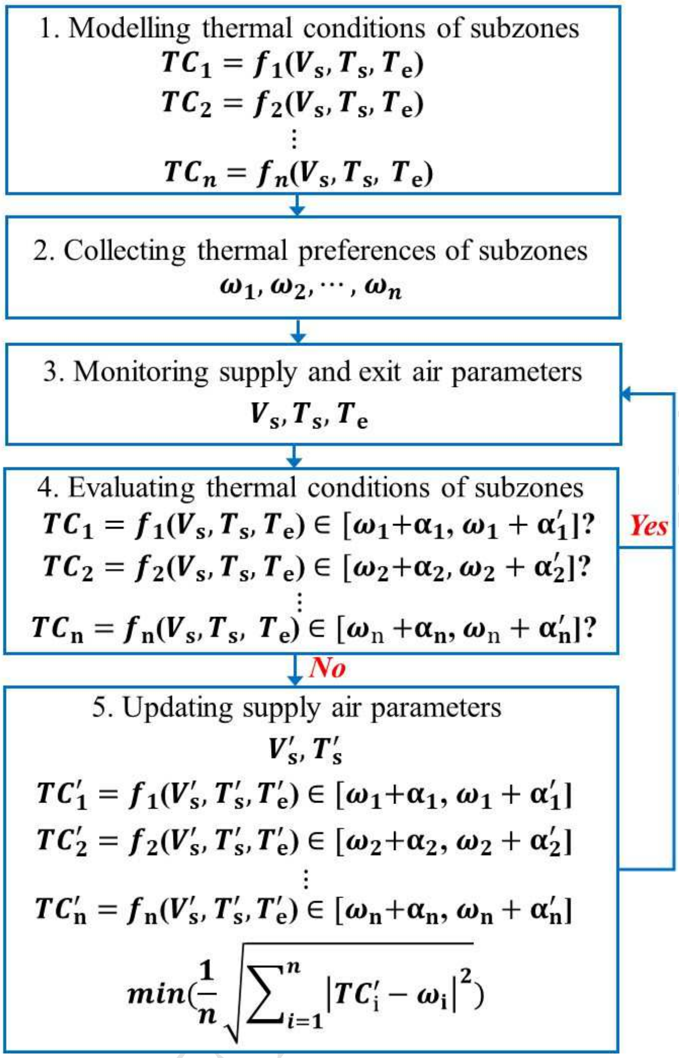
Fig.1. Comparisons between control mechanisms of proposed method and conventional method.



Note: E and S indicate the exit louver and supply diffuser respectively, and M denotes a sampling point at the height of 1.1 m above the floor.

Fig.2. Configuration of environmental chamber.

The detailed processes of the proposed method are explained as follows (Figure 3). The first step is to model the thermal condition of each subzone. Although the thermal condition of each subzone can be directly measured, the measurements would increase the cost of the sensors in operation [17]. Moreover, the sensors might disturb the space usage and the occupants could affect the accuracy of the sensors [23]. These problems can be solved by the indoor thermal environment simulations, e.g., Computational Fluid Dynamics (CFD) simulations and zonal models. CFD simulations and zonal models can reasonably predict the thermal condition of each subzone, with the inputs of wall temperatures/heat fluxes [30]. Since the building management system generally does not monitor the wall temperatures/heat fluxes, additional sensors are required for the wall temperatures/heat fluxes, which increases the cost and complexity of the sensor system [19]. This study models the thermal condition of each subzone using the supply and exit air parameters (i.e., the supply airflow rate, supply air temperature and exit air temperature). Both the supply and exit air parameters can be readily obtained from the building management system [19]. Thus, no additional sensors are required. Zhang et al. [17] found the indoor air velocity of stratum ventilation can be modelled by the indoor air temperature and supply airflow rate, and the indoor air temperature is a function of the supply air parameters and cooling load [19]. The cooling load can be calculated by the supply and exit air parameters [18]. Thus, the indoor air temperature and velocity can be modelled by the supply and exit air parameters. This was experimentally confirmed by Zhang et al. [31]. The PMV is widely used to evaluate the thermal condition of stratum ventilation [4, 17, 19, 27]. For example, for a stratum-ventilated office with two occupants, PMV has been used to investigate the effects of the asymmetrically distributed heat gains on thermal comfort [32]. With near sedentary activities, the PMV can be modelled by the indoor air temperature and velocity [17, 26]. Thus, the PMV has the potential to be modelled by the supply and exit air parameters (i.e., f_1-f_n in Figure 3). Experiments will be conducted (Section 2.2) to develop and validate the PMV models of the subzones (Section 3.1). In real applications, similar to most of the model predictive control methods [12, 14, 19], the PMV models can be developed during the commissioning stage. During operation, the thermal conditions of the subzones are predicted by the developed PMV models, and no sensors in the subzones for thermal conditions are required.



Note: TC is the thermal condition; T_s *and* T_e *are the supply and exit air temperatures respectively;* V_s *is the supply airflow rate;* ω *is the thermal preference;* α *(<0) and* α' *(>0) are the allowed deviations from the thermal preference defined by the thermal constraint; the subscript i indicates Subzone i; and n is the number of subzones.*

Fig.3. Flowchart of subzone control method.

The second step is to collect the thermal preference of each subzone. The advent and exponential growth of ubiquitous computing devices (e.g., smartphones) offer an opportunity for the occupants to express their thermal preferences, which is a popular method of data collection in modelling and controlling personalized thermal comfort [33, 34]. The third step is to monitor the supply and exit air parameters, which can be conveniently executed by the building management system [19].

With the supply and exit air parameters monitored from the third step, Step 4 employs the thermal condition models of the subzones from Step 1 to evaluate the thermal condition of each subzone. If the predicted thermal conditions of all subzones by the thermal condition models fulfill the respective thermal constraints, the supply air parameters will be maintained invariable. For each subzone, the thermal constraint can be expressed by the allowed deviations (e.g., α_1 and α'_1in Figure 3) from the thermal preference (e.g., ω_1 in Figure 3) or determined according to thermal comfort standards (e.g., PMV within ± 0.75 [29]). If not all the thermal constraints of the subzones are met, Step 5 is conducted to update the supply air parameters. With the updated supply air parameters, the thermal condition of each subzone should meet the respective thermal constraint. Moreover, the supply air parameters are determined to minimize the deviation of the thermal conditions of the subzones from the respective thermal preferences (Equation 1). More specifically, the exhaustive research method [6] is used to determine the update of the supply air parameters. For the constant-air-volume system, the research domain includes all the possible supply air temperatures, e.g., 31 different values between 20°C and 26°C with equal intervals in the case studies (Section 4) [9]. For the variable-air-volume system, the research domain includes all the possible supply airflow rates, e.g., 21 different values between 0.201 m^3/s and 0.373 m^3/s with equal intervals in the case studies (Section 4) [19]. For the system with both variable supply air temperature and supply airflow rate, the research domain includes all the possible combinations of the supply air temperature and supply airflow rate, e.g., 651 different combinations with the 31 different supply air temperatures and 21 different supply airflow rates in the case studies (Sections 3 and 4). For each of the alternatives in the research domain, firstly, the thermal conditions of the subzones are calculated using the thermal condition models (i.e., f_1, f_2, …, f_n in Figure 3). The exit air temperature in the thermal condition models can be determined by Equation 2, while the cooling load in Equation 2 is assumed to be same as that before updating the supply air parameters [12, 19]. If the calculated thermal conditions of the subzones do not fulfill the respective thermal constraints, the corresponding alternative is removed from the research domain. Secondly, for each of the remaining alternatives in the research domain, the deviation between the achieved thermal conditions of the subzones and the respective thermal preferences is calculated using Equation 1. The alternative with the minimal deviation is selected to be the update of the supply air parameters. Steps 3-5 need to be conducted repeatedly to maintain comfortable thermal conditions of the subzones [35]. Also, the thermal preferences of the subzones should be timely updated (Step 2). For example, if the subzones are occupied by other new occupants, the thermal preferences of the new occupants can be different from the thermal preferences of the previous occupants [36].

$$Deviation = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left|TC_i' - \omega_i\right|^2} \tag{1}$$

where TC' is the thermal condition after updating the supply air parameters; ω is the thermal preference; the subscript i indicates Subzone i; and n is the number of subzones.

$$Q_{\mathrm{cl}} = \rho c_{\mathrm{p}} V_{\mathrm{s}}(T_{\mathrm{e}} - T_{\mathrm{s}}) \tag{2}$$

where c_{p} is the specific heat capacity of air ((kJ/(kg·°C); ρ is the air density (kg/m^3); Q_{cl} is the cooling load (kW); T_{e} and T_{s} are exit air temperature and supply air temperature respectively (°C); V_{s} is the supply airflow rate (m^3/s).

2.2 Experimentation

To develop and validate the PMV models of subzones (Section 2.1), experiments are conducted in a stratum-ventilated classroom (Figure 2), which is located at City University of Hong Kong. The classroom has dimensions of 8.8 m (length) × 6.1 m (width) × 2.4 m (height). The cool air is horizontally supplied into the breathing zone from the supply diffusers S1-S4 on the front wall at the height of 1.3 m above the floor, and then exhausted through the exit louvers E1-E4 on the rear wall at the same height. Sixteen thermal manikins representing the students are arranged into two rows, each with dimensions around 400 mm (length) × 250 mm (width) × 1200 mm (height). The thermal manikin is heated by a 100 W light bulb [16]. The occupied zone is evenly divided into four subzones according to the arrangement of the seats (Figure 2). Two sampling points are arranged in each subzone for measuring the air temperature and velocity. The averaged air temperature and velocity of the two sampling points are used for the PMV calculation of each subzone. The typical summer clothing level in Hong Kong of 0.57 clo and the near-sedentary activity level of 1.0 met are used to calculate the PMV [17, 27]. The mean radiant temperature can be assumed to be the same as the air temperature for this classroom [17, 26, 27]. The relative humidity of

58.5% is used for the PMV calculation because the relative humidity generally ranges from 55% to 62% during the experiments. Chow et al. [37] found when the relative humidity was between 50% and 80%, the variation of the relative humidity imposed negligible effects on thermal sensation, which was consistent with the results of Fong et al. [38].

The sampling points (M1-M8 in Figure 2) are placed at the height of 1.1 m above the floor, which is adequate for thermal comfort evaluation of stratum ventilation [17, 27]. The SWEMA omnidirectional hot-wire anemometers with a data logger are used. The measurement accuracy is ±0.2°C for the air temperature between 10°C and 40°C, and ±0.02 m/s and ±0.03 m/s for the air velocity from 0.07 m/s to 0.5 m/s and from 0.5 m/s to 3 m/s respectively. The supply air temperature is the averaged value of the measurements at the supply diffusers S1-S4, and the exit air temperature is the averaged value of the measurements at the exit louvers E1-E4. The supply airflow rate is the sum of the measurements at the supply diffusers S1-S4, by the ALNOR balometer capture hood EBT731 with a measurement accuracy of ±3% of the reading.

Ten experiments are randomly designed for the development of the PMV models (Experiments 1-10 in Series 1) (Table 1). The ten experiments cover a wide range of the thermal environment, with the supply airflow rate between 0.201 m^3/s and 0.373 m^3/s, the supply air temperature from 19.81°C to 29.44°C and the exit air temperature from 23.79°C to 31.95°C [9]. In this study, the regression method is used to develop the PMV models of Subzones A-D (Equations 3-6). In the field of the built environment, the regression method is widely used to model the thermal condition [36]. Generally, only the coefficient of determination (R^2) is reported to indicate the quality of the regression model, e.g., the PMV-PPD model [39], adaptive thermal comfort models [24], and thermal environment models of underfloor air distribution [40] and displacement ventilation [41]. Besides R^2, this study further designs five experiments randomly (i.e. Experiments 11-15 in Series 2) to validate the accuracy of the PMV models.

Table 1. Supply airflow rate (V_s), supply air temperature (T_s) and exit air temperature (T_e) of experiments.

Experiments		V_s (m^3/s)	T_s (°C)	T_e (°C)
Series 1	1	0.272	19.81	23.79
	2	0.272	22.24	28.01
	3	0.201	23.03	30.20
	4	0.201	23.72	31.02
	5	0.272	24.99	30.45
	6	0.272	25.94	28.09
	7	0.373	26.41	27.58
	8	0.373	29.44	31.95
	9	0.373	21.87	25.07
	10	0.272	22.35	26.74
Series 2	11	0.201	23.86	30.48
	12	0.373	26.32	30.48
	13	0.373	23.25	25.68
	14	0.373	25.30	29.71
	15	0.201	26.90	30.89

3. Results

3.1 Development and validation of PMV models of subzones

PMVs are calculated according to ASHRAE 55-2017 [26], using the CBE thermal comfort tool [42]. Figure 4 shows that the PMVs of the subzones range from around -1.5 to 2.0, indicating that stratum ventilation can satisfy a wide range of thermal preferences. Moreover, the maximal PMV difference among the subzones is from around 0.5 to 2.0 scales. This implies that stratum ventilation, on one hand, can provide a relatively uniform thermal environment across the subzones [27] and, on the other hand, has the potential to satisfy differentiated thermal preferences among the subzones. Based on Experiments 1-10, the PMV models of the subzones are obtained as shown in Equations 3-6, with R^2 of 0.945 to 0.998. For the PMV models of

Subzones A and B, because the p-value of the supply airflow rate is larger than 0.05 indicating statistical insignificance, the supply airflow rate is excluded (Equations 3 and 4) [43]. For the PMV model of Subzone C, the supply air temperature is not included because its p-value is larger than 0.05 (Equation 5). Figure 5 shows that for both Series 1 and 2, the predicted PMVs of the subzones by the obtained models are almost of the diagonal function of $y = x$ with the experiments, and the R^2 is high (0.955). These indicate that the models reasonably predict the PMVs of the subzones. Fang et al. [38] developed a model of the mean thermal sensation vote, with a diagonal function of $y = x$ between the predictions by the developed model and the results of the subjective surveys and an R^2 of 0.94. Due to the high R^2 of 0.94, the model of the mean thermal sensation vote was accepted as accurate [38]. Furthermore, for Experiments 1-15, the mean absolute errors (Equation 8) [44] of the PMV models of Subzone A, B, C and D are 0.14, 0.11, 0.07 and 0.05 scale respectively. A mean absolute error of less than 0.14 scale is good. Zhang et al. [17] modified the PMV of the occupied zone with a mean absolute error of 0.14 scale, and used the modified PMV model for the thermal comfort control of the occupied zone. Buratti et al. [45] developed a PMV model for the control of the air conditioning system, with a mean absolute error of 0.22 scale. Therefore, the PMV models developed in the current study (Equations 3-6) are validated and can be used for the thermal comfort control.

$$PMV_{\mathrm{A}} = 0.390\overline{T}_{\mathrm{s}} + 1.090\overline{T}_{\mathrm{e}}\text{-}0.160,\ \ R^2 = 0.998 \tag{3}$$

$$PMV_{\mathrm{B}} = 0.650\overline{T}_{\mathrm{s}} + 0.500\overline{T}_{\mathrm{e}}\text{-}0.440,\ \ R^2 = 0.945 \tag{4}$$

$$PMV_{\mathrm{C}} = -0.240\overline{V}_{\mathrm{s}} + 1.430\overline{T}_{\mathrm{e}}+0.490,\ \ R^2 = 0.993 \tag{5}$$

$$PMV_{\mathrm{D}} = -0.190\overline{V}_{\mathrm{s}} + 0.340\overline{T}_{\mathrm{s}} + 0.980\overline{T}_{\mathrm{e}}\text{-}0.079,\ \ R^2 = 0.995 \tag{6}$$

$$\bar{x} = \frac{2(x - x_{min})}{x_{max} - x_{min}} - 1 \tag{7}$$

where R^2 is the coefficient of determination; $\overline{T}_{\mathrm{e}}$ and $\overline{T}_{\mathrm{s}}$ are the normalized temperatures of exit air and supply air respectively (°C) (Equation 7); $\overline{V}_{\mathrm{s}}$ is the normalized supply airflow rate (m^3/s) (Equation 7); $\bar{x}$ is the normalized value between -1 and 1, which is the widely used pre-processing method of the inputs for deriving the data-driven models [6]; x is the original value of the supply air temperature, supply airflow rate or exit air temperature (Table 1); x_{min} and x_{max} are the minimal and maximal original values respectively.

$$MAE = \frac{\sum_{j=1}^{n}\left|m_j - p_j\right|}{n} \tag{8}$$

where MAE is the mean absolute error; $\left|m_j - p_j\right|$ is the absolute difference between the measurement (m_j) and prediction (p_j); j is the j^{th} case; n is the number of cases.

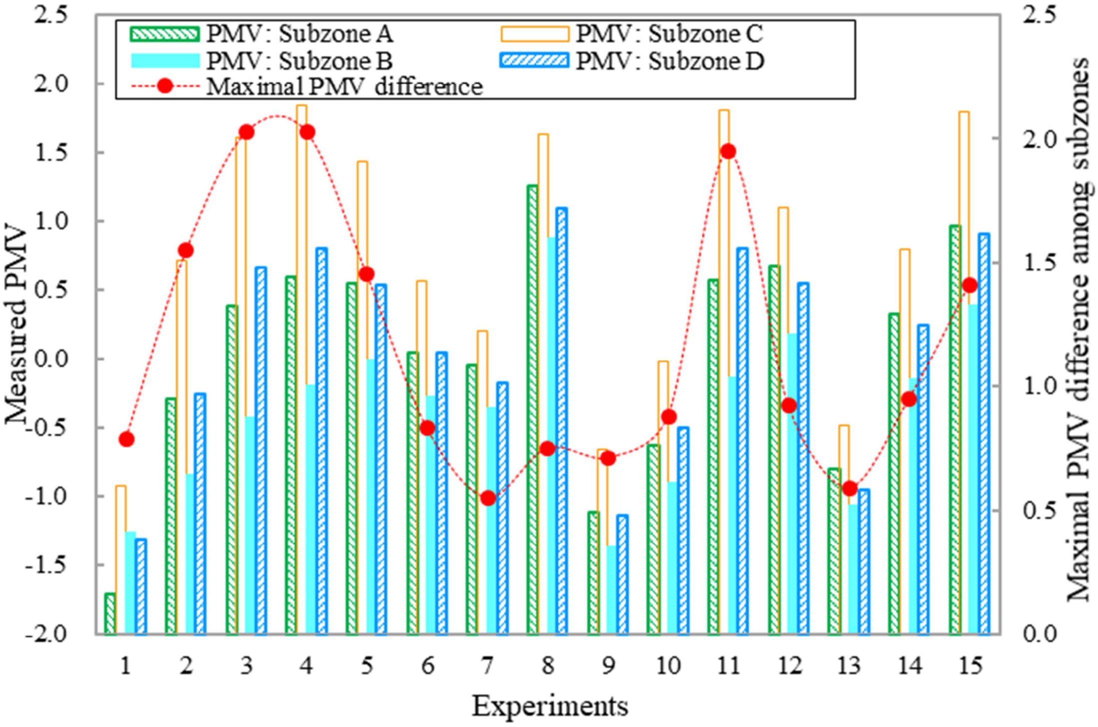
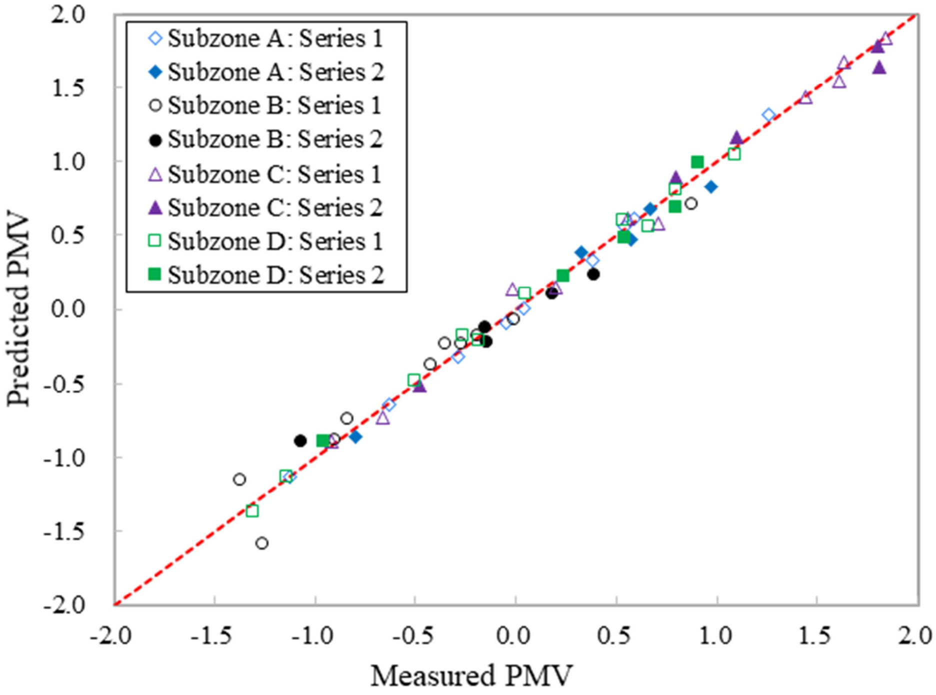


Fig.4. Measured PMVs of subzones.



Note: Series 1 refers to Experiments 1-10 (Table 1) which are used for the model development, and Series 2 refers to Experiments 11-15 (Table 1) which are not involved in the model development but used for the model validation.

Fig.5. Comparisons between predicted and measured PMVs of subzones.

3.2 Case study: Identical thermal preferences among subzones

Identical thermal preferences among the subzones are considered to demonstrate that the proposed method can improve thermal comfort by controlling the thermal conditions of the subzones instead of the averaged thermal condition of all subzones (Section 2.1). Three cases of identical thermal preferences are designed: slightly warm condition (i.e., $\omega_1 = \omega_2 = \omega_3 = \omega_4 =$ 0.25 in Figure 3), thermally neutral condition (i.e., $\omega_1 = \omega_2 = \omega_3 = \omega_4 =$ 0 in Figure 3) and slightly cool condition ($\omega_1 = \omega_2 = \omega_3 = \omega_4 =$ -0.25 in Figure 3) [26]. The thermal condition of each subzone is constrained that the PMV should be within ±0.75 [29]. The cooling load of the stratum-ventilated classroom is assumed to be 2.4 kW (Figure 2). Both the proposed method and conventional method select the supply airflow rate between 0.201 m^3/s and 0.373 m^3/s and the supply air temperature between 20°C and 26°C (Figure 1, Step 5 in Figure 3 and Table 2) [9]. The smallest supply airflow rate satisfies the requirement of indoor air quality that the fresh air for each occupant should not be less than 10 l/s [46].

For the thermal preference of slightly warm condition, the proposed method determines the supply airflow rate as 0.373 m^3/s and the supply air temperature as 23.8°C (Table 2). The achieved PMVs of Subzones A, B, C and D are 0.11, -0.40, 0.70 and -0.02 respectively, which fulfill the thermal constraints within ±0.75 (Figure 6). The deviation of the achieved PMVs of the subzones from the preferred values is 0.21 scale (Equation 1). The conventional method (Figure 1) determines the supply airflow rate at 0.244 m^3/s and the supply air temperature at 21.6°C to achieve the averaged PMV of the occupied zone at 0.25 (Table 2 and Figure 6). The averaged PMV of the occupied zone achieved by the operation strategy of the proposed method is 0.1. Thus, the operation strategy of the proposed method has not been selected by the conventional method. However, the achieved PMVs of the subzones by the conventional method risks to fail the thermal constraints. The PMV of Subzone C achieved by the conventional method is 1.27, which is out of the range of ±0.75 (Figure 6). This is because that the conventional method concerns only the averaged thermal condition of the occupied zone and is unable to take into consideration the thermal conditions of individual subzones (Section 2.1) [14, 17, 19]. The deviation of the achieved PMVs of the subzones by the conventional method from the preferred values is 0.34 scale (Table 2). Compared with the conventional method, the proposed method further improves the thermal comfort via reducing the deviation of achieved PMVs of the subzones from the preferred values by 37.6%. This is because that the proposed method targets to control the thermal conditions of the subzones as close to the preferred ones as possible (Figure 3) while the conventional method ignores the thermal variations of the subzones (Section 2.1).

Table 2. Supply air parameters determined by proposed method and conventional method and associated thermal comfort performances with identical and differentiated thermal preferences among subzones.

	Identical thermal preferences						Differentiated thermal preferences	
	Slightly warm condition $\omega_1=\omega_2=\omega_3=\omega_4=0.25$		Thermally neutral condition $\omega_1=\omega_2=\omega_3=\omega_4=0$		Slightly cool condition $\omega_1=\omega_2=\omega_3=\omega_4=-0.25$		$\omega_1=0.23$; $\omega_2=-0.70$; $\omega_3=0.52$; $\omega_4=0.65$	
	Con	*Pro*	*Con*	*Pro*	*Con*	*Pro*	*Con*	*Pro*
V_s(m^3/s)	0.244	0.373	0.244	0.373	0.330	0.373	0.210	0.373
T_s(°C)	21.6	23.8	20.8	23.4	22.0	22.6	20.2	23.8
PMV_A	0.10	0.11	-0.18	-0.03	-0.33	-0.31	-0.03	0.11
PMV_B	-0.62	-0.40	-0.82*	-0.50	-0.77*	-0.70	-0.81*	-0.40
PMV_C	1.27*	0.70	0.99*	0.56	0.43	0.27	1.35*	0.70
PMV_D	0.26	-0.02	0.01	-0.15	-0.32	-0.40	0.22	-0.02
Deviation	0.34	0.21 (+ 37.6%)	0.33	0.19 (+ 41.5%)	0.22	0.18 (+ 17.6%)	0.24	0.19 (+21.3%)

Note: "Pro" and "Con" denote the proposed method and conventional method respectively (Figure 1); V_s *is the supply airflow rate determined by the two methods;* T_s *is the supply air temperature determined by the two methods; * indicates that the achieved PMV of subzone fails to fulfill the thermal constraint (i.e.,* $-0.75 \leq PMV \leq 0.75$*); the deviation is calculated by Equation 1; + denotes the performance improvement (i.e., reduction in the deviation) by the proposed method as compared with the conventional method.*

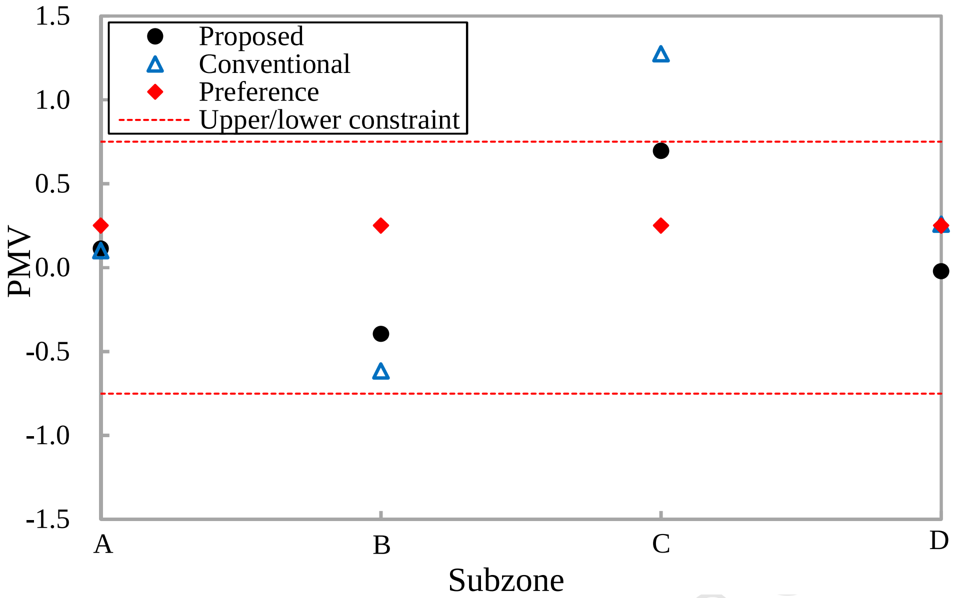


Fig.6. Comparisons of achieved PMVs of subzones by proposed method and conventional method for system with both variable supply air temperature and supply airflow rate: Identical thermal preferences of slightly warm condition.

As a summary, for the identical thermal preferences, the proposed method has two advantages over the conventional method: 1) the thermal constraints on subzones can be fulfilled; and 2) the thermal conditions of the subzones are controlled closer to the preferred conditions. These two advantages are also observed when slightly cool and thermally neutral conditions are preferred (Table 2). The proposed method can control the PMVs of the subzones all within ±0.75. The conventional method fails to meet the thermal constraints on Subzone B with the thermal preference for slightly cool condition and on Subzones B and C with the thermal preference for thermally neutral condition (Table 2). For the thermal preferences for slightly cool condition and thermally neutral condition, compared with the conventional method, the proposed method reduces the deviation of the achieved PMVs of the subzones from the preferred conditions by 17.6% and 41.5% respectively (Table 2).

3.3 Case study: Differentiated thermal preferences among subzones

Differentiated thermal preferences are considered to further demonstrate the effectiveness of the proposed method. The proposed method controls the thermal conditions of the subzones to satisfy the respective thermal preferences instead of the averaged thermal preference of all subzones (Section 2.1). The thermal condition (i.e., PMV) of each subzone is constrained to within ±0.75 [29]. The thermal preferences of Subzones A, B, C and D are randomly produced [47] to be 0.23, -0.70, 0.52 and 0.65 respectively within ±0.75 (i.e., ω_1=0.23, ω_2=-0.70, ω_3=0.52, ω_4=0.65 in Figure 3), which is consistent with Wang et al. [21]. Thus, the conventional method controls the averaged thermal condition of the occupied zone as close to 0.18 (i.e., the averaged thermal preference of the subzones) as possible. Actually, the PMV of 0.18 is not equal to the thermal preference of any of the four subzones. Both the proposed method and conventional method select the supply airflow rate between 0.201 m^3/s and 0.373 m^3/s, and the supply air temperature between 20°C and 26°C (Figure 1, Step 5 in Figure 3 and Table 2) [9]. The cooling load of the stratum-ventilated classroom is assumed to be 2.4 kW (Figure 2).

Figure 7 shows that the achieved PMVs of the subzones by the proposed method fulfill the thermal constraints, while the achieved PMVs of Subzones B and C by the conventional method fail to meet the thermal constraints. This is because the proposed method targets at the thermal conditions of the subzones and excludes the operation strategies failing to meet the thermal constraints of the subzones (Step 5 in Figure 3), while the conventional method is unable to consider the thermal conditions of the individual subzones (Figure 1) [14, 19]. The proposed method further improves thermal comfort by reducing the deviation of achieved PMVs of the subzones from the preferred conditions by 21.3% when compared with the conventional method. The deviation of achieved PMVs of the subzones from the preferred conditions of the conventional method is large because the conventional method targets to achieve the averaged PMV of the occupied zone to be 0.18, while the PMV of 0.18 is not equal to the thermal preference of any of the four subzones. The proposed method can significantly reduce the deviation of achieved PMVs of the subzones from the preferred ones, because the proposed method targets to achieve the PMV of each subzone to be the respective preferred condition (Figures 1 and 3).

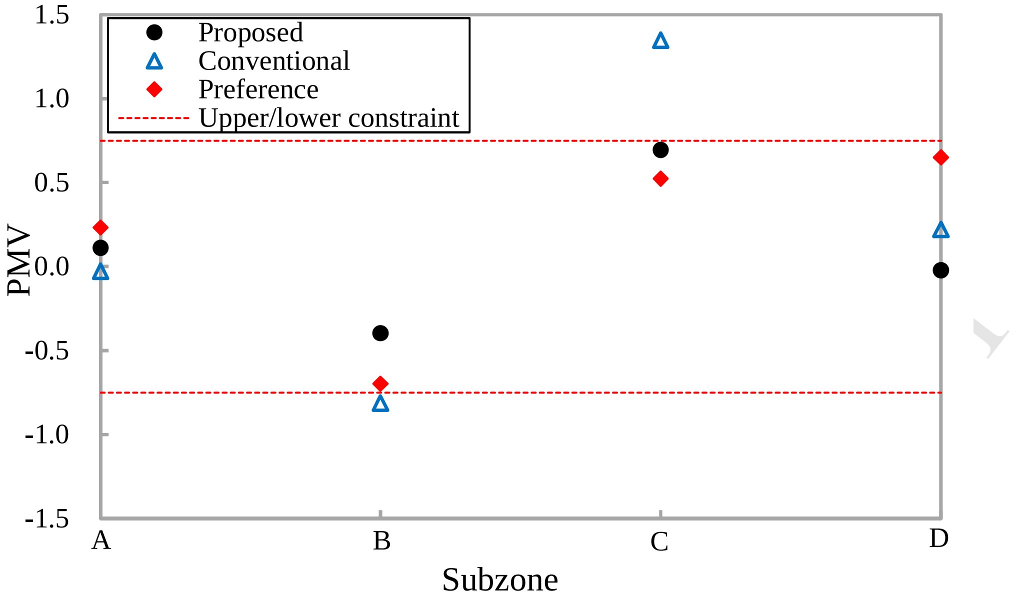


Fig.7. Comparisons of achieved PMVs of subzones by proposed method and conventional method for system with both variable supply air temperature and supply airflow rate: Differentiated thermal preferences.

Thus, when differentiated thermal preferences are considered, the proposed method also has two advantages over the conventional method: 1) the thermal constraint of each subzone is fulfilled, and 2) the thermal preference of each subzone is better satisfied. When the thermal preferences of the subzones change in practice, a thermal comfort improvement by the proposed method can also be expected because the proposed method controls the thermal condition of each subzone to satisfy the respective thermal constraint and thermal preference of that particular subzone, while the conventional method is unable to consider the thermal conditions, thermal constraints and thermal preferences of the individual subzones (Section 2.1).

4. Discussion

The contributions of this study are to propose a method to improve thermal comfort by overcoming the two defects of the conventional method. Firstly, the conventional method would lead to thermal discomfort in subzones, e.g., Subzone C in Figure 6, and Subzones B and C in Figure 7. Secondly, the conventional method is unable to maximally satisfy the thermal preferences of the subzones. The proposed method can provide thermal comfort for all subzones and minimize the deviation between the achieved thermal conditions of the subzones and the respective thermal preferences.

For example, Figures 6 and 7 show that the proposed method achieves thermal comfort for all subzones, and reduces the deviation between the achieved thermal conditions of the subzones and the respective thermal preferences by 37.6% and 21.3% respectively as compared with the conventional method.

For different ventilation systems with different capabilities to control the thermal environment, the achieved thermal comfort performance by the proposed method can be different. For example, the system with both variable supply air temperature and supply airflow rate is expected to better satisfy the thermal preferences of the subzones as compared with the constant-air-volume system and the variable-air-volume system, because the constant-air-volume system and the variable-air-volume system can only adjust one of the two supply air parameters. Figure 8 shows the achieved PMVs of the subzones of the three ventilation systems using the proposed method. The differentiated thermal preferences and thermal constraints of the subzones in Figure 8 are set to be the same as those in Section 3.3. The supply airflow rate setting of the constant-air-volume system is 0.3 m^3/s and the supply air temperature setting of the variable-air-volume system is 22°C [9]. The three ventilation systems all meet the thermal constraints that the PMVs of the subzones should be within ±0.75 (Figure 8). The achieved PMVs of the subzones of the system with both variable supply air temperature and supply airflow rate are generally closer to the respective thermal preferences as compared with the other two systems. Regarding the deviation of the achieved PMVs of the subzones from the preferred ones, the system with both variable supply air temperature and supply airflow rate outperforms the variable-air-volume system by 15.9%, while the constant-air-volume system outperforms the variable-air-volume system by 3.3% (Figure 9). The constant-air-volume system outperforms the variable-air-volume system because the indoor thermal condition under stratum ventilation is more sensitive to the supply air temperature than to the supply airflow rate [17]. It is noted that although the system with both variable supply air temperature and supply airflow rate improves thermal comfort moderately, its system complexity should also be taken into account when designing the ventilation system.

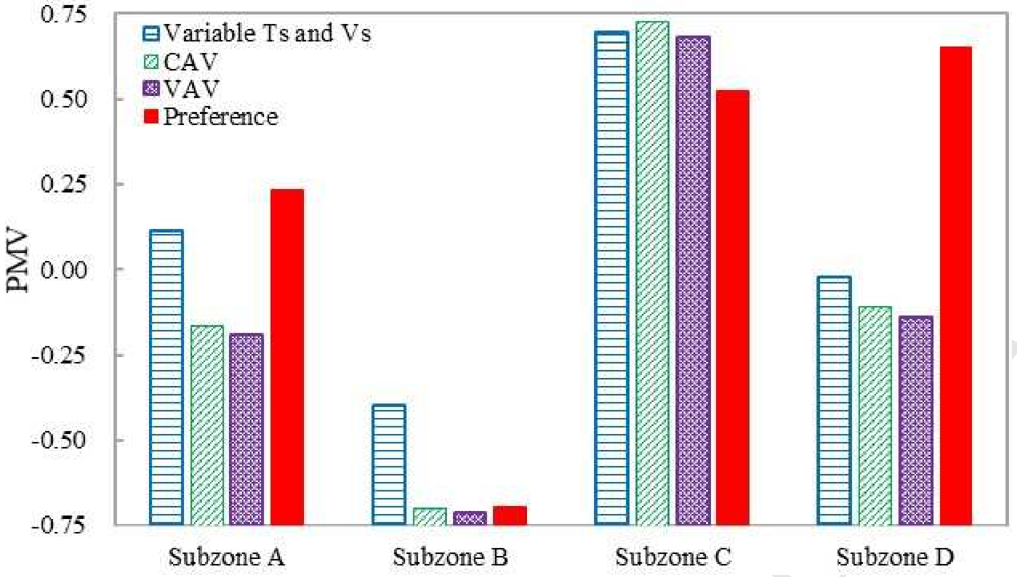
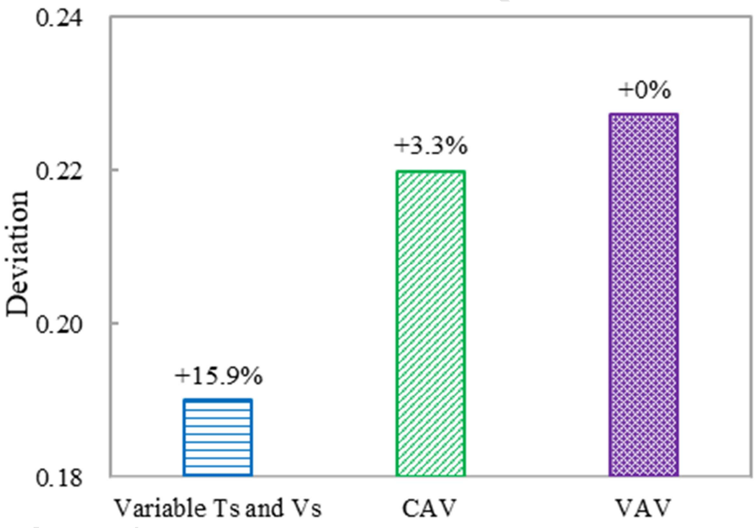


Fig.8. Comparisons of achieved PMVs of subzones by proposed method for system with both variable supply air temperature (T_S) and supply airflow rate (V_S), constant-air-volume system (CAV) and variable-air-volume system (VAV).



Note: The deviation is calculated by Equation 1; + denotes the performance improvement (i.e., reduction in the deviation) as compared with the variable-air-volume system (VAV).

Fig.9. Comparisons of deviations between achieved PMVs by proposed method and preferred ones for system with both variable supply air temperature (T_S) and supply airflow rate (V_S), constant-air-volume system (CAV) and variable-air-volume system (VAV).

In the above case studies, each subzone includes a small group of occupants (i.e., four occupants) (Figure 2). Theoretically, the subzone can be smaller to include only one occupant, so that the individual thermal preferences can be satisfied. For example, the occupied zone of the classroom in Figure 2 can be divided into 16 subzones and each subzone includes only one occupant. However, when the difference of the 16 individual thermal preferences is excessively large, stratum ventilation might fail to meet the thermal constraints of all the 16 subzones simultaneously. Thus, the divisions of the subzones should consider the capability of the ventilation system to satisfy differentiated thermal preferences. Figures 8 and 9 indicate the system with both variable supply air temperature and supply airflow rate can better satisfy differentiated thermal preferences than the constant-air-volume and variable-air-volume systems. To further improve the capability of the ventilation system to satisfy differentiated thermal preferences, the supply air parameters of the supply diffusers S1-S4 (Figure 2) can be independently controlled. However, this could increase the cost and system complexity of the ventilation system. The design of the ventilation system should balance the capability to satisfy differentiated thermal preferences and the increased cost and system complexity, e.g., using the multi-criteria decision-making method [48].

The proposed method is also promising for other collective ventilations, e.g., displacement ventilation and mixing ventilation. It can be seen from Figure 3 that, as long as the thermal condition models of a particular type of the collective ventilation for the subzones are available, the proposed method is applicable. The studies of Zhang et al. [17, 18, 31] and Deng et al. [49] confirmed that the indoor air temperature and velocity of mixing ventilation and displacement ventilation could be modelled by the supply and exit air parameters. Thus, the PMVs of the subzones of mixing ventilation and displacement ventilation are also promising to be modelled by the supply and exit air parameters (Section 2.1). However, the capabilities of different collective ventilations (e.g., mixing ventilation, displacement ventilation and stratum ventilation) to satisfy differentiated thermal preferences need to be further investigated and compared.

It is noted that, in the proposed method (Figure 3), the thermal conditions of the subzones can also be indicated by other thermal comfort models, e.g., the models of the thermal sensation vote and the thermal comfort vote. Similar to existing studies [4, 17, 19, 27], this study employs the PMV to evaluate the thermal condition of stratum ventilation. However, when the data of thermal sensation votes and thermal comfort votes of the subzones are available, e.g., using data collection method of smartphones [33, 34], the thermal sensation votes and thermal comfort votes of the subzones can also be modelled by the supply air and exit air parameters. This is because that, similar to the PMV, the thermal sensation vote and thermal comfort vote have been widely recognized to be the function of the indoor air temperature and velocity [9, 50, 51] while the indoor air temperature and velocity are in the function of the supply air and exit air parameters [17, 19, 49].

It is also noted that the proposed method is only applicable to cases where the thermal comforts of all occupants are equally important. If the thermal comforts of some occupants are prioritized, the proposed method needs further modification, e.g., using weighting factors [48] to prioritize the thermal comforts of the occupants concerned particularly. This study only presents the PMVs of the subzones at the height of 1.1 m which are adequate for the evaluation of thermal comfort under stratum ventilation, and more detailed information about the microclimates of stratum ventilation can be found in Studies [15, 32].

In summary, the proposed method controls the thermal conditions of the subzones to fulfill the respective thermal constraints and to be as close to the respective thermal preferences as possible. The applicability of the proposed method is not affected by the division of the subzones. However, the division of the subzones is limited by the capability of the ventilation system to satisfy differentiated thermal preferences. If the division of the subzones is beyond this capability, the proposed method would find that no supply air parameters can make the thermal conditions of the subzones to fulfill the respective thermal constraints (Section 2.1), indicating that the division of the subzones is inappropriate. The evaluation method of the capability of the ventilation system to satisfy differentiated thermal preferences and the optimal division method of the subzones for thermal comfort improvement are recommended to be further investigated. In operation, the thermal preferences and cooling loads could vary in a stochastic manner [13, 48]. The evaluation method of the capability of the ventilation system to satisfy differentiated thermal preferences and the optimal division method of the subzones should be able to treat the stochastic variations of the thermal preferences and cooling loads robustly.

5. Conclusions

This study proposes a subzone control method for stratum ventilation to improve thermal comfort. The proposed method divides the occupied zone into subzones, and controls the thermal conditions of the subzones to satisfy the respective thermal preferences of the subzones. Thus, compared with the conventional method which controls the averaged thermal condition of the occupied zone to satisfy the averaged thermal preference of the occupied zone, the proposed method can improve the thermal comfort by 1) controlling the thermal conditions of the subzones which better represents the thermal environment of the occupants in the subzones than the averaged thermal condition of the occupied zone; and 2) aiming at the thermal preferences of the subzones which more accurately represent the thermal preferences of the occupants in the subzones than the averaged thermal preference of the entire occupied zone.

In the case studies, a stratum-ventilated classroom with sixteen occupants is evenly divided into four subzones, and experiments are conducted to model and validate the thermal condition model (i.e., PMV) of each subzone in the function of the supply airflow rate, supply air temperature and exit air temperature. The mean absolute errors of the PMV models are between 0.05 and 0.14 scale. Using the validated PMV models, three cases with identical thermal preferences among the subzones are tested (i.e., slightly cool condition, thermally neutral condition and slightly warm condition), and the proposed method reduces the deviation of achieved PMVs of the subzones from the preferred ones by 17.6% to 41.5%, compared with the conventional method. The case study on differentiated thermal preferences among the subzones shows that the proposed method reduces the deviation of achieved PMVs of the subzones from the preferred conditions by 21.3%, compared with the conventional method. Moreover, the proposed method can fulfill the thermal constraints of the subzones for thermal comfort while the conventional method fails. Therefore, the proposed method can effectively improve the thermal comfort of stratum ventilation. The proposed method is also promising to be applicable to other collective ventilations (e.g., mixing ventilation and displacement ventilation) for thermal comfort improvement. The division of the subzones should consider the capability of the ventilation system to satisfy differentiated thermal preferences. The robust evaluation method of the capability of the ventilation system to satisfy differentiated thermal preferences and the optimal division method of the subzones for thermal comfort improvement are recommended for further studies.

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Highlights

- Thermal conditions of subzones are controlled to fulfill respective thermal constraints.
- Thermal conditions of subzones are controlled to be as close to respective thermal preferences as possible.
- Deviation of achieved PMVs of subzones from preferred ones is reduced by 17.6% to 41.5%.
- Division of subzones should consider capability of ventilation system to satisfy differentiated thermal preferences.
- Besides stratum ventilation, subzone control method is promising for other collective ventilations.