Experimental investigation into thermal comfort and energy utilization efficiency of stratum ventilation under heating mode

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Abstract. Stratum ventilation (SV) can energy-efficiently provide satisfactory thermal comfort under cooling mode. However, thermal comfort and energy efficiency of SV under heating mode can be different from those under cooling mode due to the distinct airflow patterns. In this study, thermal comfort and energy utilization efficiency of SV were investigated for six cases under heating mode. Air velocity and temperature were measured in the occupied zone of a multi-occupant room with dimensions of 8.4 m (L) × 5.4 m (W) × 2.6 m (H). Based on the measured air velocity and temperature, the thermal comfort indicators including vertical air temperature difference between head and ankle levels (ΔT), draught rate (DR), predicted mean vote (PMV) and energy utilization efficiency were calculated. The results showed that the energy utilization efficiency of SV was higher than one under heating mode, indicating energy saving. The draught rate under SV satisfied the requirement of Category B of thermal environments stipulated in ISO 7730. The PMV of SV can meet the acceptable range for general thermal comfort under the cases with suitably high supply air temperature according to ASHRAE 55-2017. The vertical air temperature difference between head and ankle levels can achieve acceptable results for SV under heating mode.

1. Introduction
Existing studies of stratum ventilation (SV) focused on cooling applications. It has been demonstrated that SV can save energy consumption annually by at least 44% and 25% respectively as compared with mixing ventilation (MV) and displacement ventilation (DV) while achieving a thermally comfortable environment under cooling mode [1, 2]. Thermally neutral temperature of SV was up to about 27°C, which was about 2.5°C higher than MV and about 2.0°C higher than DV [3]. Both objective experimental measurements and subjective human tests demonstrated that the thermal environment in the occupied zone can be uniform [4].

However, due to the short development history of SV (less than 15 years), few studies on SV under heating mode have been carried out [5]. Zhang et al [6, 7] analysed the effects of operation parameters (i.e. supply air velocity, supply air temperature and supply vane angle) on performances of SV (i.e. predicted mean vote (PMV), vertical air temperature difference between head and ankle levels (ΔT) and energy utilization coefficient (EUC)) under heating mode using CFD (computational fluid dynamics). An efficient method for the improvement of the operation performance of SV under heating mode was proposed.

Current works on stratum ventilation (SV) under heating mode were very limited compared with that under cooling mode. In this study, thermal comfort including vertical air temperature between head and ankle levels (ΔT), draught rate (DR), predicted mean vote (PMV) and energy utilization efficiency...
of SV under heating mode were experimentally investigated in a multi-occupant room. This study helps to apply SV better in the zones needing both cooling and heating. The data obtained in this study can also provide a reference for the design and optimization of SV under heating mode.

2. Methods

2.1. Experimental chamber

The experiments were carried out in an environmental chamber located in Chengdu Research Institute of City University of Hong Kong. The orientation of the chamber was shown in Figure 1 (a). This chamber resembled a classroom with dimensions of 8.4 m (length) × 5.4 m (width) × 2.6 m (height). It had two double-glazed windows with dimensions of 1.40 m (length) × 2.30 m (width) and 1.75 m (length) × 2.30 m (width) respectively located on the right exterior wall. The other three walls were interior. There were 12 seats for occupants with 6 seats on each row. A rectangular box with dimensions of 0.40 m (length) × 0.25 m (width) × 1.20 m (height) was used to represent an occupant. It has been experimentally confirmed that the rectangular thermal manikin was adequate to simulate the effect of a human body on the global air distribution of SV [8]. The students in a classroom were usually seating accompanied by few movements. A light bulb of 100 W was placed inside each dummy to simulate human body heat [9]. Six ceiling lamps with the heat load of 15 W each were installed on the ceiling. Thus, the internal heat gain was about 7.9 W/m². The warm air was supplied from six double deflection grilles with dimensions of 0.18 m × 0.18 m located at the height of 1.35 m above floor, and then exhausted via six double deflection grilles with dimensions of 0.18 m × 0.18 m located at the height of 0.49 m above floor. For heating applications, the supply vane angle should be appropriately controlled to generate a downward initial momentum of the supply air due to the effect of thermal buoyancy, so the vane angle of supply air in this study was set as 30°. We tested six different cases. The boundary conditions of these cases were summarized in Table 1.

Table 1. Information on cases.

| Case | Ventilation method | Supply air velocity (m/s) | Supply air temperature (°C) | Air changes per hour (ACH) |
|------|--------------------|---------------------------|-----------------------------|---------------------------|
| 1    | SV                 | 1.4±0.3                   | 25.9±0.39                   | 8.3                       |
| 2    | SV                 | 1.4±0.3                   | 28.0±0.61                   | 8.3                       |
| 3    | SV                 | 1.4±0.3                   | 29.9±0.44                   | 8.3                       |
| 4    | SV                 | 1.8±0.3                   | 26.1±0.38                   | 10.7                      |
| 5    | SV                 | 1.8±0.3                   | 28.1±0.45                   | 10.7                      |
| 6    | SV                 | 1.8±0.3                   | 30.2±0.62                   | 10.7                      |

Figure 1. (a) The layout of the sampling lines (Sampling Lines: L1-L6), and (b) the layout of the room with the dummy.

2.2. Measurement instruments

The air velocity and temperature of the supply air inlets and exhausts were measured using SWEMA omnidirectional hot-wire anemometers. The air velocity and temperature in the occupied zone were also measured using SWEMA omnidirectional hot-wire anemometers. The temperatures on the surfaces (i.e.
walls, windows, floor and ceiling) were recorded by WZY-1. The relative humidity (RH) was measured by PSENSE II. All instruments had been calibrated prior to the experiments. The details of measurement instruments were summarized in Table 2.

### Table 2. Information on measurement instruments.

| Type of instruments | Measuring range | Measuring accuracy | Measuring range | Measuring accuracy | Measuring range | Measuring accuracy |
|---------------------|-----------------|--------------------|-----------------|--------------------|-----------------|--------------------|
| SWEMA 03+           | 0.05-10         | ±0.03              | 10-40           | ±0.2               | /                | /                  |
| WZY-1               | /               | /                  | -20+80          | ±0.5               | /                | /                  |
| PSENSE II           | /               | /                  | /               | /                  | 0.1-99.9         | ±3                 |

#### 2.3. Measurement procedure

The experiments were carried out from December 10 to December 14, 2018. The outdoor temperatures were about 6 °C (standard deviation was 2.3 °C) and had no sunlight during our measurement period. All the measurements were conducted under steady states. When the monitoring air parameters reached statistically steady, a steady state was assumed to be achieved. For Sampling Lines L1-L6 (see Figure 1(a)), the air temperatures and velocities were measured at the heights of 0.1 m, 0.6 m, 1.1 m, 1.7 m and 2.2 m above floor by attaching the measurement instruments to a vertical bar. These heights represented the ankle level, the abdomen level, the breathing zone for sedentary, the breathing zone for standing, and the upper of the room, respectively. Due to the limited instruments, five anemometers were employed to conduct the measurements one Sample Line by one Sample Line. For two adjacent Sample Lines, at least 10 min was kept to ensure that the flow fields reached statistically steady again after moving. For each Sample line, the measuring duration was 10 min. The sampling frequency was 8 Hz.

#### 3. Results and discussion

##### 3.1. Velocity and temperature distributions

![Figure 2](image-url) (a) The distribution of air velocity (m/s), and (b) the distribution of air temperature (°C).

Figure 2 shows the distributions of air velocity and temperature for the six cases. Figure 2(a) shows that the air velocities at the height of 1.1 m were higher than those at other heights. This was because the supply air jet under SV was directly delivered to the head-chest level through the downward supply vane angle. The minimum air velocity and temperature were found at the height of 0.1 m, as the supply air jets from the supply diffusers turned up gradually due to the effect of thermal buoyancy. Figure 2(b) shows that SV produced a temperature stratification with the lowest temperature at the ankle level. It was seen that the most obvious temperature stratification occurred at Case 3. This was because for this case, the supply air jets with low supply air velocity and high supply air temperature was hard to reach the lower zone of the room due to the strong thermal buoyancy.
3.2. Draught rating (DR)

Draught rating (DR) was determined according to ISO 7730 (2005) [10]. Table 3 summarizes the results of DR for all cases.

Table 3. Results of draught rating (%).

| Case | Sampling Line | DR (%) | Case | Sampling Line | DR (%) |
|------|---------------|--------|------|---------------|--------|
|      | 1             | 2      | 3    | 4             | 5      | 6      |
| 1    | 1.7m          | 4.3    | 10.1 | 8.4           | 11.7   | 13.1   | 0      |
|      | 1.1m          | 12.7   | 13.5 | 10.5          | 4.3    | 6.4    | 7.7    |
|      | 0.6m          | 5.7    | 6.2  | 9.2           | 0      | 1.0    | 0      |
|      | 0.1m          | 0      | 0    | 6.1           | 0      | 0      | 0      |
| 3    | 1.7m          | 9.6    | 11.8 | 7.5           | 9.7    | 10.7   | 0      |
|      | 1.1m          | 12.0   | 12.9 | 13.8          | 0      | 3.5    | 0.7    |
|      | 0.6m          | 4.9    | 6.9  | 6.4           | 0      | 0      | 0.5    |
|      | 0.1m          | 0      | 0    | 0             | 0      | 0      | 0      |
| 5    | 1.7m          | 4.9    | 8.2  | 9.6           | 8.3    | 9.8    | 5.4    |
|      | 1.1m          | 10.8   | 11.6 | 11.5          | 6.2    | 8.1    | 7.5    |
|      | 0.6m          | 10.2   | 9.4  | 9.4           | 0      | 5.2    | 5.7    |
|      | 0.1m          | 6.6    | 8.0  | 8.5           | 3.8    | 0      | 0      |

As shown in Table 3, DRs were generally higher at the height of 1.1 m, where the air velocities were relatively higher than at other heights due to the effect of supply air jet. DRs under all cases were all below 20%, satisfying the requirement of Category B of thermal environments stipulated in [11]. This showed that for SV under heating mode, the draft risk was low.

3.3. Vertical air temperature differences

Vertical air temperature difference between the head and ankle levels is an important evaluation index for local thermal comfort. Vertical air Temperature differences between the head and ankle level (1.7 m and 0.1 m above the floor, $\Delta T_1$) for a standing person and a sedentary person (1.1 m and 0.1 m above the floor, $\Delta T_2$) were summarized in Figure 3.

Figure 3. (a) The results of $\Delta T_1$, and (b) the results of $\Delta T_2$.

Large air temperature gradient appeared under some cases, especially for the cases with low supply air velocity and high supply air temperature (e.g., Case 3). This was because supply airflow with low air velocity was easy to flow upwards due to the thermal buoyancy. The majority of $\Delta T_2$ was higher than $\Delta T_1$. It was because the supply air jet under SV was directly delivered to the head-chest level (1.1 m for a sedentary person), leading to a higher air temperature at the height of 1.1 m. For the front row, under cases with high supply air velocity (i.e., Cases 4, 5 and 6), because the supply airflow was sent downward with high momentum, the air temperature at the height of 0.1 m was higher than upper levels. However, the vertical air temperature differences between head and ankle levels under the cases with the lower supply air temperature (i.e., Cases 1, 4 and 5) were within the range of -1.1 to 2.8 °C, which
was below 3 °C, meeting the requirements of ASHRAE 55-2017 [11]. The results showed that SV under heating mode could provide an acceptable vertical temperature difference between head and ankle levels.

### 3.4. PMV

Based on the measurements, the PMV value was calculated to evaluate general thermal comfort. In this paper, the metabolic rate of human body was chosen as 1.1 met when sitting and writing [7]. The subjects wore typical winter clothing with the thermal resistance of 1.0 clo. The calculations of PMV were based on the air temperature, air velocity and relative humidity collected at the height of 0.6 m above floor, as recommended by ISO 7726 for sedentary occupants [12]. The average radiation temperature was calculated by multiplying the average wall temperature by the corresponding area, then summing it up and dividing it by the total area [13]. PMV was calculated according to the ASHRAE 55-2017 [11].

![Figure 4. The PMV values for each case.](image)

The distributions of PMV values for each case were presented in Figure 4. For the cases with low supply air temperature (i.e., Cases 1 and 4), the average PMV values were lower than -0.5, indicating that the thermal sensation was slightly cool [11]. The other cases met the requirements of ASHRAE 55-2017. This showed that PMV of SV under heating mode could provide satisfactory general thermal comfort.

### 3.5. Energy utilization efficiency

The index, $E$, is widely used to quantify the magnitude of energy utilization of supply air [6, 7]. A larger $E$ indicated that the supply air was more efficiently used for warming the occupied zone, resulting in a higher energy efficiency. The calculation formula is as follows: $t_s$ is supply air temperature, $t_e$ is exhaust air temperature, and $t_n$ is the average air temperature of the occupied zone. Because the occupants were assumed to be sedentary, the occupied zone referred to the zone below 1.3 m.

$$E = \frac{t_s - t_e}{t_s - t_n}$$

![Table 4. Energy utilization efficiency.](image)

| Case | $t_s$ (°C) | $t_e$ (°C) | $t_n$ (°C) | Energy utilization efficiency |
|------|------------|------------|------------|-------------------------------|
| 1    | 26         | 19.9       | 21.6       | 1.4                           |
| 2    | 28         | 21.2       | 22.7       | 1.3                           |
| 3    | 30         | 20.6       | 22.7       | 1.3                           |
| 4    | 26         | 20.5       | 22.6       | 1.7                           |
| 5    | 28         | 22.1       | 22.1       | 1.6                           |
| 6    | 30         | 22.2       | 24.5       | 1.5                           |

Table 4 lists the energy utilization efficiency of each case. We could see that the energy utilization efficiency of SV can be up to 1.7 (i.e., Cases 4), which was higher than conventional ventilation methods (e.g. one for perfect mixing ventilation) [14]. This showed that SV under heating mode exhibited the obvious potential of energy-saving.
4. Conclusions
In this study, the thermal comfort and energy utilization efficiency of SV under heating mode were studied experimentally. Based on the experimental results, it can be concluded that SV could provide PMV of -0.5 to +0.5 under heating mode. The vertical air temperature difference between head and ankle levels could be below 3°C. The DR satisfied the requirement of Category B of thermal environments stipulated in ISO 7730. The energy utilization efficiency of SV can be up to 1.7, which was significantly higher than conventional ventilation methods under heating mode.

Acknowledgments
The study has been supported by the China National Key R&D Program (Grant No. 2018YFC0704405).

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