Experimental investigation into perceived air quality and sick building syndrome of stratum ventilation under heating mode

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Abstract. Stratum ventilation was able to provide satisfactory thermal sensation under heating mode, but its performance on perceived air quality and SBS (sick building syndrome) was still unknown. This study objectively measured indoor CO₂ concentration and subjectively surveyed human responses to perceived air quality and SBS symptoms in a stratum-ventilated classroom under the heating mode. Three cases with different supply air velocities and temperatures were designed. Twenty-three subjects were recruited to attend this study. The results showed that indoor CO₂ concentration under the three cases were all below 900 ppm and the contaminant removal effectiveness could be up to 1.9, indicating good indoor air quality. With proper designs of supply air velocity and temperature, the perceived air was fresh, and the perceived air quality was acceptable. The percentage of the subjects having SBS symptoms were below 20%. Therefore, stratum ventilation could bring satisfactory perceived air quality with few SBS symptoms under the heating mode.

1. Introduction
Stratum ventilation has been proposed to accommodate the elevated room temperatures recommended by several governments in East Asia [1]. The supply air terminals are located on the side and/or front wall(s) at a height slightly above the head of occupants [2]. In summer, stratum ventilation horizontally supplies the cool air into the breathing zone to achieve satisfactory thermal comfort and quality inhaled air [3]. It was validated to be able to provide lower inhaled contaminant concentration and higher heat removal efficiency as compared with mixing ventilation and displacement ventilation [4, 5]. Different from summer cooling which delivers the cool air horizontally, under the heating mode, the warm air was delivered with a downward vane angle to resist the upward thermal buoyancy for achieving good ventilation performances [6]. Thus, for stratum ventilation, the airflow pattern under the heating mode was distinct from that under the cooling mode. Previous studies showed that stratum ventilation can provide satisfactory thermal sensation with acceptable air temperature stratification, and the supply air temperature of stratum ventilation could be lower than mixing ventilation in winter [7]. However, no research has studied the performance on perceived air quality and SBS (sick building syndrome), which are important to the health and well-being of occupants.
As an indicator of indoor air quality, the indoor CO\textsubscript{2} concentration distribution was related to the ventilation strategies [8]. Riberon et al. [9] reported that the air stuffiness was strongly associated with the indoor CO\textsubscript{2} concentration. Furthermore, in a classroom, the good performances of a ventilation strategy on perceived air quality and SBS are crucial to the well-being and learning performance of students [10].

The experiments were conducted in a classroom served by stratum ventilation under the heating mode. Firstly, the indoor CO\textsubscript{2} concentration was measured to evaluate indoor air quality. Secondly, the questionnaire survey on perceived air quality and SBS symptoms was carried out. Three cases were designed to investigate these performances under different supply air temperatures and velocities.

2. Methodology

The experiments were carried out in City University of Hong Kong Chengdu Research Institute, China. As shown in Figure 1, the dimensions of the room are 8.4 m (length) × 5.4 m (width) × 2.6 m (height). In this study, the air-conditioning system with primary return air was used. Stratum ventilation was adopted to supply warm air into the room for conditioning indoor environment. Two rows were arranged in the room to resemble the typical layout of a classroom. Up to 12 subjects were allowed to be seated in the room simultaneously. The external wall is located on the left side of the room, which contains two windows with a total area of 7.25 m\textsuperscript{2}. Six supply air inlets were located on the front wall at the height of 1.3 m above floor, and six air outlets were located on the same wall as the air inlets at the height of 0.49 m above floor. The supply air inlets and exhaust air outlets have the same dimensions of 0.18 m × 0.18 m each. To counteract the upward momentum due to the thermal buoyance of the warm air, the supply vane angle was set at around 35° downwards [6].

In order to investigate the effects of supply air velocity and temperature on perceived air quality and SBS, three cases with different supply air velocities and temperatures were designed. The detailed supply air parameters are summarized in Table 1. Twenty-three subjects (11 females and 12 males) participated all the cases. However, in the experimental process, one of the female subjects felt uncomfortable because of her physical health problem. Thus, all of her questionnaires were not used for analysis. Table 2 shows the anthropometric data of the subjects. The clothing insulation of the subjects was estimated as 1.10 ± 0.16 clo. Their metabolic rates were assumed to be 1.1 met since they were reading/writing in their seats. Before starting the experiments, the environmental room was conditioned for at least 30 minutes to ensure that the indoor environment was stable. The subjects were required to enter the environmental room 10 minutes earlier than the formal experiments for acclimatization. Each session lasted for one hour, during which the subjects were asked to complete the six same questionnaires. The time intervals between two adjacent questionnaires were shown in Figure 3. The questionnaire concerned air freshness sensation, air quality acceptability and SBS symptoms in the environmental room. According to the questionnaire, the subjects reported their air freshness sensation on a 7-level scale (–3 very stuffy, –2 stuffy, –1 slightly stuffy, 0 neutral, +1 slightly fresh, +2 fresh and +3 very fresh). The acceptability of air quality was evaluated with a 6-level scale (–2 clearly unacceptable, –1 unacceptable, –0.1 just unacceptable, +0.1 just acceptable, +1 acceptable and +2
clearly acceptable). Six SBS symptoms (i.e. nausea and dizziness, eye-discomfort, dry tongue and extreme thirsty, nose-discomfort, dry skin and losing attention) were given on the questionnaire.

Figure 3. Experimental procedure.

Table 1. Experimental conditions.

| Case | Tn (°C) | Ts (°C) | Us (m/s) | Ti (°C) | Qe (m³/h) | ACH | RH (%) |
|------|---------|---------|----------|---------|-----------|-----|--------|
| 1    | 30      | 29.9 ± 0.2b | 1.4      | 24.1    | 979.8     | 8.3 | 36 ± 6 |
| 2    | 30      | 29.8 ± 0.1 | 1.8      | 25.1    | 1259.7    | 10.7| 37 ± 6 |
| 3    | 26      | 26.1 ± 0.3 | 1.8      | 23.0    | 1259.7    | 10.7| 37 ± 3 |

a Tn, nominal supply air temperature.
b Ts, actual supply air temperature.
c Us, supply air velocity.
d Ti, air temperature in the breathing zone.
e Qe, supply airflow rate.
f ACH, air changes per hour.
g RH, relative humidity.
h The data of Ts and RH are presented in mean ± SD (standard deviation).

Table 2. Characteristics of subjects involved in experiments.

| Gender | Number | Age (years) | Weight (kg) | Height (cm) | BMI a |
|--------|--------|-------------|-------------|-------------|-------|
| Male   | 12     | 20.2 ± 2.6  | 66.4 ± 11.0 | 173 ± 7     | 22.0 ± 2.9 |
| Female | 10     | 19.4 ± 1.3  | 50.8 ± 3.4  | 160 ± 4     | 19.8 ± 1.4 |
| All    | 22     | 19.8 ± 2.1  | 59.3 ± 11.5 | 167 ± 9     | 21.0 ± 2.6 |

a BMI, body mass index, BMI = (Weight / Height²) × 10⁴.

Table 3. Information on measurement instruments.

| Parameters | Tn | Ts | Us | C² | Ti | RH |
|------------|----|----|----|----|----|----|
| Type of instruments | Swema 03+ | Swema 03+ | pSENSE II | pSENSE II | pSENSE II |
| Measuring range      | 10—40 °C | 0.05—10.00 m/s | 0—9999 ppm | −20—60 °C | 0.1—99.9% |
| Measuring accuracy   | ± 0.2 °C | ± 0.03 m/s ± 3% of reading | ± 30 ppm ± 5% of reading | ± 0.3 °C | ± 3.0% |

a C, CO₂ concentration.

The supply air temperatures and velocities were measured by the omnidirectional hot-wire anemometers (Swema 03+). Throughout the entire experiment, the CO₂ concentration, indoor air temperature as well as the relative humidity were measured using the data logger pSENSE II. These parameters were monitored at the measuring points “M1” and “M2” in the occupied zone at the height of the desk (0.74 m above the floor) (see Figure 1). The sampling frequency of pSENSE II was 0.2 Hz. The detailed information of the measurement instruments is listed in Table 3.

All statistical analyses were conducted using the IBM SPSS Statistics 23. The distribution of the data was all non-normal according to the Shapiro-Wilk tests, so non-parametric Wilcoxon Matched-Pair Signed-Ranks tests were adopted and Spearman correlation coefficients were used to show the correlations between variables. On the basis of the test results, the last two votes were analyzed since there was no significant difference between them. The statistical analysis was conducted at the significance level of 0.05.
3. Results and discussion

3.1. CO$_2$ concentration

The measured CO$_2$ concentrations are summarized in Table 4. It was seen that the CO$_2$ concentration was within 900 ppm for all the cases, which could provide good indoor air quality for the subjects since the CO$_2$ level within 900 ppm conforms to the requirement by Category III in ISO 17772-1:2017(E) in non-residential buildings [11]. From Table 4, the values of CRE for all the cases were greater than 1, indicating that stratum ventilation could efficiently remove CO$_2$ under the heating mode.

Table 4. Measurement results of CO$_2$ concentration.

| Case | $C_s$ (ppm) | $C_i$ (ppm) | $C_e$ (ppm) | CRE$^d$ |
|------|-------------|-------------|-------------|--------|
| 1    | 654 ± 10    | 867 ± 9     | 918 ± 22    | 1.2    |
| 2    | 542 ± 32    | 707 ± 67    | 750 ± 68    | 1.3    |
| 3    | 498 ± 48    | 582 ± 86    | 658 ± 100   | 1.9    |

$^a$ $C_s$, CO$_2$ concentration in the supply air.
$^b$ $C_i$, CO$_2$ concentration in the occupied zone.
$^c$ $C_e$, CO$_2$ concentration in the exhaust air.
$^d$ CRE, CO$_2$ removal effectiveness, CRE = ($C_e - C_s$) / ($C_i - C_s$).

Among the three cases, the CRE of Case 1 was lowest. It was mainly because the supply air temperature was highest and the supply air velocity was lowest under Case 1. For one thing, the higher supply air temperature resulted in higher thermal buoyancy, which prevent the warm air from arriving at the occupied zone. This was also illustrated by the comparison that the CRE of Case 2 was lower than Case 3 (with same supply air velocity). For the other, the lower supply air velocity implied that less conditioned air was used to dilute the pollutants. Therefore, the value of CRE under Case 2 was greater than that under Case 1.

3.2. Perceived air quality

The results of Wilcoxon Matched-Pair Signed-Ranks tests showed that there was no significant difference between Case 1 and Case 2 with regard to air freshness sensation ($P > 0.05$), but Case 3 was significantly different from Case 1 ($P < 0.05$). As shown in Figure 4, the mean vote of air freshness sensation was around 0.8 (i.e. fresh side) for Case 3 while this value was below 0 (i.e. stuffy side) for Cases 1 and 2. Theoretically, the indoor environment should not be stuffy since the CO$_2$ concentration accords well with the Category III in ISO 17772-1:2017(E). This might be ascribed to the lower air temperature in the breathing zone under Case 3 (see Table 1).

With respect to the air quality acceptability, the mean votes of the three cases are presented in Figure 4. The mean votes of the air quality acceptability were above 0.5 for all the cases, which demonstrated that the subjects were satisfied with the air quality provided by stratum ventilation. Under Case 3, the air quality acceptability was the highest, which was in line with the air freshness sensation. This may be owing to the lowest CO$_2$ concentration and the lowest ambient air temperature among the three cases. As seen from the Figure 4, with the lower CO$_2$ concentration, both the air freshness sensation and air quality acceptability become better. In fact, it was found from the data analysis that all the Spearman correlation coefficients between the air acceptability and CO$_2$ concentration for Cases 1, 2 and 3 were very strong (i.e. $-1$). This indicated that the CO$_2$ concentration had a close relationship with the perceived air quality, as also seen in other studies [9].
In summary, with low supply air temperature and high supply air velocity, more fresh air could arrive at the occupied zone, and thus remove CO$_2$ more efficiently. Besides, according to the results on CO$_2$ concentration and perceived air quality, lower CO$_2$ concentration led to a better air quality acceptability and air freshness perception. Under Case 3, good air quality acceptability and air freshness perception could be achieved. Therefore, Stratum ventilation can provide the occupants with satisfactory perceived air quality under the heating mode.

3.3. SBS symptoms

The SBS often appeared with the harmfulness to the well-being of occupants [12]. Figure 5 illustrates the votes on SBS symptoms for each case. On the whole, there was no significant difference between the votes of three cases (P > 0.05). The complaints on dry skin had the most votes. Other symptoms as eye-discomfort, nose-discomfort and extreme thirsty also occurred in varying degrees. One of the reasons was the relative humidity which was below 40% during the whole experiment (see Table 1), which is a common problem under the heating mode, especially for the all-air heating system [13]. The low relative humidity might cause the irritation of the eyes and nose [14], thus eye-discomfort as well as other humidity-related uncomfortable symptoms arose. Therefore, the measures to increase the relative humidity in a room with all-air heating system need further studies.

As seen from Figure 5, under Case 3, the votes on all SBS symptoms were below 10%, indicating good comfort. Under Cases 1 and 2, the votes on SBS symptoms were varied between 2% and 16%, which were below 20%. Previous studies showed that the percentage of occupants reporting SBS symptom should be less than 20%, otherwise the occupants would suffer from SBS [12]. In other words, the results showed that the stratum ventilation could bring the low percentages of occupants reporting SBS symptoms under the heating mode.

4. Conclusion

This study carried out the measurements on the indoor CO$_2$ concentration and subjective surveys on perceived air quality and SBS symptoms of the occupants in a classroom. The results of statistical analysis showed that the perceived air quality had close relationship to the indoor CO$_2$ concentration. Since the values of CRE were greater than 1 and CO$_2$ concentrations were lower than 900 ppm, stratum
ventilation could efficiently remove CO$_2$ and provided good perceived air quality under the heating mode. Furthermore, compared with Cases 1 and 2, Case 3 showed better perceived air quality and lower percentage of occupants reporting SBS symptoms. This indicated that with proper designs of supply air temperature and velocity, the performances of stratum ventilation could be optimized. In all, as the air quality was well acceptable and the percentages of votes on SBS symptoms were below 20%, stratum ventilation could satisfy the requirements of air quality under heating mode.

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References
[1] Lin, Z., Chow, T.T., Tsang, K.F., Chan, L.S. (2009) Stratum ventilation – A potential solution to elevated indoor temperature. J. Build. Environ., 44: 2256–2269.
[2] Cheng, Y., Lin, Z. (2015) Experimental study of airflow characteristics of stratum ventilation in a multi-occupant room with comparison to mixing ventilation and displacement ventilation. J. Indoor Air, 25: 662–671.
[3] Lin, Z., Yao, T., Chow, T.T., Fong, K.F., Chan, L.S. (2011) Performance evaluation and design guidelines for stratum ventilation. J. Build. Environ. 46: 2267–2279.
[4] Zhang, S., Cheng, Y., Huan, C., Lin, Z. (2018) Heat removal efficiency based multi-node model for both stratum ventilation and displacement ventilation. J. Build. Environ., 143: 24–35.
[5] Cheng, Y., Zhang, S., Huan, C., Oladokun, M.O., Lin, Z. (2019) Optimization on fresh outdoor air ratio of air conditioning system with stratum ventilation for both targeted indoor air quality and maximal energy saving. J. Build. Environ., 147: 11–22.
[6] Zhang, S., Lin, Z., Ai, Z., Wang, F., Cheng, Y., Huan, C. (2019) Effects of operation parameters on performances of stratum ventilation for heating mode. J. Build. Environ. 148: 55–66.
[7] Kong, X., Xi, C., Li, H., Lin, Z. (2019) A comparative experimental study on the performance of mixing ventilation and stratum ventilation for space heating. J. Build. Environ. In press.
[8] Geelen, L.M.J., Huijbregts, M.A.J., Ragas, A.M.J., Bretveld, R.W., Jans, H.W.A., van Doorn, W.J., Evertz, S.J.C.J., van der Zijden, A. (2008) Comparing the effectiveness of interventions to improve ventilation behavior in primary schools. J. Indoor Air 18: 416–424.
[9] Canha, N., Mandin, C., Ramalho, O., Wyart, G., Riboron, J., Dassonville, C., Hanninen, O., Almeida, S.M., Derbez, M. (2016) Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France. J. Indoor Air 26: 350–365.
[10] Mendell, M.J., Heath, G.A. (2005) Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor Air 15:27–52.
[11] ISO 17772-1:2017(E) (2017) Energy performance of buildings – Indoor environmental quality – Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings. S. Geneva. International Organization for Standardization.
[12] ASHRAE. 2009 ASHRAE Handbook—Fundamentals, Chapter 10. M. Altanla. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[13] Lin, B., Wang, Z., Sun, H., Zhu, Y., Ouyang, Q. (2016) Evaluation and comparison of thermal comfort of convective and radiant heating terminals in office buildings. J. Build. Environ. 106: 91–102.
[14] EN 15251 (2007) Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels. S. European Committee for Standardization.