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Experimental study into turbulent characteristics of airflows under stratum ventilation with pulsating air supply: comparison to steady air supply

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Abstract. Stratum ventilation is more energy-efficient than conventional ventilation strategies, whereas its thermal comfort can be further improved. Compared with steady airflows, dynamic airflows are capable of improving thermal comfort. Turbulent characteristics of airflows can affect human thermal comfort. This study aims to investigate the turbulent characteristics of airflows in the occupied zone under stratum ventilation with pulsating air supply, which can produce dynamic airflows. The turbulent characteristics were compared with that under conventional steady air supply. Experiments were conducted in a classroom mock-up using stratum ventilation. Five cases, namely, one with steady air supply and four with pulsating air supply were designed. The turbulent intensity (Tu) and power spectrum of air velocity signals were analysed. The results showed that the Tu of the airflows in the occupied zone under pulsating air supply was greater than that under steady air supply by 10-15%. Power spectrum density exponents (β) of airflows under the two air supplies fluctuated within the same range of 0.5 to 1.2. However, the power spectrum density function showed different distributions on low frequency area. The turbulent characteristics of airflows created by pulsating airflows may provide better thermal comfort.

1. Introduction

With the need of reduce energy consumption in buildings, stratum ventilation has been proposed. It was proved to be able to provide occupants with satisfactory indoor environment with low energy consumption [1, 2]. The primary concept of this ventilation method is to cool the head-chest zone of occupants by elevated air movement with a higher room temperature [2]. However, the potential draft risk still exists under stratum ventilation, and thermal conditions at different distances from the supply diffusers can be different [3]. Pulsating air supply can provide satisfactory indoor climate, including good ventilation performance and thermal comfort [4, 5]. With pulsating air supply, the air velocity follows variations like signal wave. It can be deduced that pulsating air supply can also be used in stratum ventilation to reduce the draft risk associated with enhanced air movement, thus improving thermal comfort.

Pulsating air supply produces dynamic airflows with a pulsating air velocity profile in the occupied zone. The airflows are typically turbulent. Previous studies have shown turbulent characteristics of the airflow around human have significant influence on thermal comfort [6]. Analytical tools like power



spectrum density analysis have also been used to describe the different characteristics between dynamic airflows and steady airflows [7].

In this study, the turbulent intensity and power spectrum density functions were utilized to distinguish characteristics of airflows in the occupied zone from pulsating air supply and steady air supply under stratum ventilation. This study helps to apply stratum ventilation better to save energy for creating comfortable indoor environment.

2. Methods

2.1. Test room

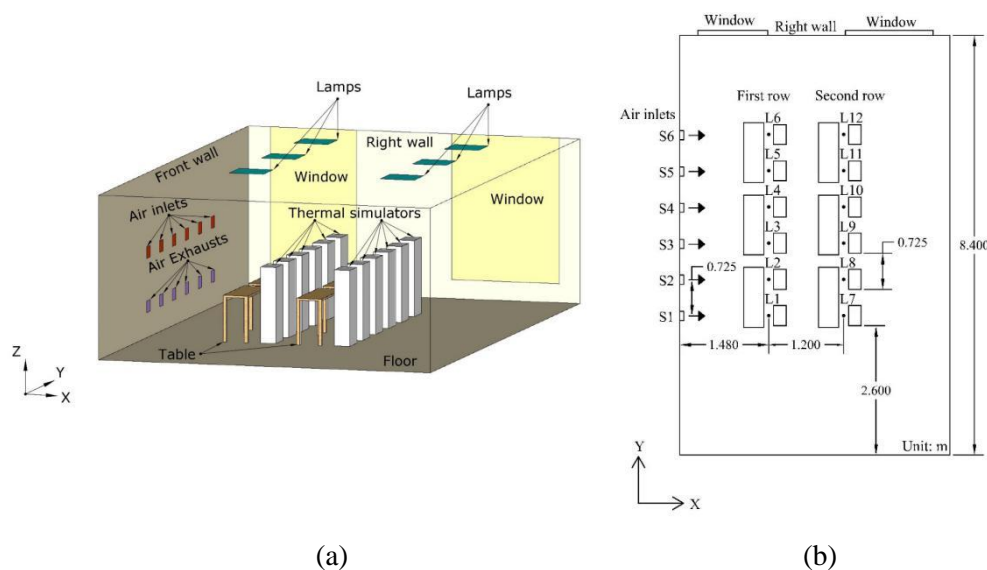


Figure 1. (a) Layout of the experimental room. (b) Locations of physical measurements (S1-S6: air inlets; L1-L12: Sampling Lines).

The experiments were conducted in a room with dimensions of 8.4 m (length) \times 5.4 m (width) \times 2.6 m (height) in City University of Hong Kong Chengdu Research Institute, China. The room was configured as a classroom mock-up with stratum ventilation systems. Figure 1 shows the layout of the room. It had two windows located on the right exterior wall. The other three walls were interior. There were 12 seats for occupants with 6 seats in each row. The occupant was represented by a rectangular thermal simulator with dimensions of 0.40 m (length) \times 0.25 m (width) \times 1.20 m (height). A light bulb of 100 W was placed inside each thermal simulator to simulate human heat. There were six ceiling-mounted lamps with a heat load of 15 W each. The temperature fluctuations of the exterior wall and the windows during the experimental periods were small (within 1°C). Full fresh air is supplied horizontally to the breathing zone from six grilles at the height of 1.35 m above the floor, and then exhausted through six exits at the height of 0.49 m above the floor. The air inlets/exhausts had the same dimensions of 0.17 m \times 0.17 m.

The supply air temperature and supply airflow rate were controlled by a control system by changing the opening of the chill water valve and the frequency of the supply fan, respectively. Figure 2 shows the measured air velocity at the supply outlet S3 under Cases A and B. For pulsating air supply, the time lengths of the whole cycle, duty period when the air velocity was high, idle period when the air velocity was low, and the frequencies of the supply fan for the duty period and the idle period can be set.

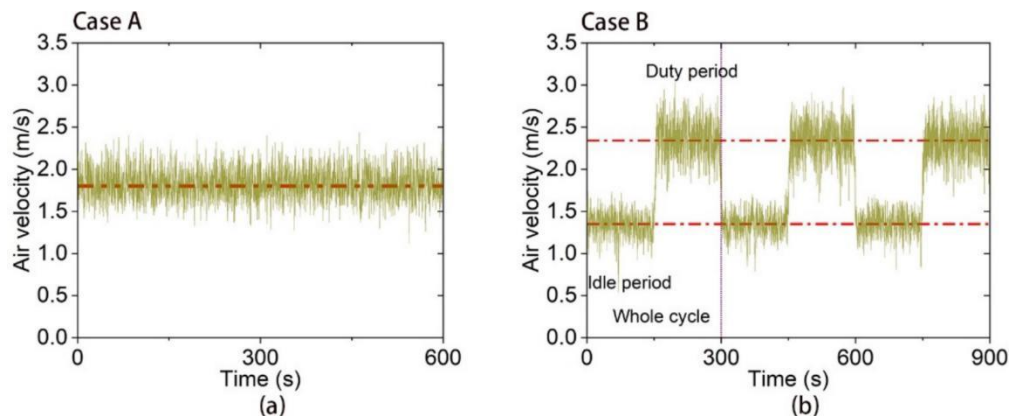


Figure 2. Air velocity variations of steady and pulsating air supplies measured at S3.

2.2. Studied cases

The studied cases are presented in Table 1. Room air temperature was measured by a sensor positioned at the geometric centre of this test room. The room air humidity was between 45% to 50%. The supply airflow rate was the sum of the measurements at the six air supply inlets S1-S6. A cycle was divided into the duty period when the air velocity was high, and the idle period when the air velocity was low. The time lengths of the duty period and idle period were the same during one cycle. In total, five cases were studied.

Table 1. Information on cases

| Case | | | A | B | C | D | E |
|------------------------------|------------------|---------|-----------|-----------|-----------|-----------|-----------|
| Air supply method | | | Steady | | Pulsating | | |
| Room air temperature (°C) | | | 26.6±0.1 | 26.7±0.3 | 28.0±0.3 | 26.5±0.3 | 27.0±0.4 |
| Supply air temperature (°C) | | | 21.7±0.2 | 21.5±0.1 | 23.5±0.2 | 21.6±0.3 | 21.6±0.2 |
| Exhaust air temperature (°C) | | | 26.6±0.2 | 26.3±0.1 | 27.9±0.1 | 26.6±0.0 | 27.1±0.0 |
| Air changes per hour (ACH) | | | 9.0 | 9.0 | 9.0 | 9.0 | 7.9 |
| Air supply velocity (m/s) | The whole cycle | Nominal | 1.70 | 1.70 | 1.70 | 1.70 | 1.50 |
| | | Actual | 1.72±0.13 | 1.66±0.53 | 1.64±0.38 | 1.78±0.49 | 1.48±0.30 |
| | Duty period | Nominal | / | 2.21 | 2.21 | 2.21 | 1.70 |
| | | Actual | / | 2.07±0.29 | 1.99±0.13 | 2.21±0.27 | 1.75±0.15 |
| | Idle period | Nominal | / | 1.36 | 1.36 | 1.36 | 1.36 |
| | | Actual | / | 1.25±0.11 | 1.30±0.12 | 1.35±0.10 | 1.21±0.07 |
| | Cycle time (min) | | / | 5 | 5 | 2 | 2 |

2.3. Measurement instruments

Table 2. Information on measurement instruments

| Type of instruments | Air velocity (m/s) | | Air temperature (°C) | |
|---------------------|--------------------|--------------------|----------------------|--------------------|
| | measuring range | measuring accuracy | measuring range | measuring accuracy |
| SWEMA | 0.07-0.5 | ±0.02 | 10-40 | ±0.2 |
| | 0.5-3.00 | ±0.03 | | |
| KIMO VT 100 | < 3.00 | ±0.1 | -20-+80 | ±0.3 |
| WZY-1 | | | -20-+80 | ±0.3 |

All the instruments were calibrated prior to measurements. Air velocity and temperature at the six air supply inlets and six exhausts were measured by SWEMA omnidirectional hot-wire anemometers. Air

velocity and temperature in the occupied zone were measured using SWEMA and KIMO VT 100 omnidirectional hot-wire anemometers. The temperatures on the surfaces were measured by WZY-1. The details of measurement instruments were summarized in Table 2.

2.4. Experimental procedure

Each case was pre-set at least 2 hours before the measurements. Measurements in the occupied zone were conducted using a sensor rig made out of aluminium tubes. The sensors were positioned at the rig with a vertical array at the desired measurement height. It was moved around the room to draw a grid of Sampling Lines. The air temperature and velocity in the occupied zone were measured at Sampling Lines L1-L12, as shown in Figure 1(b). The Sampling Lines were located 10 cm in front of the thermal simulator. For each Sampling Line, air velocity and temperature were measured at the heights of 1.1 m, 0.6 m and 0.1 m above the floor [8]. The measurement period for air velocity and temperature was ten minutes for Case A, three cycles under pulsating air supply, i.e., fifteen minutes for Cases B and C, six minutes for Cases D and E. The sampling frequency was 8 Hz. A twenty-minute interval was applied between moving the sensors and performing the next measurements. The temperatures of the surfaces (walls, windows, floor and ceiling) and room air temperature were measured during the entire experimental periods with an interval of 1 min.

3. Results and discussion

For stratum ventilation, the airflows at the height of 1.1 m above the floor have a dominant effect on thermal comfort [3]. Therefore, the airflow characteristics at the height of 1.1 m were mainly discussed.

3.1. Turbulent intensity

Turbulent intensity, Tu , is defined as the ratio of the standard deviation of the fluctuating instantaneous air velocity to the mean air velocity [9]:

$$Tu = \frac{S}{\bar{v}} \quad (1)$$

Where S is the standard deviation; \bar{v} is the mean air velocity (m/s).

S is calculated from the following Equation:

$$S = \sqrt{\frac{1}{N} \sum_{i=1}^N (v_i - \bar{v})^2} \quad (2)$$

Where v_i is the instantaneous air velocity (m/s); N is the total number of the measured data.

High Tu promotes heat transfer and gives more stimulation to the skin of occupants [10-12], thus enhancing the human body cooling. Figure 3 shows that the Tu values became larger with the increasing distance from the air inlets under all the cases. The Tu values in the second row was higher than in the first row. For Cases B-E, the Tu values in the second row was above 50%.

In the first row, the Tu values under Cases B-E was approximately 15% higher than that under Case A. In the second row, the Tu values under Cases B-E was approximately 10% higher than that under Case A. Thus, pulsating air supply increased Tu . This was because under pulsating air supply, there were large drops or rises in the air velocity. Even though the airflow rate under Case E was lower than Case A, the Tu values was higher than under Case A by 15-20%. This indicates that the usage of pulsating air supply with lower supply airflow rate can realize the same cooling effect of human body as the steady air supply. This implies an energy-saving potential for the pulsating air supply.

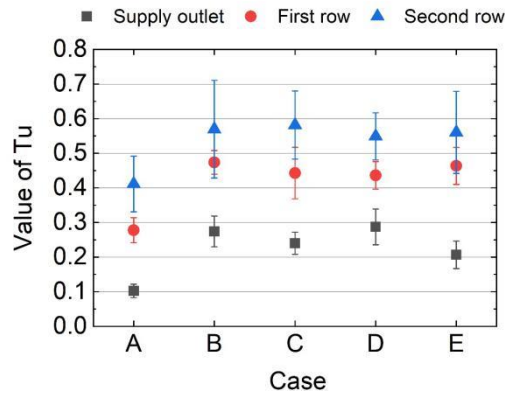


Figure 3. Values of Tu

3.2. Power spectrum density

The power spectrum density is a common method in signal processing within the frequency domain. It was widely used in previous studies [6, 13, 14] as it can relate the eddies energy distribution in the turbulent airflows to the corresponding frequency. The power spectrum density was calculated using the Fourier Transform. The calculating procedure is below:

$$\int_0^{\infty} E(f) df = \overline{v'^2} \quad (3)$$

Where f is the frequency (Hz); $E(f)$ is the power spectrum density function.

For the discrete sample function, the discrete frequency is selected as:

$$f = \frac{n}{N \cdot \Delta t}, \quad n=0,1,2, \dots, N-1 \quad (4)$$

Where Δt is the sampling interval (s).

The power spectrum density function $E(f)$ is calculated by:

$$E(f) = \frac{2\Delta t}{N} |v(n)|^2 = \frac{2\Delta t}{N} v^*(n)v(n) \quad (5)$$

Where $X(n)$ is the Fast Fourier Transfer (FFT) of sample data $v(t)$ of instantaneous velocity; $v^*(n)$ is conjugate complex number of $v(n)$.

Since the power spectrum density of airflows under Cases B-D was similar, the results under Case C were presented. Figure 4 compares the power spectrum density of airflows under Case A and Case C. In general, the power spectrum density decreased as the frequency increased. Studies showed that people were sensitive to a certain range of frequency, mostly below 1 Hz [14-16]. This indicated that the large-scale eddies with low frequency mainly affected thermal comfort. In this study, the frequency range of 0.01-1 Hz was regarded, and the negative slope of the power spectrum density curves (β value) was calculated. The β value reflects the energy distribution of eddies of different scales. The larger the β value, the more turbulent energy in the eddies of large scales.

Figure 5 shows the β values of five cases. It was seen that the β values in the second row were significantly higher than in the first row. This corresponded to the results reported in the former study [13]. It was found that the natural wind had β value higher than 1.1 [13]. In this study, the β values under Case A were close to those under Cases B-E, indicating that there was insignificant difference between β values of airflows produced by steady and pulsating air supply. The β values were mostly distributed between 0.5 and 1.2. However, from Figure 4, it can be seen that under Case C, there were peak values of $E(f)$ at the low frequency area, which were not observed under Case A. The peak values of $E(f)$ at the low frequency area were also observed in cases with sinusoidal airflows which were proved to be more comfortable than steady airflows [13, 17].

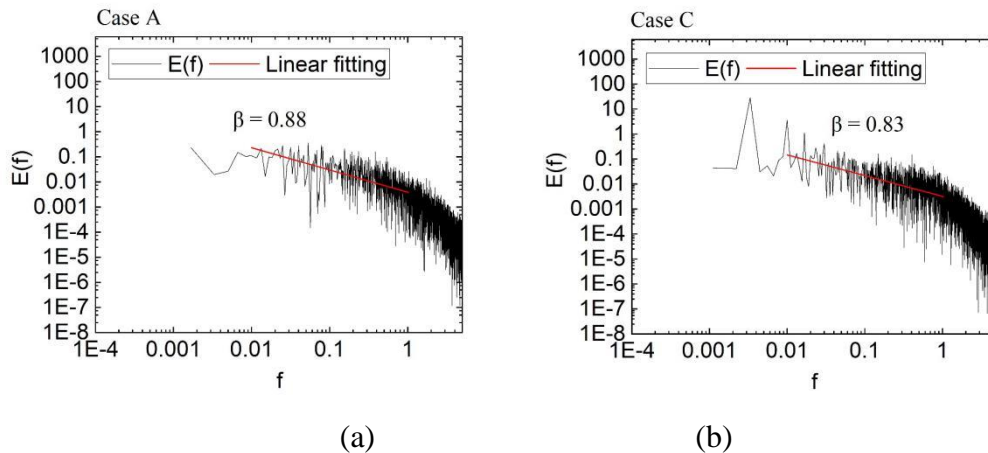


Figure 4 (a)-(b). Power spectrum exponent fitting of airflows at L3 at the height of 1.1 m

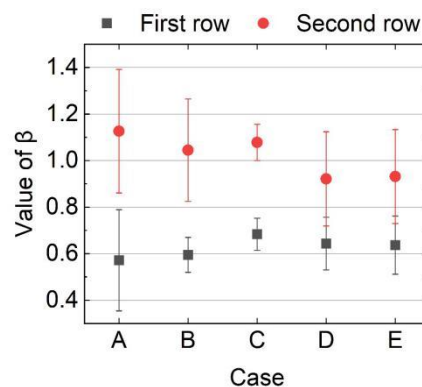


Figure 5. β values under Cases A-E

4. Conclusions

In this study, the pulsating air supply and steady air supply were applied under stratum ventilation. The differences on turbulent characteristics of airflows created by the two supply methods were investigated. The turbulent intensity of airflows in the occupied zone under pulsating air supply was greater than that under steady air supply by 10-15%. Using the power spectrum density method, the β values of airflows under the two supply methods were mostly distributed within the same range, from 0.5 to 1.2. But, the power spectrum density distributions at low frequency area were distinct. The turbulent characteristics of airflows created by pulsating airflows were more similar to that of dynamic airflows proved to be more comfortable. This indicated that pulsating air supply had potentials to provide better thermal comfort than steady air supply.

Acknowledgments

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