Experimental comparison on dynamic characteristics of the airflows produced by pulsating and steady air supply under stratum ventilation

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Abstract. Stratum ventilation has been proved to be more energy-efficient than conventional ventilation methods. Thermal comfort of stratum ventilation can be further improved. Compared with steady airflows, dynamic airflows have potentials to improve thermal comfort due to distinct dynamic characteristics. This study aims to investigate and compare the dynamic characteristics of airflows produced by steady and pulsating air supply under stratum ventilation. Experiments were conducted, in which steady and pulsating air supply were used to condition a classroom served by stratum ventilation, respectively. Five test conditions including one with steady air supply and four with pulsating air supply were designed. Analysis on skewness and kurtosis showed that the air velocity distributions of steady air supply were closer to normal distributions than pulsating air supply. Multi-scale decomposition of instantaneous air velocity signals was performed by using wavelet analysis. The one-dimensional continuous wavelet transform (CWT) showed that the airflows produced by the two supplies had differentiated CWT coefficients with time. In conclusion, the dynamic characteristics of airflows created by pulsating air supply were more similar to that of natural winds, which may provide better thermal comfort.

1. Introduction
In order to reduce the energy consumption of air-conditioning systems, stratum ventilation has been proposed. Previous studies showed that this ventilation method could provide occupants an acceptable indoor environment with low energy consumption [1, 2]. Its primary concept is to cool head-chest zone of occupants by elevated air movement. The thermal neutral temperature of stratum ventilation is higher than both mixing ventilation and displacement ventilation [2]. However, the potential draft risk still exists under stratum ventilation, and thermal conditions at different distances from the supply diffusers can be differentiated due to the entrainment of supply air jet [3]. Pulsating air supply was proved to have good performances on ventilation and thermal comfort [4, 5]. It can be inferred that pulsating air supply could be used for stratum ventilation to improve thermal comfort.

When the pulsating air supply is applied, the air velocity follows variations like signal wave. It consequently generates fluctuating airflows with a pulsating air velocity profile in the occupied zone. Previous studies have shown that dynamic characteristics of the airflows around human had a significant impact on thermal comfort [6, 7]. Analytical methods like the statistical analysis and wavelet transform method have been used to study the different characteristics between dynamic airflows and steady airflows [7]. However, these dynamic characteristics of airflows produced by pulsating air supply have not been examined and compared to steady airflows or natural winds.
In this paper, the statistical parameters and wavelet transform method were utilized to distinguish the characteristics of airflows in the occupied zone from pulsating air supply and steady air supply under stratum ventilation. The characteristics of airflows were evaluated at two different distances from the air inlets. This study can enrich our knowledge on stratum ventilation and airflows produced by pulsating air supply, which is helpful to create a satisfactory indoor environment with low energy consumption.

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).](image)

Figure 1 shows the layout of the experimental room. The size of the room is 8.4 m (length) × 5.4 m (width) × 2.6 m (height). It is located in City University of Hong Kong Chengdu Research Institute, China. It is configured as a classroom with stratum ventilation systems. It has two windows located on the right exterior wall. The other three walls are interior walls. There are 12 seats for occupants with 6 seats in each row. A rectangular thermal simulator with dimensions of 0.40 m (length) × 0.25 m (width) × 1.20 m (height) is used to represent an occupant. A light bulb of 100 W is placed inside each thermal simulator to simulate body heat. Six lamps with a heat load of 15 W each are mounted on the ceiling. During the experiments, the temperatures of the exterior wall and the windows fluctuated small (within the range of 1°C). Thus, the cooling load can be considered constant. The air inlets and air exhausts are double deflection grilles. The air inlets are positioned at the height of 1.35 m above the floor, and the air exhausts along the same wall as the air inlets are located at the height of 0.49 m above the floor (see Figure 1). The air inlets/exhausts have the same dimensions of 0.17 m × 0.17 m. Full fresh air is supplied horizontally. The air inlets can send air in a steady or pulsating way. Under pulsating air supply, air was sent following a cycle which was divided into duty period and idle period (see Figure 2). 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 can be set through a control system.

2.2. Cases studied

Table 1 lists the cases studied. Five cases, including one case of steady air supply and four cases of pulsating air supply, were designed. Room air temperature was measured by a sensor placed at the geometric centre of the room. The room air humidity was monitored between 45% and 50%. The supply airflow rate was the sum of the measurements at the six air supply inlets S1-S6. During one cycle, the time lengths of the duty period and idle period were the same. Figure 2 shows the air velocity variations of steady and pulsating air supplies measured at S3 under Cases A and B.
addition, the mean air velocities at the height of 1.1 m above floor were similar for all the cases (about 0.4 m/s), creating a close-to-neutral overall thermal sensation in the room [8].

Table 1. Information on cases.

| Case | A | B | C | D | E |
|------|---|---|---|---|---|
| Air supply method | Steady | Pulsating |
| Room air temperature (℃) | 26.6±0.1 | 26.7±0.3 | 28.0±0.3 | 26.5±0.3 | 27.0±0.4 |
| Supply air temperature (℃) | 21.7±0.2 | 21.5±0.1 | 23.5±0.2 | 21.6±0.3 | 21.6±0.2 |
| Exhaust air temperature (℃) | 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 |
| The whole cycle | Nominal | Actual |
| Air supply velocity (m/s) | 1.70 | 1.70 | 1.70 | 1.70 | 1.50 |
| Duty period | Nominal | Actual |
| | / | 2.21 | 2.21 | 2.21 | 1.70 |
| Idle period | Nominal | Actual |
| | / | 1.36 | 1.36 | 1.36 | 1.36 |
| Cycle time (min) | / | 5 | 5 | 2 | 2 |

Figure 2. Air velocity variations measured at S3. (a) steady air supply; (b) pulsating air supply.

2.3. Measurement instruments

All the instruments were calibrated prior to the experiments. For the six air supply inlets and six exhausts, air velocity and temperature were measured by SWEMA omnidirectional hot-wire anemometers. For the occupied zone, air velocity and temperature were measured using SWEMA and KIMO VT 100 omnidirectional hot-wire anemometers. The temperatures on the surfaces were recorded by WZY-1. 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 |
|---------------------|-----------------|--------------------|-----------------|--------------------|
| SWEMA               | 0.07-0.5        | ±0.02              | 10-40           | ±0.2              |
| KIMO VT 100         | 0.5-3.00        | ±0.03              | -20-+80         | ±0.3              |
| WZY-1               | < 3.00          | ±0.1               | -20-+80         | ±0.3              |

2.4. Experimental procedure

Before the measurements, each case was pre-set at least 2 hours. Measurements in the occupied zone were conducted using a sensor rig. The sensors were placed at the rig with a vertical array at three measurement heights (i.e., 1.1 m, 0.6 m and 0.1 m above the floor [8]). 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 (see Figure 1(b)). The measurement period for air velocity and
temperature was 10 minutes for Case A, three cycles under pulsating air supply, i.e., 15 minutes for Cases B and C, 6 minutes for Cases D and E. The sampling frequency was 8 Hz. A twenty-minute interval was applied between placing 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 following analysis were based on the data collected at the height of 1.1 m above the floor.

3.1. Skewness and kurtosis

Skewness measures deviation from a normal distribution, see Equation (1).

\[
SK = \frac{\sum (v_i - \bar{v})^3}{S^3 \cdot N}
\]  

(1)

Where SK is the skewness, \(v_i\) is the instantaneous air velocity (m/s), \(\bar{v}\) is the mean air velocity (m/s). \(N\) is the total number of the measured data. \(S\) is the standard deviation, which is calculated by:

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

(2)

Skewness represents asymmetry. Skewness can be positive, negative or zero. A negative value indicates that the tail on the left side of the distribution is either longer or fatter than the right side, vice versa. A zero value indicates that the analysed values are evenly distributed on both sides of the mean value.

Kurtosis is used to describe the distribution shape, see Equation (3).

\[
K = \frac{\sum (v_i - \bar{v})^4}{S^4 \cdot N}
\]  

(3)

Where \(K\) is the kurtosis. When the kurtosis is large, the shape of the distribution plot will be tall and thin. When the kurtosis is small, the distribution plot will be short and fat. The kurtosis of a normal distribution is 3.

Figure 3 (a)-(b) shows the results of skewness and kurtosis at the air inlet, the first row (R1) and the second row (R2) under Cases A-E. For skewness, the mean values were all positive, indicating that most of the data lay to the left of the mean, namely, the air velocity values were smaller than the median value. Compared with steady air supply, the skewness values of pulsating air supply were generally higher. In other words, the airflows of steady air supply were closer to a symmetric distribution. For kurtosis, at the air inlet, the first row (R1) and the second row (R2), the kurtosis
values of pulsating air supply were all farther from 3 than those of steady air supply. It can be concluded that the air velocity distributions of steady air supply were closer to normal distribution. For common mechanical wind, the air velocity distributions were closer to normal distribution than natural wind [6]. Therefore, the airflows produced by pulsating air supply were closer to natural wind than steady air supply.

3.2. One-dimensional CWT

The airflow can be seen as the superposition of a series of eddies with different scales. The one-dimensional CWT is used to reveal correlation between the air velocity profiles and the scaled wavelet, and to investigate the information in the energy distribution of the eddies. The CWT is calculated via Equation (4) [9]:

\[(T_{w}^{\text{wav}}f)(a, b) = |a|^{-1/2} \int dt f(t) \psi \left( \frac{t-b}{a} \right) \]  

(4)

Where \( b \) is the time factor, \( a \) is the time length, the function \( \psi \) is called the mother wavelet. In this study, we assume that \( \psi \) satisfies the following correlation:

\[ \int dt \psi(t) = 0 \]  

(5)

A typical choice for \( \psi \) is:

\[ \psi(t) = (1 - t^2)e^{-(t^2/2)} \]  

(6)

It is also called the Mexican hat function [9]. The Mexican hat function is well localized in both time and frequency. CWT with the Mexican hat function is adopted for this study.

Figure 4. Contours of CWT coefficients with time at L3 and L9 at the height of 1.1 m above the floor.

Figure 4 shows the CWT coefficients, which are represented by the colour. In this study, we found that the distributions of CWT coefficients in the occupied zone under pulsating air supply were similar for different cases. Case B was thus selected to be compared with Case A. For both cases at small scales, the arrangement of dark and light shades looked intense, indicating the small-scale eddies in the turbulent flow were in the high frequency areas. The shade arrangements of airflows at small scales under Cases A and B were similar. With increasing the scales, the shade bands changed more and more slowly. At large scales, the shade arrangements under Case B were relaxed and harmonized. But, under Case A, it was still intense. This is because when the pulsating air was supplied, more of the
surrounding air was entrained, causing more low frequency areas in the airflows. The thermal comfort of occupants is affected by the airflows with low frequency [10]. The CWT features of pulsating airflows were more similar to these of natural winds [6, 10]. Thus, occupants may feel more comfortable under pulsating air supply than under steady air supply.

4. Conclusions

The differences on dynamic characteristics of airflows created by steady and pulsating air supply were studied under stratum ventilation. From statistical analysis, the air velocity distributions under steady air supply were closer to normal distribution than pulsating air supply. Based on one-dimensional CWT analysis, the airflows produced by the two supplies have differentiated distributions of CWT coefficients with time and scale. The dynamic characteristics of airflows created by pulsating airflows were closer to these of natural winds. As natural winds were preferred by the occupants in neutral-to-warm environments, pulsating air supply may provide better thermal comfort than steady air supply.

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