Experimental study on the robustness of ventilation systems in the control of walking-induced disturbances under different walking modes and temperatures

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Abstract. Ventilation system’s effectiveness can be affected by walking-induced disturbances. A series of experiments were performed in a chamber in this study (6.0 m × 5.9 m × 2.5 m) to measure the walking-induced temperature/flow/pollution field fluctuation characteristics. A method for quantifying the robustness of a ventilation system in the control of walking-induced fluctuations was used in this study. The experimental results showed that the cumulative particle exposure levels under walking modes W1, W2 and W3 were 2.04 ± 0.27, 1.72 ± 0.26 and 0.87 ± 0.12 times the exposure levels without human walking. The four ventilation systems all performed well in indoor temperature disturbance control; however, different walking modes and ventilation systems would result in different walking-induced disturbances of the flow and pollutant fields. For the flow field, the highest range scale robustness value was achieved by the side supply and side return (SS) system. For the pollutant field, the range scale robustness value of the SS system was still the highest, 18.7% larger than the lowest value. With the increase in temperature from 18 °C to 28 °C, the range and time scale robustness of the different ventilation systems decreased by 7.7–18.4% and 1.3–15.7%, respectively.
1 Introduction

Outbreaks of the coronavirus disease (COVID-19) and other highly infectious diseases have brought challenges to the world economy and human health [1]. Most of the epidemiological evidence has indicated that viruses spread in indoor environments in the form of aerosols [2] and cause great harm to the health of people who have been indoors for a long time [3]. Recent studies have suggested that human walking could cause resuspension and diffusion of indoor aerosol particles [4] and could carry aerosol particles, thus increasing the risk of cross-infection [5]. The wake flow generated by human walking has a significant effect on the indoor flow field distribution and particle transmission [5].

Computational fluid dynamics (CFD) is currently the most commonly used tool for studying human walking disturbances. For example, Hang et al. [6] and Liu et al. [5] used the dynamic mesh technique to simulate the influence of medical staff on patients in hospital wards and operating theatres. They found that when the walking motion started, there was a noticeable wake that affected the airflow organization behind the walking individual and could increase the concentrations of bacteria-carrying particles. The dynamic mesh technique was also used by Eslami et al. [7] and Mahaki et al. [8] to simulate human walking. Cao et al. [9] proposed a momentum source method to investigate human walking-induced disturbances. However, CFD simulation has certain limitations, and it can only be used for simple back-and-forth movements at the current stage [5]. Experimental research on the interference caused by walking has been relatively limited in the literature [5]. In addition, the influence of human walking on indoor air mixing has long been overlooked, and walking has been found to affect particle exposure [10].

Ventilation systems have been widely used to control indoor particle exposure [1]. However, the control effect of ventilation systems on walking-induced disturbances has seldom been investigated. In fact, a variation in walking mode (speed, route, etc.) would have an impact on the effectiveness of a ventilation system [11]. Systematic experimental studies as well as quantitative methods for comparing the effectiveness of various ventilation systems in the control of walking-induced disturbances are important, especially for ventilation systems used in specific settings: cleanrooms [11], operating rooms [5], isolation rooms [6], etc. According to recent studies, the particle-removal efficiency of a ventilation system is affected by the indoor temperature [12]. However, the influence of indoor temperature on walking-induced disturbances needs to be further investigated.

To address the research gaps described above and provide further information about the effects of different ventilation systems on controlling walking-induced fluctuations, a series of experiments were conducted in a full-scale chamber in this study: four ventilation systems, three temperature levels, and three walking modes were taken into account. A method to quantitative analysis the control effect of ventilation system on fluctuations [13], was used in this study.

2 Methods

2.1 Experimental setup

Fig.1. Diagram of the experimental chamber. Four different ventilation systems were studied: CS (yellow inlets/outlets in Fig.1a), CC (blue inlets/outlets in Fig.1a), SC (Contrary to CS, yellow inlets/outlets in Fig.1a), and SS (green inlets/outlets in Fig.1a). Three walking modes were studied: W1 (Fig.1b), W2 (Fig.1c) and W3 (Fig.1d).

Experiments were conducted in a full-scale chamber (6.0 m × 5.9 m × 2.5 m) to measure the walking-induced temperature/flow/pollutant field fluctuation characteristics. Three beds were placed in the experimental chamber. NaCl particles, as a contaminant source under a flow rate of 6.5 L/min, were generated through the mouth of the left-hand dummy. The other two dummies acted as receivers. To simplify the experimental conditions, none of the dummies were heated, and no breathing pattern was simulated for the generator of the dummies. Four ventilation systems were evaluated: ceiling supply and side return (CS), ceiling supply and ceiling return (CC), side supply and ceiling return (SC), and side supply and side return (SS). The supply air volume was maintained at 885 m³/h (air exchange rate of 10/h). The temperature in the chamber was well controlled [1]. Three different indoor temperature levels (18 °C, 23 °C and 28 °C) were evaluated in this study. Figure 1(a) show the arrangement of air diffusers under the four ventilation systems. There were two rows of air inlets/outlets on the two opposing side walls: one row located 0.7 m above the ground, and the other row located 1.1 m above the ground. The size of the diffusers on the side walls was 0.2 m × 0.2 m. There were six diffusers on the ceiling with a size of 0.5 m × 0.5 m. Before each experiment, the floor of the chamber was carefully cleaned at least twice to prevent walking-generated resuspension of particles from the floor.
Three movement routes, namely, W1, W2 and W3, were evaluated in this study, as shown in Figure 1(b), (c) and (d). A male volunteer (who is also the author of the paper) with a height of 1.75 m and weight of 60 kg started to walk in the chamber along pre-fixed routes. The volunteer wore protective apparel, a mask, examination gloves, glasses and a bracelet pedometer. The volunteer’s arm sway naturally when he was walking, and a pedometer was used to count the walking speed based on arm swing. Therefore, the volunteer kept a constant speed of approximately 60 steps/min according to the pedometer. As shown in Figure 1, the start and end positions of each walk remained consistent, both on the left side of the experimental chamber. For route W1, the volunteer turned back following the path shown in Figure 1(b) after passing by each bed. For W2, the volunteer turned back following the path after passing by each bed. For W3, the volunteer randomly walked around the back part of the chamber and randomly passed by each bed. For walking routes W1 and W2, the volunteer walked in the chamber three times, each lasting 5 minutes. The interval between walks was 10 minutes. For route W3, the volunteer walked in the chamber two times, each lasting 10 minutes. The interval between the two walks was 10 minutes. The pollutant field measurement was carried out for 70 minutes for each ventilation scenario, and the particles were released continuously. The ventilation system was turned on 15 minutes after the beginning of particle release. Measurement of the temperature and flow fields started 25 minutes after the particle release began.

2.2 Cumulative exposure level (CEL)

The cumulative exposure level (CEL) with or without human walking was calculated by Eq. 1 [1]:

\[ CEL = \int_0^T N_t \, dt \]  \hspace{1cm} (1)

where \( N_t \) (particles/cm\(^3\)) is the particle number concentration measured at a given measurement point over time. The CEL was obtained by integrating the exposure duration and particle concentration.

2.3 Robustness evaluate index of the ventilation system

A full description of the data processing method of robustness used in this work can be found in Ren et al. [13], and it is briefly summarized as follows.

First, the walking-induced fluctuations of temperature, flow and pollutant fields was denoising by Fourier transform filtering and wavelet noise reduction. Second, using Gaussian function to fit the filtered curve and extract the range and time scale eigenvalues of walking-induced. Finally, the liner dimensionless range scales robustness (RSr) and time scales robustness (TSr) evaluation index of ventilation system was constructed with eigenvalues. The robustness for the temperature field and flow field range scales can be calculated by Eq. 1, and that for the pollutant field range scale can be calculated by Eq. 2. The robustness of the field time scale was calculated by Eq. 3:

\[ D_{R1} = 1 - \left[ \frac{\sum_{i=1}^{n} \sum_{k=1}^{n} Avg_k(\gamma_{max})}{\sum_{k=1}^{n} \sum_{i=1}^{n} Avg_k(\gamma_{max})} \right] \]  \hspace{1cm} (2)

\[ D_{R2} = 1 - \left[ \frac{\sum_{i=1}^{n} \sum_{k=1}^{n} Avg_k(\gamma_{max})}{2} \right] \]  \hspace{1cm} (3)

\[ D_T = 1 - \left( \frac{\sum_{k=1}^{n} \sum_{i=1}^{n} Avg_k(S_i)}{\sum_{k=1}^{n} i} \right) \]  \hspace{1cm} (4)

The values of \( D_{R1}, D_{R2} \) and \( D_T \) range from 0-1. Where \( i, j, k=1, 2, 3, ..., n, k \) is the different ventilation systems (such as CS, CC, SC, SS) in this study, and \( i \) is number of walks (such as 1st walk, 2nd walk and 3rd walk). Particularly, \( P_j \) is the baseline of Gaussian fitting.

3 Results

3.1 Cumulative exposure level

Figure 2 shows the change in the average cumulative exposure in the breathing zones (at a height of 0.7 m) of the middle and right-hand dummy receivers with and without human walking. The cumulative particle exposure levels under modes W1, W2 and W3 were 2.04 ± 0.27, 1.72 ± 0.26 and 0.87 ± 0.12 times the level without human walking, respectively.

It was not surprising to find that walking modes W1 and W2 increased the cumulative particle exposure. Liu et al. [5] used CFD to simulate human walking that was similar to the W1 and W2 modes. Walking along a patient’s bed would bring an increase in the concentration of local particles, and the ventilation system could not filter local particles in a timely manner, resulting in an increased infection risk. In the present study, the experimental results indicated that walking mode W3 could promote the removal of particles by the ventilation system. This may have been caused by the fact that the W3 mode fully mixed the indoor pollutant field. A uniform pollutant field would be more beneficial for filtration with a centralized ventilation system [14].

Another important factor in cumulative exposure was the temperature level. When the temperature increased by 5 °C, the cumulative exposure increased by 7.4–54.0%, as shown in Table 1. Therefore, the walking mode and temperature were important factors in the
robustness of the ventilation systems and required further analysis.

**Table 1. Summary of cumulative exposure levels under different temperature levels.**

| Temperature (°C) | CS | CC | SC | SS |
|------------------|----|----|----|----|
| 18°C             | 2.39E+0 | 6.05E+0 | 4.77E+0 | 2.57E+0 |
| 23°C             | 3.68E+0 | 7.62E+0 | 6.23E+0 | 2.76E+0 |
| 28°C             | 4.02E+0 | 7.70E+0 | 7.09E+0 | 3.05E+0 |

**3.2 Robustness of ventilation systems**

Fig. 3. Fluctuations of the temperature(a-c), flow(d-f) and pollutant field(h-j) caused by different walking modes: W1, W2 and W3.

The range scale and time scale robustness of the temperature field, flow field and pollutant field under different ventilation systems were calculated; they are summarized in Table 2. For the temperature field, the range and time scale robustness values for the SS system were the highest among the four ventilation systems. This may have been caused by the fact that the supply air outlets of the SS system were located in the center of the experimental chamber in the vertical direction. The indoor airflow passed evenly throughout the entire experimental chamber. Therefore, the temperature gradient of the indoor air was slightly smaller than the gradient under the other ventilation systems, and the robustness value was highest. However, as discussed previously, the differences were relatively small.

For the flow field, when the ventilation system was not operating, the disturbances caused by different walking modes were larger than those when the system was operating, as depicted in Figure 3(d-f). Furthermore, as shown in Table 1, the use of the four ventilation systems increased the range scale robustness values by 4.0–18.2% compared with the values when the ventilation system was off. The highest range scale robustness value was achieved by the SS system, and it was 14.7% larger than the lowest value. In comparison, the largest difference in the time scale robustness was only 7% among the four ventilation systems. The SS system also exhibited the best performance in time scale disturbance control.

For the pollutant field, particle concentrations under different ventilation systems were much lower than those observed in the absence of ventilation. The use of the four systems increased the range scale and time scale robustness by 23.0–44.0% and 11.5–23.3% compared with the values when the ventilation system was off. The highest range scale robustness value was still achieved by the SS system, and it was 18.7% higher than the lowest value. For the time scale, it was found that the robustness value of the SS (0.83) was the second highest, and that of the CS (0.86) was the highest. At the same time, the range scale robustness of the CS (0.90) was similar to that of the SS (0.91). Therefore, the CS and SS systems were the most robust. Moreover, a robust ventilation system has generally good control effects on different walking modes, as shown in Table 1. For public places that require high degrees of cleanliness and thermal comfort and in which human movement is very complicated, such as small-scale walking (W1), large-scale walking (W2) and irregular large-scale and long-term walking (W3), the SS ventilation system can be considered.

It is interesting that the SS system exhibited the highest robustness values for the temperature field, flow field and pollutant field. This finding indicates that the SS system can effectively control the disturbances created by people walking indoors while maintaining good indoor environment quality. Furthermore, the finding agrees with results reported by Kong et al. [1] and Tian et al. [15]. Sidewall supply can provide satisfactory thermal comfort [15] and improve the energy utilization coefficient and contaminant removal efficiency [1].
3.3 Influence of temperature level on robustness of ventilation system

As shown in Figure 4, the robustness of the ventilation systems was related to the temperature level. Table 3 summarizes the average range scale and time scale robustness values under the four ventilation systems. Under the four ventilation systems, as the temperature increased, the range scale and time scale robustness decreased by 7.7–18.4% and 1.3–15.7%, respectively. Different ventilation systems were the most robust at 18 °C. For the range scale robustness, when the temperature was maintained at 18 °C, the highest robustness values were achieved by the SS system (0.90) and SS system (0.91), and the cumulative exposure levels increased gradually. For the time scale robustness, as the temperature increased, the fluctuations of the pollutant field caused by human walking would take longer to reconstruct [13]. The highest time scale robustness values were also achieved by the CS and SS system. In addition, the time scale robustness of the CS system was slightly higher than that of the SS system. However, in most cases, the range scale robustness was first and foremost, and the time scale robustness was secondary. Therefore, the SS system was the most robust at the three temperature levels.

Table 3. Summary of the average range scale and time scale robustness values under different ventilation systems (18 °C, 23 °C and 28 °C).

| Field type | Ventilation system | Temperature | Total | $D_r$ | $D_t$ |
|------------|--------------------|-------------|-------|-------|-------|
| Pollutant field | CS | 18°C | 0.90 | 0.86 |
| SS | 0.91 | 0.83 |
| CS | 0.78 | 0.80 |
| CC | 0.67 | 0.77 |
| SC | 0.71 | 0.70 |
| CC | 0.84 | 0.74 |
| SS | 0.84 | 0.72 |
| SC | 0.84 | 0.75 |

4. Conclusions

(1) In this study, an experimental database of indoor temperature, flow and pollutant field fluctuations under different human walking modes and ventilation systems was established. In addition, a new data analysis method was developed to analyze the robustness of four different ventilation systems in disturbance control.

(2) The cumulative particle exposure levels under walking modes W1, W2 and W3 were 2.04 ± 0.27, 1.72 ± 0.26 and 0.87 ± 0.12 times the levels without human walking, respectively. As the temperature rose, the cumulative exposure increased gradually.

(3) All four ventilation systems performed well in indoor temperature control. In contrast, different walking modes and ventilation systems would result in different walking-induced disturbances of the flow and pollutant fields. The walking range and walking frequency were very important factors in these disturbances.

(4) For the flow field, the use of the four ventilation systems increased the range scale robustness value by 4.0–18.2% compared with the values when the ventilation system was off. The highest range scale robustness value was achieved by the SS system, and it was 14.7% higher than the lowest value. For the pollutant field, the use of ventilation systems increased the range scale and time scale robustness by 23.0–44.0%
and 11.5–23.3%, respectively. The range scale robustness value of the SS system was still the highest, at 18.7% higher than the lowest value. With an increase in temperature from 18 °C to 28 °C, the range and time scale robustness of the four ventilation systems decreased by 7.7–18.4% and 1.3–15.7%.

In summary, the air flow organization and temperature was significant to the ventilation system’s effectiveness. In fact, the ventilation system was particularly important for the control of walking-induced disturbances in specific places that require a highly stable indoor environment (cleanrooms, operation rooms, isolation rooms, etc.). Therefore, quantifying the control effect of the ventilation system could provide a reference for the above scenarios.

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