Effect of Walking Modes and Temperatures on the Robustness of Ventilation Systems in the Control of Walking-induced Disturbances

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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 considering the following parameter variations: four types of ventilation systems (i.e., ceiling supply and side return, ceiling supply and ceiling return, side supply and ceiling return, side supply and side return), three temperature levels (18°C, 23°C, 28°C), and three walking modes (W1, W2, W3). The test 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 can maintain a high stability of the indoor temperature field; however, different walking modes and ventilation systems would result in different walking-induced disturbances of the pollutant and flow fields. For the flow field, the range scale robustness (RSr) value with ventilation system was 4.0%–18.2% higher than that without ventilation system. The highest RSr value was achieved by the side supply and side return (SS) system. For the pollutant field, the RSr and time scale robustness (TSr) can be increased by 23.0%–44.0% and 11.5%–23.3% due to the ventilation systems, respectively. The RSr value of the SS system was still the largest, 18.7% larger than the smallest value. With the increase in temperature from 18°C to 28°C, the RSr and TSr of the different ventilation systems decreased by 7.7%–18.4% and 1.3%–15.7%, respectively. A ventilation system with high particle-removal efficiency may not be effective in controlling indoor disturbances. The database and method developed in this study could be beneficial for the control of human walking-induced disturbances in those settings that require a highly controlled indoor environment.

Keywords: Denoising, Gaussian fitting, Robustness, Ventilation system, Particle control

1 INTRODUCTION

Creating a good indoor environment is particularly important for human health (Zhang et al., 2020). At present, ventilation systems have been widely used to control indoor particle exposure (Zhou et al., 2021a; Ratajczak et al., 2022). However, outbreaks of the coronavirus disease (COVID-19) show that indoor environment control still face many new challenges (Li et al., 2021).

Most of the epidemiological evidence have indicated that viruses spread in indoor environment in the form of aerosols (Li et al., 2022; Pochtovyi et al., 2021), and cause great harm to the health of people who have been indoors for a long time (Riediker and Monn, 2021). Recent studies have shown that human walking could not only cause resuspension and diffusion of indoor aerosol particles (Wang et al., 2021), but could also carry aerosol particles, thus influence the effectiveness of ventilation systems (Ding et al., 2022).

The original indoor sources generated by human activity play a significant role in the effect of indoor environment control (Al Assaad et al., 2019). Some studies suggest ventilation systems
should be controlled basing on indoor occupancy (Rahman and Han, 2021). Rahman and Han (2021) applied the demand ventilation to control ventilation rates in office rooms. However, once the human activity intensified, the ventilation system at this time was still unable to meet the demand. For instance, Salma et al. (2013) monitored PM$_{10}$ and CO$_2$ in university classrooms for 7 days. Even with the heating ventilation and air condition system (HVAC), the concentration of particulate matter in the classrooms still exceeded the standard due to students’ walking. This result agrees with the study reported by Ren et al. (2020), who conducted two years’ particles concentration assessments in 39 classrooms at seven high schools in the central Texas. Even though the classrooms were equipped with mechanical ventilation systems, particles concentration caused by student walking still exceed limits. Therefore, above studies potentially confirmed that human walking would have an impact on the effectiveness of a ventilation system (Liu et al., 2020).

In order to further confirm this point, visualization of wake flow generated by walking-induced using computational fluid dynamics (CFD) was used to evaluate ventilation system’s performance (Hang et al., 2014). Al Assaad et al. (2019) used dynamic mesh technology to investigate the performance of personalized ventilation (PV) system on the control of the disturbance of resident walking. Their results showed that resident walking significant affected PV system’s efficiency. Hang et al. (2014) employed the dynamic mesh technology to evaluate the ability of a ventilation system to control disturbances created by human walking with either ceiling-level or floor-level exhausts. Their results showed that the ceiling-level exhausts controlled airborne transmission better than the floor-level exhausts. However, CFD simulation has certain limitations, for example, it can only be used to simulate simple back-and-forth movements at the current stage (Wu and Gao, 2014; Tao et al., 2018; Liu et al., 2020). In addition, the influence of human walking on indoor air mixing has always been overlooked (Al Assaad et al., 2019).

It is relatively difficult to obtain high-quality data from experimental studies of walking-induced disturbances (Hang et al., 2014). Therefore, experimental research on the interference caused by walking has been relatively limited in the literature (Liu et al., 2020). Lv et al. (2019) evaluated a ceiling exhaust and a slit exhaust when human walking was considered, their results indicated that the control effect of the ceiling exhaust was better than the slit exhaust. Wu and Lin (2015) conducted a series of tests to research the performance of stratum, displacement and mixing ventilation on controlling the disturbance caused by moving manikins. The results show that stratum ventilation has application potential under the condition of frequent walking. Systematic experimental studies as well as quantitative methods are important, especially for ventilation systems used in specific settings: cleanrooms (Ren et al., 2020), operating rooms (Liu et al., 2020), isolation rooms (Hang et al., 2014), etc. According to recent studies, the particle-removal efficiency of a ventilation system was affected by the indoor temperature (Xue et al., 2020). However, the influence of indoor temperature on walking-induced disturbances needs to be further investigated.

To address the research gaps described, a series of experiments were conducted in a full-scale chamber: four ventilation systems, three temperature levels, and three walking modes were taken into account. A method (Ren et al., 2022) was employed to quantify the disturbance of human activities on indoor temperature/flow/pollutant fields. This method introduced robustness as an index to quantify the effect of ventilation systems on walking induction control. The higher the robustness value of the ventilation system, the better the control effect of walking-induced. It is possible to directly compare the performance between ventilation systems through the final calculation results. The cumulative particle exposure levels with and without human walking were also quantitatively measured and compared.

Based on the database obtained from the experiments and the above methods, this study aimed to (1) establish a database of indoor fluctuations under different human walking modes and ventilation systems; (2) use the denoising, fitting, feature-extraction method to extract the range scale eigenvalues (RSe) and time scale eigenvalues (TSe) of four different ventilation systems; (3) analyze the robustness of ventilation systems through the range and time scale eigenvalues, and discuss the relationship between particulate matter removal and disturbance control; and (4) investigate the effect of temperature on ventilation system robustness.
2 METHODS

2.1 Experimental Setup

The full-scale chamber (6.0 m × 5.9 m × 2.5 m) was used to measure the parameters including the walking-induced temperature, air flow and pollutant field fluctuations. To conduct the experiments, there were three beds placed in the chamber. According to the report by Papineni and Rosenthal (1997), the particle size distribution of human exhaled particulate matter was mainly below 1 µm (80%–90%). The size distribution of NaCl particle (range 0.1–10 µm, 95% of particle size was below 1 µm) was similar to the human exhaled particles. Therefore, it was chosen as the contamination source and generated from the mouth of the left-hand index dummy at a flow rate of 6.5 L min⁻¹ by a particle generator (Model 9302, TSI, Inc., St. Paul., MN). The particle concentration of the outlet was kept at 50,000 particles cm⁻³, and the baseline pollutant concentration was 290,000 ± 150,000 particles cm⁻³ (mean ± SD). The other two dummies were receivers to the index dummy. The background concentration of particulate matter in the chamber was kept at 30,000 particles cm⁻³ before each experiment. 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 tested for the assessments: 1) ceiling supply and side return (CS); 2) ceiling supply and ceiling return (CC); 3) side supply and ceiling return (SC); and 4) side supply and side return (SS). The supply air volume was consistent at 885 m³ h⁻¹ (i.e., air exchange rate of 10 h⁻¹). The temperature in the chamber was well controlled (Kong et al., 2021). Three different indoor temperature levels (18°C, 23°C, and 28°C) were evaluated in this study. Fig. 1(a) shows the arrangement of air diffusers under the four ventilation systems. The layouts of the air inlets/outlets were 2 row × 7 diffusers on the opposing side walls: one row was located 0.7 m above the ground, and the other row was located 1.1 m above the ground. Each diffuser on the side walls was 0.2 m × 0.2 m. The six diffusers on the ceiling were 0.5 m × 0.5 m each.

Three movement routes, namely, W1, W2 and W3, were evaluated in this study, as shown in Figs. 1(b), 1(c), and 1(d). A volunteer 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 while walking, and a pedometer was used to count the walking speed based on arm swing. Therefore, the volunteer walked at a constant speed of approximately 60 steps min⁻¹, which was measured by the pedometer. As shown in Fig. 1, the start and end positions of each walk remained consistent, and they were both on the left side of the chamber. For route W1, the volunteer turned back following the path shown in Fig. 1(b) after passing by the second bed from left to right. 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 every two walks was 10 minutes, as depicted in Fig. 2. For route W3, the volunteer walked in the chamber two times, each lasting 10 minutes. The impacts of each ventilation system on the particle concentrations were investigated for 70 minutes during the pollutant field measurements. The particles were generated continuously. Each ventilation system was initially turned on for 15 minutes once the particles were started to being released. After 25 minutes since the particles were generated, the temperature and flow fields were measured.

2.2 Measuring Instruments and Locations

To monitor the walking-induced fluctuations, the T-type thermocouples (Model 34972A, Aglient, Santa Clara, CA), nine hot-wire anemometers (Model 440, Testo Inc., Lenzkirch, Germany), and two particle counters (Aerotrak 9306-V2, TSI, Inc., St. Paul., MN) were used to determine the temperature/flow/pollutant fields in the walking route, respectively. T-type thermocouples were evenly distributed in the experimental chamber. Three hot-wire anemometers were placed on each bed, located the breathing area of the dummy, the left side of the bed and the back of the bed, respectively. Particle counters were only placed in the middle and right-hand dummies breathing zones, because this study aimed to evaluate the particle exposures in the breathing
Fig. 1. Diagram of the experimental chamber. Four different ventilation systems were studied: CS (yellow inlets/outlets in (a), CC (blue inlets/outlets in (a)), SC (Contrary to CS, yellow inlets/outlets in (a)), and SS (green inlets/outlets in (a)). Three walking modes were studied: (b) W1, (c) W2, and (d) W3.

zone of the dummies. A schematic diagram of the location of the experimental equipment and more information of these instruments is shown in Fig. 3 (Ren et al., 2022). The report data of temperature/flow/pollutant fields were the average values of the same kinds of instruments. All instruments were pre-calibrated before each experiment, and the same kinds of instruments were compared with each other to maintain the consistency of the experimental results.

2.3 Cumulative Exposure Level (CEL)

The cumulative exposure level (CEL) with or without human walking was calculated by Eq. (1) (Kong et al., 2021):
Fig. 2. The timeline of three walking modes.

\[ \text{CEL} = \int_{t_0}^{t} N_t \, dt \]  

(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.

**2.4 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. (2022), and it is briefly summarized as follows.
First, the walking-induced fluctuations of temperature, flow and pollutant fields were 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 linear 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. (2), and that for the pollutant field range scale can be calculated by Eq. (3). The robustness of the field time scale was calculated by Eq. (4):

\[
D_{R,1} = 1 - \frac{\sum_{k=1}^{n} \text{Avg}_k (y_{\text{max},i})}{\sum_{k=1}^{n} \text{Avg}_k (y_{\text{max},i})} 
\]

\[
D_{R,2} = 1 - \left[ \frac{\sum_{k=1}^{n} \text{Avg}_k (y_{\text{max},i})}{2} + \frac{\sum_{k=1}^{n} \text{Avg}_k (P_i)}{2} \right] 
\]

\[
D_T = 1 - \frac{\sum_{k=1}^{n} \text{Avg}_k (S_i)}{\sum_{k=1}^{n} \text{Avg}_k (S_i)} 
\]

The values of \(D_{R,1}, D_{R,2}\) 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.

For the flow field filtering and wavelet denoising, it was suitable for the periodic signal, and aperiodic signal, respectively. Therefore, the approximately periodic temperature and flow fields were processed using flow field filtering, while the aperiodic pollutant fields were processed using wavelet noise reduction. Besides, the denoising process (including choice of cut-off frequency and wavelet function selection) can be found in Ren et al. (2022).

3 RESULTS

3.1 Cumulative Exposure Level

Fig. 4 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. (2020) 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 (Hsu and Hsiau, 2015).

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.
3.2 Disturbance of Temperature Field Caused by Human Walking

The fluctuations of the temperature field (at a height of 1.2 m) caused by different human walking modes are depicted in Fig. 5. In general, the temperature field disturbance caused by the different walking modes was small. Table 2 summarizes the RSe and TSe of the temperature field. For the different walking modes, the RSe and TSe were 0.07–0.36°C and 3.9–11.4 min, respectively. Thus, the different ventilation systems can maintain a high stability of the indoor temperature field. This finding agrees with that of a study by Wu and Lin (2015). They reported that the influence of occupant movements on the temperature profile was relatively small under three different ventilation systems. Meanwhile, Feng et al. (2021) investigated the temperature stratification of indoor air under different ventilation systems. They found that stratification could occur in the indoor environment and could be disrupted or weakened by certain dynamic factors, such as the movement of the human body (Feng et al., 2021). The change in temperature was caused mainly by the temperature gradient of the indoor air (Zhang and Yao, 2022). In the present study, the vertical and horizontal temperature gradients were negligible according to the experimental results.

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

| Temperature | CS  | CC  | SC  | SS  |
|-------------|-----|-----|-----|-----|
| Cumulative exposure level (particles cm⁻³) | 18°C | 2.39E+06 | 6.05E+06 | 4.77E+06 | 2.57E+06 |
| 23°C        | 3.68E+06 | 7.62E+06 | 6.23E+06 | 2.76E+06 |
| 28°C        | 4.02E+06 | 7.70E+06 | 7.09E+06 | 3.05E+06 |

Fig. 5. Fluctuations of the temperature field (at a height of 1.2 m) caused by three walking modes: (a) W1, (b) W2, and (c) W3.
Table 2. Summary of the RSe and TSe of the temperature field under different ventilation systems.

| Ventilation system | W1   |   | W2   |   | W3   |   |
|--------------------|------|---|------|---|------|---|
|                    | $\gamma_{\text{max},i}$ ($^\circ$C) | $S_i$ (min) | $\gamma_{\text{max},i}$ ($^\circ$C) | $S_i$ (min) | $\gamma_{\text{max},i}$ ($^\circ$C) | $S_i$ (min) |
| CS                 | 0.11 | 4.7 | 0.24 | 5.5 | 0.13 | 10.5 |
| CC                 | 0.18 | 7.5 | 0.22 | 6.5 | 0.36 | 7.7  |
| SC                 | 0.12 | 4.7 | 0.19 | 4.9 | 0.18 | 11.4 |
| SS                 | 0.10 | 3.9 | 0.07 | 4.3 | 0.14 | 9.1  |

3.3 Disturbance of Flow Field Caused by Human Walking

As shown in Fig. 6, the disturbance of the flow field (at a height of 1.2 m) caused by human walking was relatively significant. Table 3 summarizes the RSe and TSe of the flow field under different walking modes. The RSe and TSe caused by human walking were 0.01–0.05 m s$^{-1}$ and 2.8–9.5 min, respectively. Previous CFD simulation results have clearly demonstrated that human walking produces a wake flow (Hang et al., 2014; Liu et al., 2020) behind the body and strongly affects the surrounding airflow (Mahaki et al., 2021), resulting in the resuspension and diffusion of indoor particles (Wang et al., 2021). For example, Tao et al. (2018) used the dynamic meshing model to study the influence of walking on the surrounding airflow organization. According to their findings, the movement of people had a significant influence on the flow field, and this point of view has been confirmed by the experimental results in the present study.

For mode W1, the RSe and TSe were 0.01–0.04 m s$^{-1}$ and 2.8–5.1 min, respectively. On the basis of W1, the volunteers’ walking route was extended in the experiment chamber, denoted as W2 mode. The RSe and TSe were 0.02–0.05 m s$^{-1}$ and 3.3–4.6 min, respectively. Meanwhile, mode W3 had an indeterminate route, a larger range and a longer duration. Its RSe and TSe were 0.03–0.04 m s$^{-1}$ and 6.6–9.1 min, respectively. The results indicate that walking for a longer time did not increase the RSe and TSe. Furthermore, the walking range of W2 was greater than that of W1, but its RSe and TSe were similar. This may have been due to the fact that for the same sampling point, the walking frequency of W1 was higher than that of W2. It can be deduced that the walking range and frequency were very important factors in the disturbance of the flow field. For the time scale eigenvalues, due to control by the ventilation system, the impact time was shorter than the actual duration of the walking.

Table 3. Summary of the RSe and TSe of the flow field under different ventilation systems.

| Ventilation system | W1   |   | W2   |   | W3   |   |
|--------------------|------|---|------|---|------|---|
|                    | $\gamma_{\text{max},i}$ (m s$^{-1}$) | $S_i$ (min) | $\gamma_{\text{max},i}$ (m s$^{-1}$) | $S_i$ (min) | $\gamma_{\text{max},i}$ (m s$^{-1}$) | $S_i$ (min) |
| CS                 | 0.03 | 4.8 | 0.04 | 4.0 | 0.04 | 9.1 |
| CC                 | 0.04 | 5.1 | 0.05 | 4.6 | 0.03 | 9.5 |
| SC                 | 0.03 | 4.7 | 0.02 | 4.2 | 0.03 | 6.6 |
| SS                 | 0.01 | 2.8 | 0.02 | 3.3 | 0.03 | 8.4 |

Fig. 6. Flow field fluctuations (at a height of 1.2 m) caused by different walking modes: (a) W1, (b) W2, and (c) W3.
3.4 Disturbance of Pollutant Field Caused by Human Walking

For the pollutant field, this study focused on changes in particle concentration near the dummies’ breathing zones caused by human walking. As shown in Fig. 7, the efficiency of particle removal and the influence of human walking were different under different ventilation systems. Table 4 summarizes the RSe and TSe of the pollutant field under different walking-induced modes. For different walking modes, the RSe and TSe caused by human walking were $1.40 \times 10^4$–$1.07 \times 10^5$ particles cm$^{-3}$ and 4.3–11.6 min, respectively. In fact, this finding agrees with those of previous studies. For instance, Zhou et al. (2021b) investigated the PM$_{2.5}$ concentrations in classrooms. When students were class off, the particle concentrations were higher than the limits set by the U.S. EPA. In addition, Zhang and Yao (2022) used a robot to simulate human walking. The peak particle concentrations increased significantly with robot-walking.

For the W1, W2 and W3 walking modes, the RSe and TSe were $1.84 \times 10^4$–$9.12 \times 10^4$ particles cm$^{-3}$ and 4.3–6.7 min, $1.40 \times 10^4$–$1.07 \times 10^5$ particles cm$^{-3}$ and 4.4–4.8 min, $1.85 \times 10^4$–$7.52 \times 10^5$ particles cm$^{-3}$ and 4.5–11.6 min, respectively. These results again indicate that walking for a longer time did not increase RSe, and that the walking range and walking frequency were also very important factors in the disturbance of the pollutant field. Human walking can not only cause resuspension and diffusion of particulate matter (Ren et al., 2022), but can also carry pollutants, resulting in an increase in the concentration of local particulate matter (Liu et al., 2020). Therefore, the RSe generated by routes W1 and W2, which frequently passed through the pollution source of the left-hand dummy, were higher than for W3.

The RSe of the SC and SS system were similar, and they were the smallest among the four systems. The reason was that the effect of human walking on pollutant field was reduced under the control of the CS and SS systems. In terms of the time scale eigenvalues, with the exception of the CC, the ventilation systems performed well. Similar to the flow field, when the human walking stopped, the pollutant field returned to its original state quickly.

3.5 Robustness of Ventilation Systems

Next, the RSr and T Sr of the temperature field, flow field and pollutant field under different ventilation systems were calculated; they are provided in Table 5. For the temperature field, the RSr and T Sr 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

![Fig. 7. Fluctuations of the pollutant field (at a height of 0.7 m) caused by different walking modes: (a) W1, (b) W2, and (c) W3.](image)

| Table 4. Summary of the RSe and TSe of the pollutant field under different ventilation systems. |
|-----------------------------------------------|
| **Ventilation system** | **W1** | | **W2** | | **W3** | |
| | $y_{max,i}$ (particles cm$^{-3}$) | $S_i$(min) | $y_{max,i}$ (particles cm$^{-3}$) | $S_i$(min) | $y_{max,i}$ (particles cm$^{-3}$) | $S_i$(min) |
| CS | 3.32E+04 | 4.3 | 5.55E+04 | 4.5 | 2.38E+04 | 4.5 |
| CC | 9.12E+04 | 6.7 | 1.07E+05 | 4.8 | 7.52E+04 | 11.6 |
| SC | 1.84E+04 | 6.3 | 1.40E+04 | 4.6 | 1.85E+04 | 5.7 |
| SS | 2.62E+04 | 4.6 | 2.18E+04 | 4.4 | 2.14E+04 | 7.9 |
Table 5. Summary of the R Sr and T Sr of the temperature field, flow field and pollutant field under different ventilation systems.

| Field type   | Ventilation system | W1  | W2  | W3  | Total |
|--------------|--------------------|-----|-----|-----|-------|
|              | DR     | DT     | DR     | DT     | DR     | DT |
| Temperature field | CS     | 0.77 | 0.78 | 0.67 | 0.74 | 0.84 | 0.73 | 0.76 | 0.75 |
|              | CC     | 0.65 | 0.64 | 0.69 | 0.69 | 0.56 | 0.80 | 0.63 | 0.71 |
|              | SC     | 0.76 | 0.77 | 0.74 | 0.77 | 0.78 | 0.71 | 0.76 | 0.75 |
|              | SS     | 0.80 | 0.81 | 0.90 | 0.80 | 0.83 | 0.76 | 0.84 | 0.79 |
| Flow field   | CS     | 0.77 | 0.78 | 0.82 | 0.81 | 0.78 | 0.79 | 0.79 | 0.79 |
|              | CC     | 0.71 | 0.77 | 0.76 | 0.78 | 0.79 | 0.78 | 0.75 | 0.78 |
|              | SC     | 0.83 | 0.79 | 0.89 | 0.8  | 0.84 | 0.85 | 0.85 | 0.81 |
|              | SS     | 0.91 | 0.87 | 0.92 | 0.84 | 0.82 | 0.8  | 0.88 | 0.84 |
| Pollutant field | Off    | 0.77 | 0.78 | 0.62 | 0.78 | 0.77 | 0.78 | 0.72 | 0.78 |
|              | CS     | 0.91 | 0.86 | 0.87 | 0.83 | 0.91 | 0.90 | 0.90 | 0.86 |
|              | CC     | 0.75 | 0.78 | 0.74 | 0.82 | 0.74 | 0.73 | 0.74 | 0.78 |
|              | SC     | 0.87 | 0.79 | 0.86 | 0.83 | 0.87 | 0.87 | 0.87 | 0.83 |
|              | SS     | 0.90 | 0.85 | 0.92 | 0.84 | 0.91 | 0.82 | 0.91 | 0.83 |
|              | Off    | 0.57 | 0.71 | 0.58 | 0.69 | 0.56 | 0.69 | 0.57 | 0.69 |

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 off, the disturbances caused by different walking modes were greater than those that were during operation of the system, as shown in Fig. 6. Furthermore, as shown in Table 3, the range scale robustness (R Sr) value with four ventilation system was 4.0%–18.2% higher than that without ventilation system. Among them, the SS system was much higher than that with system control. The use of the four systems increased the R Sr difference in the T Sr 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, particulate matter concentration without ventilation system control was much higher than that with system control. The use of the four systems increased the R Sr and T Sr by 23.0%–44.0% and 11.5%–23.3%. The R Sr value for the SS system was the highest, which 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 CC (0.86) was the highest. At the same time, the R Sr of the SS (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 4. 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. (2021) and Tian et al. (2021). Sidewall supply can provide satisfactory thermal comfort (Tian et al., 2021) and improve the energy utilization coefficient and contaminant removal efficiency (Kong et al., 2021). Meanwhile, the CS system was sufficiently robust in controlling pollutant disturbances, but the robustness values of the temperature field and flow field were lower. This issue will be discussed later.

3.6 Influence of Temperature Level on Robustness of Ventilation System

As shown in Fig. 8, ventilation systems’ robustness was related to the temperature level. Table 6 summarizes the average R Sr and T Sr values. Under the four ventilation systems, as the temperature increased, the R Sr and T Sr decreased by 7.7%–18.4% and 1.3%–15.7%, respectively. The different ventilation systems were the most robust at 18°C. For the R Sr, when the temperature was maintained at 18°C, the highest robustness values were achieved by the CS system (0.90) and SS
Fig. 8. Fluctuations of pollutant field with temperature levels of (a–c) 18°C, (d–f) 23°C and (h–j) 28°C under different ventilation systems and walking modes.

Table 6. Summary of the average RSr and TSr values under different ventilation systems (18°C, 23°C, and 28°C).

| Field type       | Ventilation system | Temperature | $D_{R}$ | $D_{T}$ |
|------------------|--------------------|-------------|---------|---------|
| Pollutant field  | CS                 | 18°C        | 0.90    | 0.86    |
|                  | CC                 |             | 0.74    | 0.78    |
|                  | SC                 |             | 0.87    | 0.83    |
|                  | SS                 |             | 0.91    | 0.83    |
|                  | CS                 | 23°C        | 0.78    | 0.80    |
|                  | CC                 |             | 0.67    | 0.77    |
|                  | SC                 |             | 0.71    | 0.70    |
|                  | SS                 |             | 0.84    | 0.74    |
|                  | CS                 | 28°C        | 0.80    | 0.77    |
|                  | CC                 |             | 0.63    | 0.76    |
|                  | SC                 |             | 0.73    | 0.72    |
|                  | SS                 |             | 0.84    | 0.75    |
system (0.91), and the cumulative exposure levels were \(2.39 \times 10^6\) particles cm\(^{-3}\) and \(2.57 \times 10^6\) particles cm\(^{-3}\), respectively, as shown in Table 1. However, when the temperature was at 23°C and 28°C, the robustness values of the SS system (0.84 and 0.84, respectively) were higher than those of the CS system (0.78 and 0.80, respectively). In addition, the cumulative exposure level of the SS system was lower than that of the CS system, with reductions of 25% and 24%, respectively, at the two temperature levels. For the Ts, as the temperature increased, the fluctuations of the pollutant field caused by human walking would take longer to reconstruct (Ren et al., 2022). The highest Ts values were also achieved by the CS and SS system. In addition, the Ts value of the CS system was slightly higher than that of the SS system. However, in most cases, the Rs was first and foremost, and the Ts was secondary. Therefore, the SS system was the most robust at the three temperature levels.

3.7 Disturbance of Particles of Different Sizes as a Result of Human Walking

Next, the control effect of the SS ventilation system on particles of different sizes was evaluated. There was a significant disturbance difference between 0.3–1 \(\mu\)m and 3–10 \(\mu\)m particles. For smaller particles (0.3 \(\mu\)m, 0.5 \(\mu\)m and 1 \(\mu\)m), human walking mainly disturbed the particles suspended in the indoor air, as depicted in Figs. 9(a–c). In contrast, the fluctuation of coarse particles (3 \(\mu\)m, 5 \(\mu\)m and 10 \(\mu\)m) was mainly caused by the particle resuspension, as depicted in Figs. 9(d–f). This is because the sedimentation rate of coarse particles is higher than that of ultra-fine particles (Abdel-Salam, 2021). Therefore, for some virus-carrying aerosols with larger particle sizes, cleaning of the floor would be particularly important.

4 DISCUSSION

4.1 Relationship between Particle Removal and Disturbance Control

Both the range scale and the time scale exhibited similar robustness under the four ventilation systems, as depicted in Fig. 10. Many studies emphasized the importance of the flow field (Tao et al., 2017, 2018; Liu et al., 2020). The movement of people would cause serious disturbances to the surrounding airflow, which would affect the diffusion of particulate matter (Cao et al., 2017; Tao et al., 2021). Therefore, the high robustness value of the flow field could be reduced.

Fig. 9. Fluctuations of particles of different sizes as a result of human walking (mode W1) with the SS system and no ventilation.
Fig. 10. Average (a) RSr and (b) TSr values of the temperature field, flow field and pollutant field.

by the disturbances caused by human walking. This is consistent with the results of this study, as observed for the SC and SS systems.

Under the CS system, the robustness value of the flow field was lower than that under the SC system, but the robustness value of the pollutant field was higher. Although there would be obvious fluctuations of the pollutant field under the CS system, the particle-removal efficiency was higher than that under the SC system, as shown in Fig. 7. One possible reason was that the airflow organization varied among the four ventilation systems. The return air inlets of the CS system were located in the side walls of the experimental chamber, while those of the SC system were located in the ceiling. The side-wall return air inlets were more advantageous for particle removal. Lv et al. (2018) and Xue et al. (2020) took the walking behavior of occupants into account when evaluating the ceiling exhaust and slit exhaust systems. Their results also confirmed this point.

Many previous studies have used only the filtration efficiency of particles as the evaluation index for a ventilation system (Kong et al., 2021). However, a ventilation system with high particle-removal efficiency may not have a good control effect on indoor disturbances. Because the robustness calculation formula in the present study comprehensively considered the disturbances caused by people walking and the removal efficiency of particles, the CS system exhibited high pollution robustness but low flow field robustness. The robustness of the flow field and the air distribution of the ventilation system were very important factors in the disturbance caused by human walking and the removal of particles. For the temperature field, there was no clear evidence that it would affect the concentration of particulate matter within a very small temperature difference.

4.2 Reasons for the Influence of Temperature on Ventilation System Robustness

When a given ventilation system was operating, particles were gradually filtered under the influence of indoor airflow. Based on the experimental results, with the increasing of temperature from 18°C to 28°C, the robustness of the ventilation system decreased. Li et al. (2022) conducted a detailed study on the force of fine particles. Submicron aerosol particles were subjected to multiple complex forces, such as drag force, Brownian force and gravity. Especially for particles smaller than 0.1 μm, the Brownian motion was significant and should not be ignored (Wang et al., 2009). An increase in temperature would enhance the Brownian and thermophoretic forces on particles. The particles generated in this study were mainly smaller than 0.3 μm (Kong et al., 2021). Therefore, the Brownian force became the key factor in the removal of particles. Brownian motion could cause particles to move in a more disorderly manner and thus deviate from the
original airflow (Xiao et al., 2018). The control effect of the ventilation system was decreased. However, when there was no human walking in the chamber, the RSr of the CC system was decreased from $1.72 \times 10^6$ particles cm$^{-3}$ to $0.52 \times 10^6$ particles cm$^{-3}$. The possible reason was that the indoor thermal stratification appeared with the increased temperature. Since the air supply and return air inlets of the CC system were on the ceiling, the ceiling temperature was relatively higher than that in other systems, thus the upward plume caused by thermal stratification displaced most of the small particles from the ceiling return air inlets (Bhagat et al., 2020). After human walking, the air in the experimental chamber was evenly mixed and the thermal stratification was weakened. Some of the particles that were originally discharged remained in the experimental chamber. The intensification of the disordered motion of the particles reduced the robustness of the ventilation system. Therefore, it was necessary for the ventilation system (including a stable flow field and suitable tuyere position) to resist the influence of a temperature rise on particle movement (Brownian motion intensification) in order to achieve higher robustness. Only the SS system met these two conditions. Therefore, the SS system was the most robust under the three temperature levels. As discussed above, the airflow organization and temperature had a significant influence on ventilation system control walking-induced. In fact, the controlling of the influence of human walking was necessary for specific places that require a highly stable indoor environment (for example: cleanrooms, operation rooms, isolation rooms) (Hang et al., 2014; Liu et al., 2020). However, the superposition of many complex factors increased the difficulties of ventilation system control. Therefore, the introduction of robustness would be helpful for the designs of ventilation system in specific places. Besides, when the ventilation mode was determined, optimizations could be continued on this robustness basis to maximize the disturbance control effect.

5 CONCLUSIONS

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

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

(3) All four ventilation systems can maintain a high stability of the indoor temperature field, resulting in range and time scale eigenvalues of $0.07–0.36$°C and $3.9–11.4$ min, respectively. 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 and pollutant fields, the SS system owned the highest RSr value, 14.7% and 18.7% higher than the lowest value. Therefore, the SS system was superior to other systems in controlling indoor fluctuations and particulate matter filtration. However, a ventilation system with high particle-removal efficiency may not have a good control effect on indoor disturbances. 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%.

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DISCLAIMER

No conflict of interest declared.
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