Comparison of Airflow and Pollutant Dispersion in Multi-room Buildings under Different Cross-Ventilation Patterns

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Abstract The leakage of hazardous gases in the building environment poses a significant threat to the health and even life safety of indoor personnel. It is essential to fully understand the whole process of indoor contaminant dispersion—from source emission, transmission route, to the potential risk of personal exposure. In order to alleviate the harm caused by pollutant leakage to indoor personnel and explore the most effective way to minimize the exposure risk, the airflow pattern and pollutant dispersion features under different ventilation paths were studied in this paper by applying the tracer gas method. The experiment was conducted in a scaled multi-room chamber (1:2). A wind wall system was designed and used to simulate the naturally ventilated environments. Wind velocities at selected key positions which represent the characteristics of multi-room flow field were measured. The concentration distribution was obtained and the possible transmission route of air pollutant was analyzed.

Keywords Pollutant dispersion · Tracer gas · Natural ventilation

1 Introduction

People spent over 80% time in indoor environment [1]. Indoor air quality (IAQ) is a vital aspect of the built environment to ensure occupant health, which is strongly affected by the employed ventilation modes. Cross-ventilation is one kind of commonly used natural ventilation strategies, which requires simple and low-cost equipment, consumes little energy and protects environment. It plays a significant role in influencing human exposures to indoor pollutants as well. Thus, studying the detailed airflow paths and pollutant dispersion mechanism in indoor environment under different typical scenarios is a prerequisite for evaluating exposure risk.

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Numerous previous studies on pollutant dispersion in indoor environment have been conducted by numerical modeling via computational fluid dynamics (CFD) [2–6], scale wind tunnel tests [7–11], and on-site measurements [12, 13]. Jiang and Alexander [3] simulated the turbulent flow field in a single-opening room and predicted indoor airflow velocities and ventilation rates. Tominaga and Blocken [11] studied the velocity fields and concentration fields in the cross-ventilation flow of a generic single-zone building via wind tunnel experiments. Chang et al. studied the effect of indoor partition on indoor airflow and particulate matter transport in naturally ventilated multi-room buildings. James Lo and Atila [14] conducted an on-site experiment to measure airflow rates through small window openings, and tracer gas concentrations for a multi-zone test building.

These aforementioned studies clearly reveal that the indoor airflow characteristics in a multi-room building are quite different from those in a single-room building. Nevertheless, these works primarily focused on the airflow patterns while the ventilation paths and pollutant source characteristics were not considered. Hence, this paper presented an experimental study which was conducted in a scaled multi-room test chamber to investigate the influence of the two factors above on pollutant dispersion. A wind wall system was designed and used to simulate the cross-ventilated environment. Both airflow and pollutant concentration distributions under different scenarios were measured and analyzed. The effect induced by both internal partitions and source locations on the airflow and pollutant dispersion was quantitatively evaluated. It is expected that an enhanced knowledge of such pollutant dispersion would facilitate the assessment of risk to people from a release of an airborne hazardous contaminant in the indoor space and help to design more effective approaches to reduce occupant exposure in similar accidents.

2 Methodology

2.1 Experimental Design

The experiments were conducted in a 1:2 test chamber as shown in Fig. 1. It represents a slab-shaped building which is a very common and basic structure used in hotels, apartments, hospital wards, etc.

The dimension of the test chamber is $L \times W \times H = 4.0\ \text{m} \times 4.0\ \text{m} \times 1.5\ \text{m}$, with four rooms symmetrically distributed on both sides of corridor. Each room contains one window and one door that is opposite the window. All doors are 0.6 m in width and 1.0 m in height. The windows have the same size of 1.0 m in width, 0.6 m in height, and the lower edge is 0.5 m from the floor. The half-opened windows and doors were used as cross-ventilation openings for the experiments. Windshields were installed on the leeward side of the test chamber to minimize the impact of the ambient wind. A wind wall system as shown in Fig. 1b was used to simulate the cross-ventilation situation in the tests.

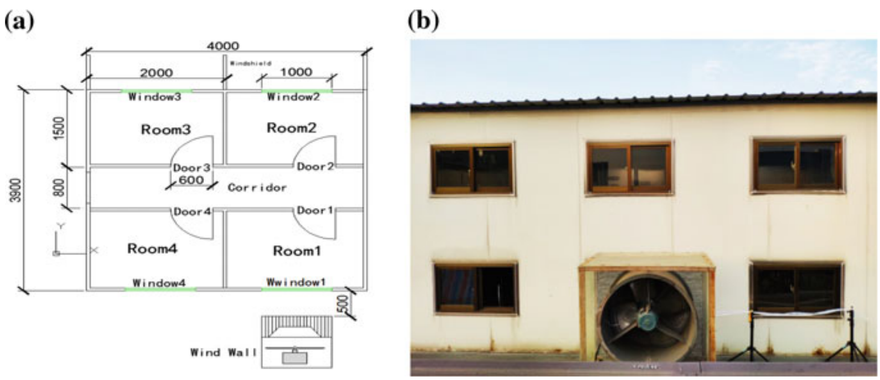

Fig. 1 Test chamber configuration and the wind wall system. Schematic plan (**a**) and photograph (**b**)

Table 1 Summary of the eight configurations

Ventilation path (VP)	Case	Source	Open door	Outlet
VP1	1/2	Center/Corner (R1)	D1–D2	W2
VP2	3/4	Center/Corner (R1)	D1–D3	W3
VP3	5/6	Center/Corner (R1)	D1–D4	W4
VP4	7/8	Center/Corner (R1)	D1–D2–D3	W2–W3

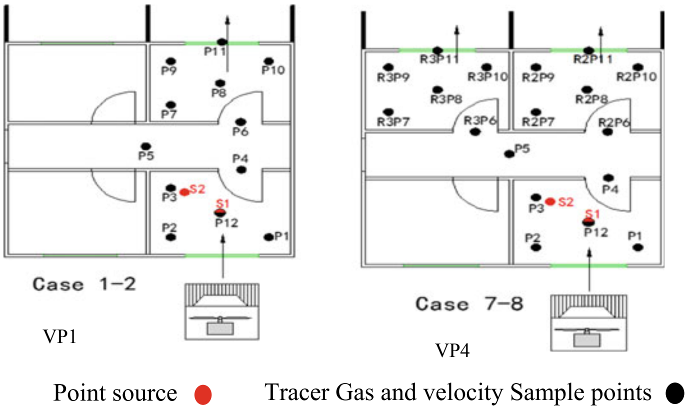

Fig. 2 Configuration of cases 1–2 and 7–8

A series of scenarios was considered as shown in Table 1. Four ventilation paths and two pollutant source locations (central and corner release) were considered. Figure 2 indicated the locations of measurement point and source under VP1 and

VP4. The four ventilation path configurations only differ from each other by the rooms while the sampling positions in the rooms were the same. The Window 1 was the inlet opening for all cases. Prior to the beginning of the experiments, the windows and doors were opened to ensure the balance between internal and external environments. Then, the windows and doors were opened or closed depending on different case setups.

The velocities at the openings and the sample points were measured by SWEMA03 anemometer at a frequency of 20 Hz. Each point was measured over ten minutes. Fourteen anemometers were placed on the openings and the measurement points at the same time. The time-average velocities were calculated from a ten-minute time-series. The wind speed at chamber height H was 1.8 m/s, and the corresponding building Reynolds number is 1.8×10^5, which is higher enough than the previously reported critical value to obtain Reynolds-number independence [15].

In these experiments, tracer gas technique was used to simulate pollutant dispersion from a point source. Sulfur hexafluoride (SF_6) of 99,999 ppm concentration was provided as the source term. The distribution of SF_6 source and sampling points was shown in Fig. 2. The height of the source was 0.45 m and all the sampling points were 0.80 m from the ground as these represented the breathing zone. The tracer gas was released during the entire experimental process at a constant flow velocity 15 ml/s. Both the SF_6 releasing and sampling analysis were obtained by using LumaSense Photoacoustic Gas Monitor INNOVA 1412 detector. Sampling of SF_6 concentration was conducted for about 7 min at each point, using the time-average values as the results of every point.

2.2 Data Analysis Approach

The ventilation rate through the test chamber could be calculated via the obtained velocity profiles through the inlet opening multiplies the corresponding areas, expressed as:

$$Q = v \times A \tag{1}$$

where Q was the ventilation rate, m^3/s, v was the velocity through the inlet opening, m/s, A was the opening area, m^2

For evaluating the personal exposure risk, an index, exposure risk E, was calculated using the following expression [16].

$$E = c \times p \times \tau \times f \tag{2}$$

where c was the relative concentration with respect to the source, p was the pulmonary ventilation rate of a person, 0.6 m^3/h [17], τ was the exposure time, 2 h, f was the unit converted factor, f = 1/24. In the present paper, these parameters were set for the comparison among the four ventilation paths. Besides, the calculated exposure risks here are relative values rather than absolute risks.

3 Discussion

3.1 Ventilation Rates

The average values of the ventilation rates for four ventilation paths are listed in Table 2. The ventilation rate in index room did not change a lot under different configurations, indicating the effect induced by ventilation path was not obvious for the index room. Due to the effect induced by internal partitions and obstacles that led to the momentum loss of the income flow, there were clear variations in ventilation rates for the receptor rooms. Various ventilation paths under different configurations have obviously impact on the internal airflow in the multi-room chamber, and the ventilation rates in different receptor rooms varied with different case setups.

3.2 Pollutant Dispersion Characteristics

The averaged Sf_6 concentrations of the eight cases were shown in Fig. 3. The locations of the sampling points were depicted in Fig. 2.

For most scenarios, the SF_6 concentrations in the index rooms were lower than that in the receptor rooms. Under all the presented ventilation paths, the measured concentration values under corner release scenario were generally larger than that of under central release configuration. Especially when pollutant was released at the corner location, the measured concentration values would increase significantly in both the index room and the receptor room. It suggested that the source locations would strongly affect pollutant dispersion features in the presented multi-room environment. When the pollutant was located at the corner, it had adverse influence on diluting and removing contaminants. In each case, the SF_6 concentrations obtained in different sensors in the same receptor room were almost the same.

Table 2 Ventilation rates $Q = U_{\text{mean}} * A_{\text{opening}}$

Ventilation path	1		2		3		4		
Openings configuration	W1–W2		W1–W3		W1–W4		W1–W2–W3		
Room	R1	R2	R1	R3	R1	R4	R1	R2	R3
Ventilation rates	0.559	0.298	0.517	0.230	0.463	0.182	0.617	0.372	0.110
Wind velocity (m/s)	1.862	0.496	1.722	0.384	1.544	0.303	2.057	0.62	0.184

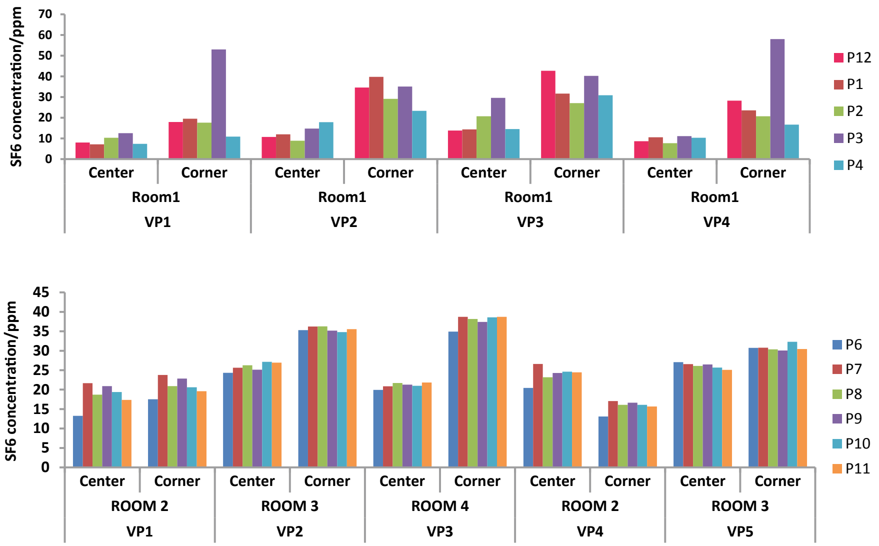

Fig. 3 SF_6 concentration profiles

It suggested that the variations of the concentration level in different sampling positions in the receptor room were not significant after the pollutant enter into the receptor room. Comparing the tracer gas concentration at the five sampling points in index room, it can be observed the point in the room center has lower concentrations than the other points in the room for center release mode. In addition, the SF_6 concentration at Point 3 was the highest than that at the other points, which may be due to the worse ventilation condition caused by the partition walls.

As shown in Fig. 3, the tracer gas concentration values varied with different ventilation paths. Meanwhile, the SF_6 concentrations under VP1 were the minimum among all the cases. It can be confirmed that the VP1 was a more effective way to eliminate pollutants. For case 7–8, the SF_6 concentrations in the Room 2 were slightly lower than those in Room 3. This is because the pass-through ventilation path is superior to the ventilation path 2 (VP2), which is more conducive to the discharge of pollutants. In terms of the receptor rooms, the concentration distribution in the rooms is relatively uniform, respectively, which indicates that for the ventilation path of one inlet opening and two outlet openings, it was a similar distribution characteristic for the tracer gases in the two receptor rooms.

3.3 *Personal Exposure Risk Assessment*

With the recorded SF_6 concentration data, the relative exposure risk of each case was calculated using the risk assessment method introduced above. The statistic results for the whole test period are shown in Figs. 4 and 5. From Fig. 4, it can be seen that in the index room (Room 1), there is no doubt that the pass-through ventilation path was the most effective to reduce the risk of exposure. For the tow source release modes, center and corner, the exposure risk of the index room represented similarly. It should be noticed the exposure risk in the index room was twice as high as the center release condition when the source released at the corner.

It can be observed the mean exposure risks in receptor rooms were higher than that in the index room from Fig. 5. These results illustrated that under multi-room environment, the pollutant observed in the receptor room, which was originating from the index room, can be higher than that of the index room and results in a higher exposure risk. With approximately the same total ventilation rate, there was a certain difference in the mean exposure risks under different ventilation routes and

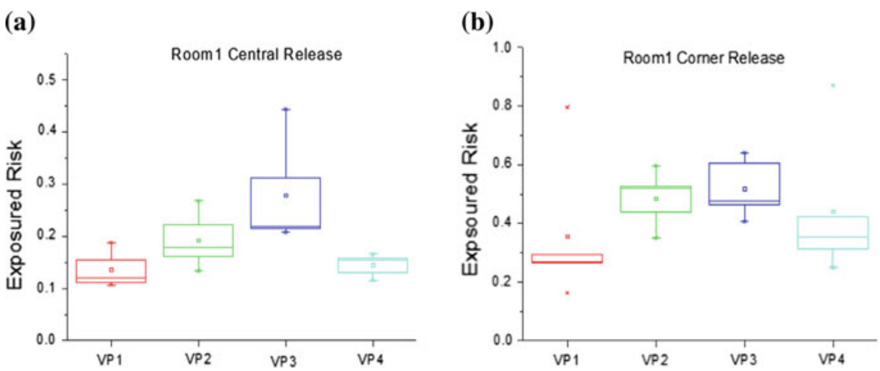

Fig. 4 Exposure risk for Room 1 under four ventilation paths and tow source locations (center (**a**) and corner (**b**))

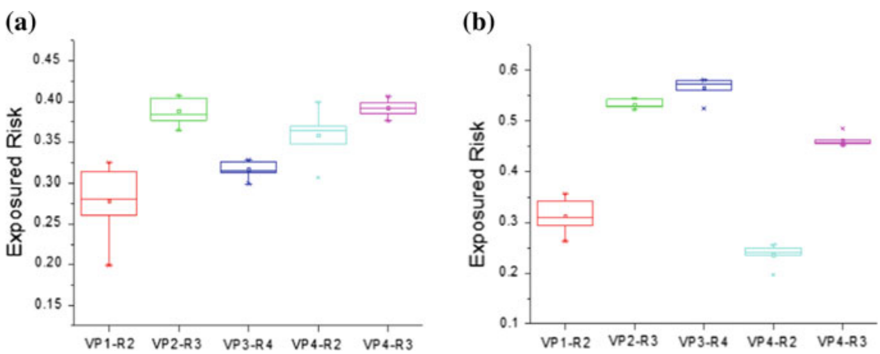

Fig. 5 Exposure risk for receptor rooms (R2, R3, R4) under four ventilation paths and tow source locations (center (**b**) and corner (**b**))

source layouts. For the center release mode, the exposure risk in Room3 was the highest while the mean exposure risk in Room 4 was relatively low. This is probably due to the relatively favorable ventilation conditions that will accelerate the pollutant transfer from the index room into the receptor room. Instead, contaminants will also accumulate in the index unit. The average exposure risk levels of the corner released mode were higher than the center release mode, which means that pollutant source at the corner would increase the exposure risk.

4 Conclusions

In this present paper, both airflow and pollutant distribution characteristics in multi-room buildings were studied in a scaled environmental chamber. The experimental results suggested that pollutant dispersion inside the slab-shaped building was quite different under different cross-ventilation paths. In the presented cases, the VP1 was a more effective way to eliminate pollutant concentration. For the point source at the center location scenarios, the tracer gas concentrations in the index rooms were lower than that in the receptor rooms. The pollutant source at the corner had a more adverse influence on diluting and removing contaminants. The source location plays a significant role in pollutant dispersion. The ventilation rates were calculated based on the wind velocity profiles. The results indicated that the total ventilation rate obtained in the inlet opening was slightly affected by the remaining openings. While owing to the effect caused by internal partitions and obstacles, there were clear variations in ventilation rates for the receptor rooms.

The potential risks of personal exposure in these circumstances were evaluated. It was found that keeping windows and doors open would reduce the exposure risks in the index room while it could not significantly reduce the risks in the receptor units because it simultaneously induced the pollutant from the index room.

In summary, this paper not only contributed to reduce the hazardous impact of pollutant routine release inside a building but also favored to prevent and control the leakage of accidental hazardous chemicals. Based on the results obtained and the personal risk assessment, it could provide a reference for the relevant departments to formulate corresponding strategies and optimization plans.

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