Experimental analysis of single-sided natural ventilation and interunit dispersion in scaled 2D street canyons

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Abstract. Interunit dispersion problems have been studied previously mainly through on-site measurements, wind tunnel tests, and CFD simulations. In this study, a scaled outdoor experiment was conducted to examine the interunit dispersion characteristics in consecutive two-dimensional street canyons. Tracer gas (CO_2) was continuously released to simulate the pollutant dispersion routes between the rooms in street canyons. The reentry ratio was analyzed to reveal the interunit dispersion of the rooms in the street canyons. This study provides authentic airflow and pollutant dispersion information in the street canyons in an urban environment.

1 Introduction

Indoor air quality (IAQ) has a significant impact on human health because people spend most of their time indoors [1, 2]. A poor IAQ, caused by the concentrations of particulate matter and gaseous pollutants in the air, may lead to harmful consequences to human health. Various pollutants, such as traffic exhaust, dust, pollen, airborne viruses, and toxic and odorous emissions, may enter indoor areas [3]. Recently, a special mode of pollutant transmission, known as interunit dispersion, has gained popularity. Interunit dispersion illustrates the cross-transmission between apartment units within the same multistory building. This airborne transmission mode is highly risky because of the relatively short dispersion distances and transportation time as compared to other modes like pollutants from special dense sources and traffic exhausts [4].

Interunit dispersion was identified during the outbreak of Severe Acute Respiratory Syndrome (SARS) in Hong Kong in 2003 [5, 6]. Since then, a substantial number of studies have continued to investigate the pollutant dispersion among units in the same building and the airflow field around the built environment [12]. Mao et al. [7] summarized the existing studies by targeting the interunit transmission and dispersion problems. Several methods, such as on-site measurements, wind tunnel experiments, and Computational Fluid Dynamics (CFD) simulations, have been adopted to investigate the coupled indoor and outdoor airflow and pollutant dispersion in a naturally ventilated environment.

Recently, researchers have adopted scaled outdoor experiments as effective alternatives to investigate the airflow field and pollutant dispersion in the urban environment. In order to further investigate the interunit dispersion problem, this study conducted an outdoor experiment in 2D street canyons on the Scaled Outdoor Model Urban Climate and Health (SOMUCH) field at Sun Yat-sen University. The tracer gas method using carbon dioxide (CO_2) was adopted to simulate the pollutant dispersion process in the street canyons. The study also intended to provide a complementary method between the on-site measurements and numerical simulations of the interunit dispersion in street canyons and provide authentic airflow and pollutant dispersion information under an urban environment. In addition, the dataset of this experiment can offer validation of further numerical simulations.

2 Experiment settings

The SOMUCH experimental field is located on the southern side of Guangzhou, China ($23°01'N$, $113°24'E$). The dimension of each building model is length $\times$ width $\times$ height $= 0.5\ m \times 0.5\ m \times 1.2\ m$. The length of each street canyon is $12\ m$. This study chose a width:height$= 1:1$ street canyon as the target area, as shown in Fig. 1. The measurements lasted from June 7 to 10, 2019; on each day.

Fig. 1. Overview of experiment field.

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Three acrylic models with two opposite rooms on each floor were customized. Each room had an opening with a height and width of $0.1\,m$ and $0.2\,m$, respectively. The dimensions of the customized and concrete models are shown in Fig. 2. Carbon dioxide (CO_2) was adopted as the tracer gas in this experiment. Three acrylic models were placed separately in the middle of three adjacent building arrays in the $1:1$ street canyons, as shown in Fig. 2(c). One model was set as the source building. During the tests, each room in this model was set as the source room, and the tracer gas was released continuously for around $30\,min$. All instruments were sampled simultaneously for the wind velocity, wind direction, and CO_2 concentrations in each room.
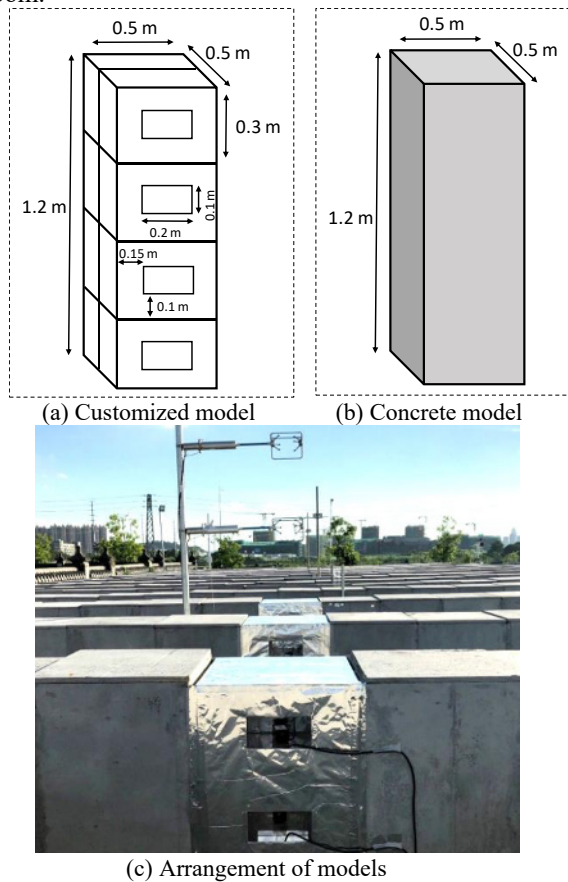

(a) Customized model   (b) Concrete model

(c) Arrangement of models

Fig. 2. Dimensions and arrangement of customized and concrete models.

3 Results and discussions

3.1 Wind conditions during test period

Fig. 3 shows the average wind components and fitted U profiles according to the monitored data from June 9, 2019. The power law is adopted to construct the wind profile equations and can be expressed by

$$\frac{U}{U_H} = \left(\frac{Z}{Z_H}\right)^\alpha \qquad (1)$$

where U is the wind velocity at height Z, U_H is the referenced velocity at the street canyon height, Z_H is the street canyon height, and α is the empirical coefficient. In this experiment, the incoming wind profiles were obtained by fitting U, $U_H = 2.46\,m/s$, $Z_H = 1.2\,m$, $\alpha = 0.245$ in phase I and $U_H = 0.63\,m/s$, $Z_H = 1.2\,m$, $\alpha = 0.495$ in phase II, as shown in Fig. 3(a) and (b), in the power law.

(a)   Phase I: 10:00:00–15:00:00
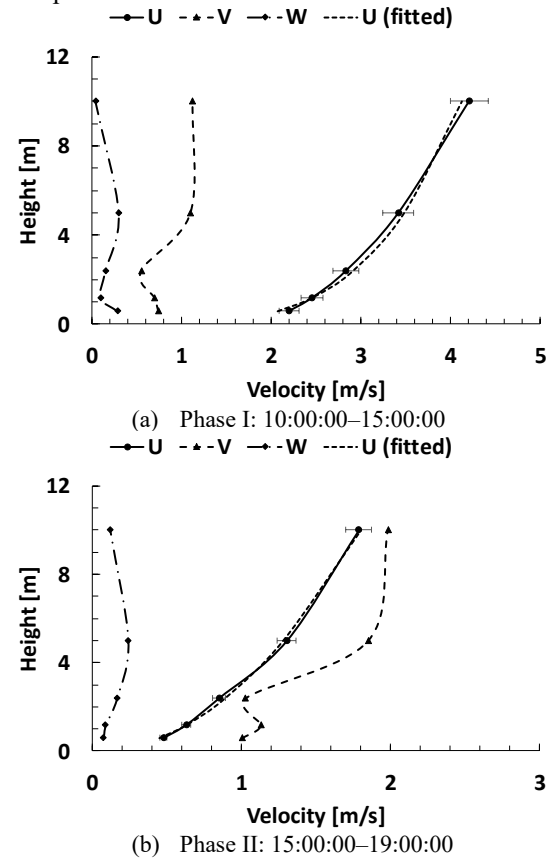

(b)   Phase II: 15:00:00–19:00:00

Fig. 3. Average wind components and fitted U profiles of June 9.

3.2 Interunit dispersion of target building

This section describes the analysis of the tracer gas dispersion to each room of one building, based on the data from June 9, 2019. The term R_k illustrates the fraction of the tracer gas in the source room that reenters another room. Fig. 4 presents box charts of the reentry ratios of each room with respect to different source locations. W represents the windward side, and L represents the leeward side. The mean and maximum values of each test are also listed. The statistical results indicated that the R_k of each room varied significantly based on the source room location, and the reentry ratio in the $1:1$ street canyon could reach 17.7% in the test of BL2. Several observations can be made from the comparisons of these tests.

First, when the source was located on the windward side, the reentry ratio of each room was generally lower than that of the leeward side. This may be partly attributed to the fact that the average incoming wind velocities during the windward tests were higher than those of the leeward tests. This accelerated the tracer gas dispersion of the source room and diluted it directly downstream.

Second, the tracer gas was mainly transported downward when the source was located on the windward side, whereas on the leeward side, the tracer

gas was mainly transported upward. This phenomenon was caused by the flow characteristics of the 2D street canyon. For an aspect ratio of $1:1$ in this experiment, the airflow in the street canyon was termed a skimming flow [8], and a large and stable vortex was formed inside the street canyon. With a strong vortex, the tracer gas transportation routes were established when the source location was fixed. The tracer transportation characteristics in the street canyon had large differences from the conditions of an isolated building [4, 9, 10] or building arrays [11, 12]. Without lateral separation flows, the tracer gas will disperse from the top of the street canyon or spread horizontally inside the street canyon. Note that in this experiment, only vertical dispersion was considered. The horizontal dispersion of the tracer gas in the street canyon should be analyzed in future studies.

The statistical results of the tests showed that the maximum values of the reentry ratio can be 200% higher than the average values observed in other rooms. Considering $R_k < 1\%$ as a negligible reentry ratio, around 17.9% and 48.2% of rooms were dangerous cases given the average R_k values and maximum R_k values, respectively. This revealed that in a real street-canyon environment, a room has a high probability of occasionally experiencing a high tracer-gas concentration, although the average reentry ratio was very low.
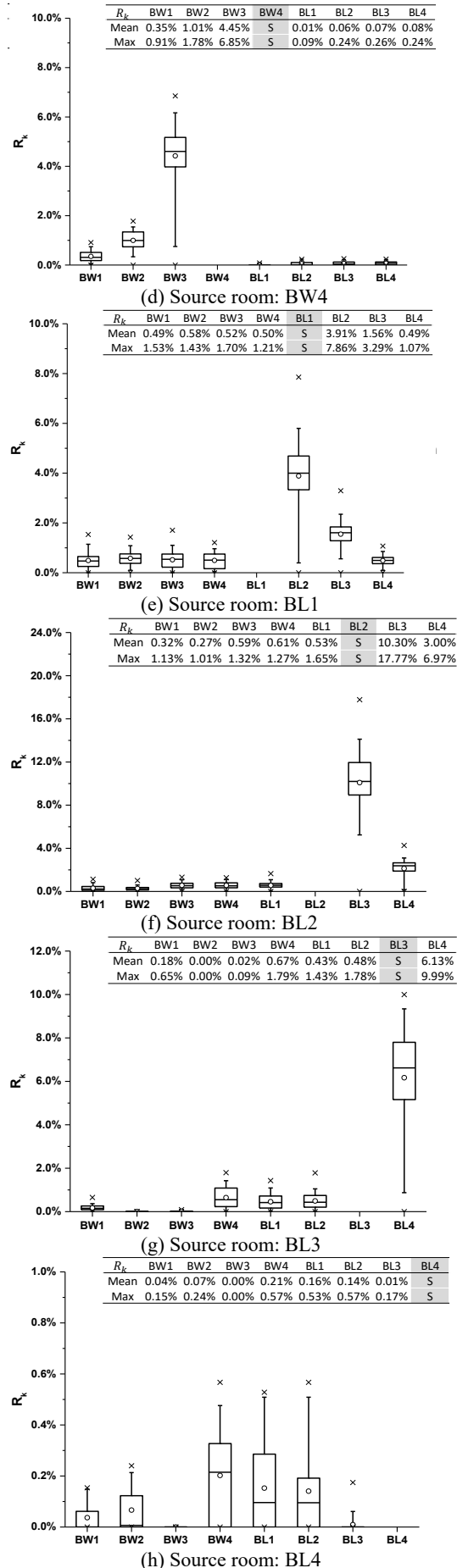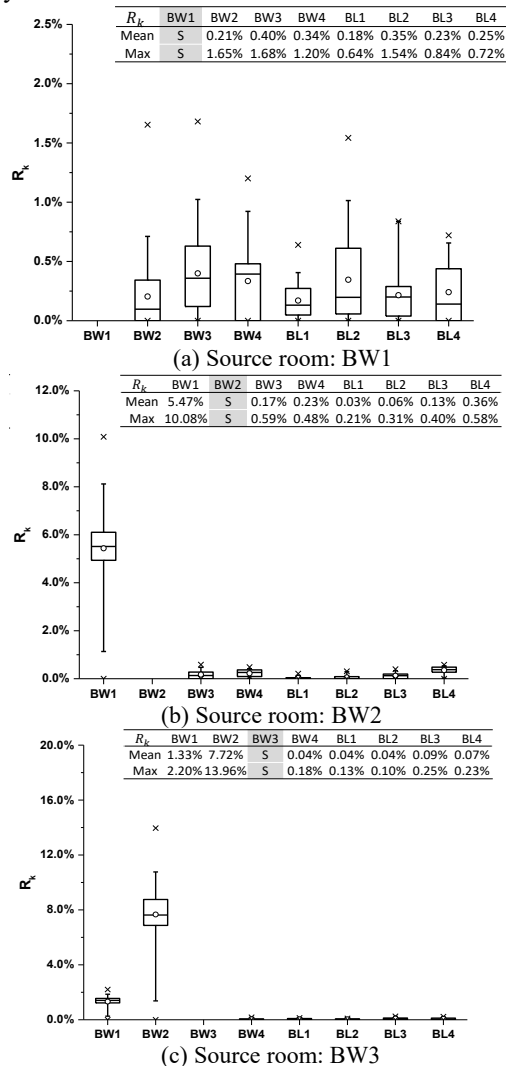
R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	S	0.21%	0.40%	0.34%	0.18%	0.35%	0.23%	0.25%
Max	S	1.65%	1.68%	1.20%	0.64%	1.54%	0.84%	0.72%

(a) Source room: BW1

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	5.47%	S	0.17%	0.23%	0.03%	0.06%	0.13%	0.36%
Max	10.08%	S	0.59%	0.48%	0.21%	0.31%	0.40%	0.58%

(b) Source room: BW2

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	1.33%	7.72%	S	0.04%	0.04%	0.04%	0.09%	0.07%
Max	2.20%	13.96%	S	0.18%	0.13%	0.10%	0.25%	0.23%

(c) Source room: BW3

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	0.35%	1.01%	4.45%	S	0.01%	0.06%	0.07%	0.08%
Max	0.91%	1.78%	6.85%	S	0.09%	0.24%	0.26%	0.24%

(d) Source room: BW4

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	0.49%	0.58%	0.52%	0.50%	S	3.91%	1.56%	0.49%
Max	1.53%	1.43%	1.70%	1.21%	S	7.86%	3.29%	1.07%

(e) Source room: BL1

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	0.32%	0.27%	0.59%	0.61%	0.53%		10.30%	3.00%
Max	1.13%	1.01%	1.32%	1.27%	1.65%	S	17.77%	6.97%

(f) Source room: BL2

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	0.18%	0.00%	0.02%	0.67%	0.43%	0.48%	S	6.13%
Max	0.65%	0.00%	0.09%	1.79%	1.43%	1.78%	S	9.99%

(g) Source room: BL3

R_k	BW1	BW2	BW3	BW4	BL1	BL2	BL3	BL4
Mean	0.04%	0.07%	0.00%	0.21%	0.16%	0.14%	0.01%	S
Max	0.15%	0.24%	0.00%	0.57%	0.53%	0.57%	0.17%	S

(h) Source room: BL4

Fig. 4. Box charts of reentry ratio of each test, with source room marked.

In addition, generally, the highest R_k value as observed room nearest to the source room along the transportation route. Taking source room BL2 as an example, Fig. 5 shows the monitored CO_2 concentrations of the source room and other rooms on the same side during the gas releasing period. It was obvious that the CO_2 concentrations of BL1, BL3, and BL4 were much lower than that of source room BL2. The highest CO_2 concentration occurred in BL3, which was the immediate upper room near BL2. The concentration in room BL3 was around one order lower than that in BL2. The second highest CO_2 concentration was observed in room BL4 at one order lower than that of BL3 and room BL4 located along the vortex path on the leeward side of the street canyon.

The lowest concentration was observed in room BL1. Although this room was very close to the source room, the concentration was three orders lower than that in BL2 as the room was located in the opposite direction of the upward flow along the façade. This phenomenon was also reflected in the value of the average reentry ratio. As shown in Fig. 4(f), the reentry ratio of 10.3% in BL3 decreased to 2.16% in BL4, and the reentry ratio was only 0.53% that of BL1. This further illustrates that the tracer gas was immediately diluted with the upward flow caused by the vortex on the leeward side of the street canyon and merely transported in the reverse direction.
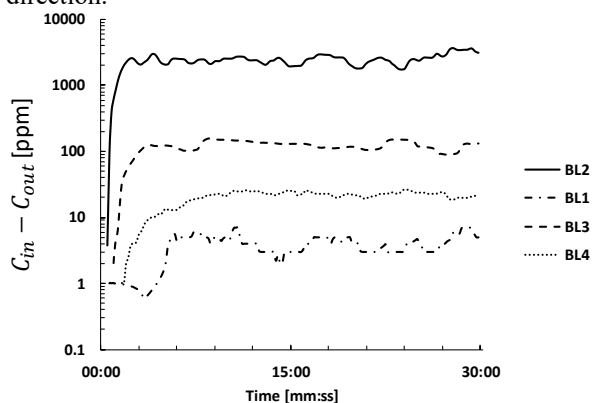

Fig. 5. CO_2 concentration of each source room (BL2) and enentry rooms during gas releasing process for 30 min.

4 Conclusions

This study conducted a scaled outdoor experiment to explore the interunit dispersion problem in a 2D street canyon with the tracer gas method. A series of measurements were performed to investigate the ventilation performance and interunit dispersion. Based on the weather conditions of the test day, the interunit dispersion between rooms in the source building changed significantly with the source room location. Owing to a large and stable vortex constructed by the freestream inside the street canyon, the tracer gas was mainly transported in the vortex direction, and the highest R_k value occurred generally in the room nearest to the source room along the transportation route.

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