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Wind tunnel tests of inter-flat pollutant transmission characteristics in a rectangular multi-storey residential building, part B: Effect of source location

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A B S T R A C T
The pollutant behavior in and around a naturally ventilated building requires to be investigated quantitatively as the growing concern on air quality within the built environment. The objective of the present study is to further investigate the wind induced inter-flat pollutant transmission and cross contamination routes in typical buildings in Shanghai. In this paper, a set of experiments was carried out in a boundary layer wind tunnel using a 1:30 reduced scale model that represented the typical configuration of rectangular multi-storey residential buildings. Sulfur hexafluoride (SF₆) was employed as a tracer gas in the wind tunnel tests. Two natural ventilation modes, single-sided ventilation and cross ventilation were considered. The conditions under prevailing wind direction with different source locations on the windward side were compared. The pressure coefficients on all of the building façades and tracer gas concentration distributions were monitored and analysed. The experimental results elucidated that contaminant released from windward units could spread vertically and horizontally to other units on the source façade and downstream units. The source location was a significant influence factor on the pollutant concentration in various units. In the single-sided ventilated building, the infected risks of leeward units were even higher than those in some windward units. In the cross ventilated building, the vertical transmission could be suppressed and the horizontal transmission was reinforced. The study is helpful for further understanding of the inter-flat airborne transmission within an isolated building.

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1. Introduction

The occupants in the urban area have exceeded 50% [1], so a trend toward high-density development of multi-storey residential estate presents to adapt the housing problem. City dwellers spend more than 80% of their time indoors [2,3], notably over half of this time in their homes. All these lead to an increasing concern to ensure a better indoor environment quality related to thermal comfort, health and productivity issues [4,5]. Natural ventilation is an effective and sustainable approach to induce the air exchange through openings of the room to improve the indoor environment and dilute the polluted indoor air by bringing fresh air from outside [6–8]. However, undesirable consequences caused by natural ventilation have been detected in recent years and aroused public concern because of the frequent occurrence of airborne epidemic diseases [9–12]. Natural ventilation is thus a seeming contradiction for the indoor pollutant control, which could dilute the indoor pollutant concentration on one hand, but on the other hand it may also introduce pollutants to uninfected flats. Airborne transmission is believed as one of the major modes that could cause the virus transmission and infection [13,14]. A special airborne infection scenario called inter-flat cross contamination was identified as an important airborne route related to natural ventilation and started to be investigated after the outbreak of severe acute respiratory syndrome (SARS) in 2003 [15,16].

Tracking the large-scale outbreak of SARS in the residential community, Li et al. [17] built up the airflow network considering the air leakage of different flat and the re-entrance space by a multi-zone model, thereby predicted the airflow path and infection pattern on different floors. Niu et al. then found the probability of the re-entry behavior of the air exhausted from a single-sided open window to an upper floor by both CFD simulation [18] and on-site experimental studies [19]. The on-site study revealed that re-entry ratio of the upward outflow driven by temperature difference from
a lower flat to the adjacent upper one could get to 7% under gentle wind conditions. Gao et al. [20] and Liu et al. [21] further explained this cascade effect by simplified CFD simulations on two adjacent rooms combined with a tracer gas method, concluding that the infection risk of the immediate upper room is lower than the source room by only 1 order of magnitude, though the concentration is lower by 2 orders of magnitude. In addition, Liu et al. [21] also discussed the probability to reduce this vertical cross-contamination by modifying the window configurations and introduced individual mechanical exhaust. A recent research by Wu et al. [22] explored the ventilation strategy using mechanical exhaust to avoid the vertical cascade transmission. Besides, Liu et al. [23,24] and Wang et al. [25] performed wind tunnel tests to investigate the wind effect on the pollutant dispersion around cross shape buildings. The results indicated that both vertical and horizontal transmission could process in the re-entry area. The dispersion characteristics can be affected by source location and wind directions. Moreover, Liu et al. [26] analysed the unsteady characteristics of gas dispersion under both open and closed window scenarios and concluded that fluctuating concentrations should be paid attention to when evaluating potential risks. Based on these wind tunnel experimental data, further numerical studies were conducted to extend the research [27,28]. Their studies mostly focused on a typical cross-shaped high-rise building, with a re-entrance space on each façade. Extensive simulation works by Cheng et al. [29] discussed the airflow within the re-entry bay of different depth and width, considering a generic H shaped high-rise building. The transmission mechanism of the gaseous pollutants inside a cross-like high-rise building driven by stack effect and a combination of stack and wind effect was well demonstrated in the twin work by Yang et al. [30] and Mao et al. [31]. Their work also revealed the complicated situation when considering the wind effect and different pollutant source locations. In consideration of the building envelop, Ai et al. [32–34] compared the wind-induced dispersion characteristics in a slab-shaped building with and without balconies with single-sided ventilation by numerical simulation on reduced scale geometries. The tracer gas transmission routes on the windward and leeward façades were revealed and compared. There are still few wind tunnel experiments on such naturally ventilated multi-storey buildings.

In general, the above inter-flat transmission cases for an isolated naturally ventilated building basically involves two external infection paths, through the re-entrance space and through building façade openings with single-sided ventilation. The results mainly focused on the infection probability of flats on the pollutant source façade. However, the contaminant from the upstream flat of a building can spread to the downstream units with the airflow, namely disperse from one façade to another [35–38]. Our previous paper [39] qualitatively and quantitatively investigated aforementioned phenomenon and compared the performances of single-sided and cross ventilation under different wind directions with the tracer gas released from a specific unit. The results showed that compared with single-sided ventilation, cross ventilation could weaken the vertical transmission for a specific windward or leeward source and reinforce the horizontal dispersion for a specific sideward source. The leeward units got high risks of infection in single-sided ventilation under normal and oblique wind directions. Nevertheless, the conditions under a certain source location can only reveal a part of pollutant dispersion characteristics in a multi-storey building. Hence, the purpose of this study is to further explore the wind-induced pollutant inter-flat transmission process within and around a rectangular multi-storey building with natural ventilation, taking into account the effect of source locations. We performed a range of experiments in an atmospheric boundary layer wind tunnel with a 1:30 scaled model. The pressure coefficient and pollutant concentration distributions along all the building façades were measured and analysed. The results obtained from the present work were expected to be useful for more effective designs and measures in the control of infection.

2. Methodology

2.1. Experiment configurations

The experiment methods and instruments used during the measurement process have been mostly described in our previous paper [39]. In this paper, we briefly outlined the experiment arrangement, and gave supplementary introduction on the measurement and analysis of pressure coefficient along the building façade, which was not shown in Ref. [39].

The experiment was performed in the TJ-1 boundary layer wind tunnel in the State Key Laboratory of Civil Engineering for Disaster Prevention, Tongji University, China. It is a low speed open circuit one. The dimension of test section in this wind tunnel is 1.8 m high, 1.8 m wide and 12 m long. The atmospheric boundary layer flow was generated by specific spires, grills and roughness elements, as shown in Fig. 1. The power law exponent of velocity profile was 0.22 [40]. The turbulence intensity of the approaching wind flow was in a range of 10%–20%. The dimensionless mean velocity profile \( U_{DP} \) defined as \( U/(h/Re) \) was presented to meet the similarity criteria of approaching boundary conditions, and the characteristic velocity \( U_{ref} \) was set as the velocity at building height. The normalized velocity profile and measured turbulence intensity were presented in Fig. 2. The height was normalized by \( h/Re \). For a scaled modelling of airflows and plume dispersion in the wind tunnel study, a series of similarity requirements between prototype and scaled model should be examined carefully as reported in literature [41]. Some of the similarity parameters can be neglected due to their poor relative importance when simulating pollutant transmission in and around buildings without thermal effect, while the Reynolds number must be paid attention to [42]. For the present tests, the mean flow velocity \( U_{ref} \) measured at the building height, which was 0.59 m in the scaled model, had a value of 2.89 m/s. Hence, the building Reynolds number, \( Re = U_{ref}/h\nu \), could be over 15,000 [43] and up to 1.15 \times 10^5, assuring that the test results were independent of the Reynolds number.

In consideration of the blockage ratio and the capability to capture the airflow patterns and tracer gas dispersion behavior, a 1:30 scaled hypothetical rectangular building model was structured. The building contains six floors and each floor contains a corridor with three units at each side. Each unit has a window on the exterior wall and a door on the inner wall. All the units have the same dimensions, as shown in Fig. 3. Geometric similarity is satisfied and the blockage ratio is 5.46%. The cross-contamination could happen caused by the single-sided ventilation in Model A with all windows open and doors closed and by cross ventilation in Model B with all windows and doors open. The tracer gas sulfur hexafluoride (SF\(_6\)) was employed to simulate the pollutant. SF\(_6\) was released at a constant flow rate of 15 ml/s during a series of concentration tests. The dosing outlet was enlarged so that the releasing velocity was low to 0.53 m/s. On account that the source location has influence on the wind induced pollutant inter-flat dispersion phenomena, according to the shape of the building model, there are 12 unique units on the windward façade under prevailing wind condition, thus 12 testing cases for single-sided ventilation mode were designed. In view of the through-building airflow characteristics of cross ventilation, 4 cases for such mode were tested, as listed in Table 1. The concentration measurement points were located at the middle of all windows’ lower frame flush with the building façade. The sampling time interval was 180s for
each measuring point. The experiments were repeated three times to obtain the mean concentration value for each case. The mean pressure coefficient distributions on the building façade were beneficial to analyse the surface flow directions, and then track the tracer gas transmission routes, which are strongly related to the airflow patterns. Totally, 168 pressure taps with the diameter of 0.5 mm were used to measure the building surface pressure, which means each floor has 28 test positions and the sequence numbers are shown in Fig. 3(c). The pressure taps were connected to three 64-channel electronic pressure scanners, which were positioned under the wind tunnel floor.

The measure objects and accuracy of instruments used in the experiment were listed in Table 2. The calibration work for each instrument was carried out and repeated before and after the
corresponding test process to ensure the stability of the equipment and reduce the systemic error.

2.2. Data analysis

The pressure coefficient distribution along the building façades could be established based on the measured pressure at the test points arranged along the exterior walls of the building. The pressure coefficient is defined as,

\[ P_c = \frac{p_s - p_{ref}}{0.5 \rho U_{ref}^2} \]  

where \( p_s \) refers to the measured surface pressure, \( p_{ref} \) is the reference static pressure examined by a Pitot-static probe at the building height.

For the analysis and comparisons of pollutant concentration distribution characteristics under different source positions, the measured tracer gas concentrations were normalized by the following equation,

\[ K = \frac{100C}{C_s} \]  

where \( K \) represents the normalized concentration, \( C \) refers to the

![Fig. 2. Approaching wind characteristics.](image)

![Fig. 3. The geometry of the six-storey building model with eight columns, i.e. UR, UM, UL, CR, CL, DR, DM, DL (source location on the windward side; - - sample location in each room and on the both sides of the corridor; ▲ pressure taps along building façade. Model A means single-sided natural ventilation in which windows are open but doors are closed. Model B represents cross natural ventilation where both windows and doors are open.).](image)

| Case No. | Source location | Model A | Single-sided ventilation | Model B | Cross ventilation |
|---------|-----------------|---------|--------------------------|---------|-------------------|
| 1       | F1st            | UR      | F1st                     | UR      | F1st              |
| 2       | F2nd            | UM      | F2nd                     | UM      | F2nd              |
| 3       | F3rd            | UL      | F3rd                     | UL      | F3rd              |
| 4       | F4th            | CR      | F4th                     | CR      | F4th              |
| 5       | F5th            | CL      | F5th                     | CL      | F5th              |
| 6       | F6th            | DM      | F6th                     | DM      | F6th              |
| 7       | F7th            | DL      | F7th                     | DL      | F7th              |
| 8       | F8th            | F3rd    | F8th                     | F3rd    | F8th              |
| 9       | F9th            | F5th    | F9th                     | F5th    | F9th              |
| 10      | F10th           | F3rd    | F10th                    | F3rd    | F10th             |
| 11      | F11th           | F5th    | F11th                    | F5th    | F11th             |
| 12      | F12th           |         |                          |         |                   |
| 13      | F13th           |         |                          |         |                   |
| 14      | F14th           |         |                          |         |                   |
| 15      | F15th           |         |                          |         |                   |
| 16      | F16th           |         |                          |         |                   |
measured tracer gas mass concentration of SF₆ and CF₃ is the measured source mass concentration. Eq. (2) means the normalized concentration at the source is 100. The dimensionless index implies the relative differences of tracer gas concentrations between source and sample points.

3. Results and discussions

3.1. Pressure coefficient distribution

Fig. 4 illustrates the measuring positions and mean pressure coefficient distribution on different building façades in Model A. Fig. 4(a) gives the pressure coefficient value at each test position. According to Eq. (1), the pressure coefficient is a relative quantity. The positive and negative values have a relation with the original measured value and the reference static pressure. It is observed that the differences of value among points at a certain floor could be distinguished, while the differences among floors were small, especially on the leeward and sideward façades. To have a better understanding of these data, a contour map was generated for qualitatively visualized wind pressure coefficient distribution on each wall surface. As shown in Fig. 4(b) and (d), the pressure coefficient distribution reflected a good symmetric tendency on the windward and leeward façades because of the symmetric geometry feature of the building. The highest Pc value was up to 0.8 around the window area of UM5th unit, forming the stagnation zone. The outflowing air from the stagnation area could spread to all around. Most Pc values were positive on the windward wall surface, while several negative ones showed at the lower floors near the edge. The Pc values on the leeward side varied in a small range. Fig. 4(d) implied a slight flow tendency from the lower two-third part to upper in the vertical direction and a main tendency from middle units to lateral ones in the horizontal direction. As shown in Fig. 4(c) and (e), the pressure coefficient distributions had a slice of difference on two corridor façades, but the range and variation trend of pressure coefficient along the façade were the same. According to ASHRAE [44], there is a fluctuating reattachment flow on the sideward for a solid rectangular bluff body under normal wind direction. Since during the test process the sideward windows were open, the unsteadiness of the airflow around the openings on the sideward of Model A could be more complicated. Overall, the negative Pc values on the leeward façade were higher than that on the corridor façades, indicating a possible surface backflow direction from leeward façade to corridor façades.

The mean pressure coefficient distributions along building façades for Model B were shown in Fig. 5. It is similar with Model A that the Pc values of different floors on the sideward and leeward sides were very close. But the contour map for each side differs from that in Model A. On the windward side, a stagnation side also showed around the window of UM5th unit. The Pc values at upper floors were higher than those at lower floors. This situation appears on the leeward side as well, resulting from the cross-building airflow. It is obvious that the values shown in the contour maps for sideward and leeward sides in Fig. 5 were higher than that in Fig. 4. In other words, compared with Model A, the pressure coefficient value difference at each floor between windward façade and leeward façade in Model B was smaller, as well as the difference between windward façade and sideward façade.

3.2. Tracer gas concentration distribution

3.2.1. Source units at the middle column on windward façade of Model A

Fig. 6 gives the tracer gas normalized concentration of Model A when the source located at the units of UM column. The framework in the graph for each case could be considered as the stretch-out view of the building façades. The number in each grid box is the average normalized concentration value in the corresponding sample location of each room. Both the signal intensity and color grade scale were used to represent the concentration level. The signal was divided into five grades, as shown in the legend. On the whole, wherever the tracer gas was released, the concentrations varied with the locations of measuring points under prevailing wind direction. The source unit got the highest concentration value and a unique full signal. The concentrations at other flats universally decreased with the distance from the releasing flat along the vertical direction. In addition, the concentration distributions along the corresponding "R" and "L" columns in each case also had good symmetric features. Tracer gas generated quite high concentrations at the units horizontally closest to the source unit.

In Fig. 6(a), when the tracer gas was releasing at the first floor of column UM, for units on the same façade, the concentration values were not sensitive to the columns. On the windward side, a sharp decrease of concentration was observed in the upward direction. The concentrations in the windward upper floors were at the lowest two grades, and the values were even lower than those in the leeward and sideward. For concentrations on the leeward side, the value decayed more slowly along the upward direction than that on the sideward façade.

Fig. 6(b) illustrates the results obtained when the source unit was the second floor at UM column. The rapid decay also appeared from the source floor to the immediate upper flat on the windward façade. The tracer gas was most likely to move from source unit to horizontally lateral units and vertically downward units. In addition, Fig. 6(a) and (b) reveal almost the same concentration distribution characteristics in the leeward and corridor sides respectively. The tracer gas tended to transport upward, resulting in a high risk of being contaminated in the upper flats. In Fig. 6(c), when the tracer gas was released at the third floor of UM, its dispersion routes were in a similar way as the second case.

Different from the front three cases, no rapid descent of concentration appeared on the windward side in Fig. 6(d), where the source location was the fourth floor of UM column. The concentrations on the windward and sideward façades showed maximum values at the fourth floor. Besides, the downward transmission trend was more obvious than the upward spread trend. On the leeward side, the concentration values seemed not sensitive to either column or height. The signal intensities for all leeward units were at the same grade. The concentrations on the sideward façade were higher than those on the leeward side, and the signal intensities were generally one grade higher.

| Measure object | Instrument | Accuracy |
|----------------|------------|----------|
| Velocity       | 3-D Cobra probe | ±0.5 m/s |
| Reference Velocity | Pitot-tube and Micro-manometer (DMP301N22) | ±0.1 Pa |
| Pressure       | 64-channel electronic pressure scanner | ±0.2% |
| SF₆ Concentration | INOVA 1303 and 1412, 7620 software | ±2% |

*a For the reference velocity, the corresponding accuracy in "m/s" is ±0.03 m/s.
It is observed from Fig. 6(e) that when the tracer gas emitted from the stagnation zone, i.e. the fifth floor of UM column, both the vertical and horizontal dispersion were evidently. All the units got nonnegligible signal intensities. The concentration variation tendency was similar to Case N4, except that the upward dispersion on windward side was more evident than that in Fig. 6(d) and the horizontal spread trend was relatively weak.

In Fig. 6(f), the source was located at the top floor of UM column. Distinctly low concentration values were obtained at all the measured points below the source floor on windward façade, and a sharp fall was shown from the top floor to the nearest lower floor. For units on the leeward and sideward façades, the values decayed along the downward vertical direction, and the gradient of downtrend for the leeward side was relatively smaller than that for sideward façade.

Generally speaking, when the source floor was below the stagnation zone, the tracer gas was more likely to move downward on the windward façade. The tracer gas released at the stagnation zone unit tended to develop an entire high concentration on all façades. For all cases, majority of the concentration in the leeward side were between 1 and 10 when the source was 100. Besides, the concentration variation in pace with column on the leeward side could be ignored. The values show an approximate linear change along with height in each case. As the source location going up, the concentration values on lower leeward units were firstly higher than upper ones and finally smaller than them.

**Fig. 4.** Measured mean pressure coefficient and fitting contour lines on building façades, Model A.
3.2.2. Source units at the lateral column on windward façade of Model A

Fig. 7 shows the tracer gas dispersion characteristics when the source located at the units of UR column. Since UR column was one of the lateral columns on the windward side, the airflow normally moved from middle column to side column along horizontal direction, source released from UR column had a slight chance to spread to the other two columns on this façade. Owing to the inherent unsteady characteristics of approaching wind and diffusion effect of contaminant, the tracer gas still could be measured at UM and UL column although the values were very low.

Fig. 7(a) gives the concentration distributions when the source located at the first floor of UR column. On the windward side, the normalized concentration decayed rapidly from 100 to below 1 in the upward vertical direction of UR column. The profile of concentration at the leeward side were alike that in Fig. 5(a). For sideward façade, the concentrations had a downtrend as height increasing and the values on “CL” column were lower than those on “CR” column. Similar concentration distributions appeared in Fig. 7(b) when the source position was at the second floor of UR column, except that a dispersion path from the second floor vertically downward to the first floor showed on the windward side.

Fig. 7(c) shows the tracer gas dispersion when the source location was on the third floor of UR column. On the windward façade,
Fig. 6. Signal intensity and color level of normalized concentration, contaminant source location is UM column, Model A Single-sided ventilation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### Normalized Concentration

|   | CR | UR | UM | CL | DL | DM | DR |
|---|----|----|----|----|----|----|----|
| (a) Case N1 |     |    |    |    |    |    |    |
| F6 | 1.87 | 0.86 | 0.74 | 0.76 | 1.66 | 3.51 | 3.30 | 3.03 |
| F5 | 2.14 | 0.75 | 1.08 | 0.83 | 2.43 | 3.93 | 3.81 | 3.77 |
| F4 | 4.51 | 0.64 | 1.02 | 0.70 | 3.85 | 4.52 | 4.37 | 4.54 |
| F3 | 5.98 | 1.58 | 1.25 | 0.67 | 5.97 | 5.12 | 6.30 | 5.95 |
| F2 | 11.85 | 2.01 | 1.83 | 0.73 | 9.57 | 8.99 | 8.51 | 9.05 |
| F1 | 27.25 | 83.04 | 100.00 | 87.53 | 32.91 | 10.63 | 11.52 | 13.06 |

| (b) Case N2 |     |    |    |    |    |    |    |
| F6 | 1.34 | 0.48 | 0.65 | 0.69 | 1.22 | 3.01 | 2.95 | 2.89 |
| F5 | 2.47 | 0.50 | 0.71 | 0.55 | 3.00 | 3.21 | 3.37 | 2.96 |
| F4 | 3.77 | 0.43 | 0.57 | 0.49 | 5.17 | 4.27 | 4.91 | 3.90 |
| F3 | 6.97 | 0.74 | 1.06 | 0.48 | 7.06 | 5.57 | 5.80 | 5.61 |
| F2 | 13.69 | 81.84 | 100.00 | 88.41 | 14.31 | 7.59 | 7.59 | 7.94 |
| F1 | 21.25 | 43.57 | 75.13 | 44.48 | 23.99 | 10.20 | 9.84 | 9.36 |

| (c) Case N3 |     |    |    |    |    |    |    |
| F6 | 1.39 | 0.28 | 0.43 | 0.17 | 2.52 | 3.43 | 4.44 | 4.67 |
| F5 | 2.51 | 0.22 | 0.39 | 0.22 | 4.60 | 3.26 | 4.30 | 4.24 |
| F4 | 4.58 | 2.47 | 0.79 | 1.94 | 5.91 | 5.81 | 5.68 | 5.81 |
| F3 | 15.14 | 85.30 | 100.00 | 84.03 | 29.77 | 6.89 | 7.36 | 6.73 |
| F2 | 18.28 | 47.80 | 76.47 | 52.67 | 16.98 | 7.97 | 8.19 | 8.08 |
| F1 | 33.52 | 42.62 | 49.92 | 50.31 | 23.48 | 10.64 | 8.77 | 4.83 |

| (d) Case N4 |     |    |    |    |    |    |    |
| F6 | 6.39 | 1.55 | 5.64 | 4.34 | 6.58 | 5.65 | 6.25 | 6.62 |
| F5 | 11.94 | 8.54 | 19.25 | 11.12 | 12.34 | 6.53 | 6.39 | 6.97 |
| F4 | 37.19 | 90.79 | 100.00 | 92.96 | 47.11 | 8.11 | 6.95 | 7.41 |
| F3 | 19.76 | 55.09 | 81.08 | 66.32 | 19.84 | 7.26 | 8.05 | 8.51 |
| F2 | 11.83 | 41.90 | 51.99 | 37.12 | 14.97 | 7.97 | 7.71 | 7.57 |
| F1 | 11.37 | 17.55 | 28.70 | 24.69 | 10.33 | 6.45 | 7.87 | 7.72 |

| (e) Case N5 |     |    |    |    |    |    |    |
| F6 | 11.96 | 25.89 | 54.20 | 30.10 | 12.99 | 6.88 | 6.55 | 6.32 |
| F5 | 29.49 | 61.33 | 100.00 | 57.65 | 19.41 | 5.48 | 5.90 | 6.01 |
| F4 | 19.94 | 49.73 | 75.83 | 33.07 | 17.88 | 5.11 | 4.82 | 5.42 |
| F3 | 8.87 | 27.73 | 41.54 | 33.36 | 9.68 | 5.25 | 5.54 | 4.47 |
| F2 | 8.27 | 16.65 | 9.84 | 11.84 | 3.57 | 5.22 | 4.86 | 4.27 |
| F1 | 3.40 | 14.60 | 5.30 | 5.42 | 5.28 | 3.31 | 3.17 | 1.76 |

| (f) Case N6 |     |    |    |    |    |    |    |
| F6 | 49.67 | 47.05 | 100.00 | 53.22 | 51.33 | 7.76 | 7.31 | 6.97 |
| F5 | 3.61 | 0.58 | 4.87 | 0.52 | 5.16 | 4.36 | 4.05 | 5.10 |
| F4 | 1.49 | 0.38 | 1.19 | 0.36 | 2.49 | 2.85 | 4.41 | 3.35 |
| F3 | 1.47 | 0.38 | 0.75 | 0.36 | 1.44 | 2.33 | 2.82 | 2.81 |
| F2 | 0.68 | 0.34 | 0.65 | 0.36 | 0.79 | 1.95 | 1.77 | 1.59 |
| F1 | 0.61 | 0.35 | 0.47 | 0.36 | 0.64 | 0.58 | 1.16 | 0.63 |
| Fig. 7. Signal intensity and color level of normalized concentration, contaminant source location is UR column, Model A Single-sided ventilation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) |

| Normalized Concentration | 100.00 | 75.00 | 10.00 | 1.00 | 0.00 |
|--------------------------|--------|-------|-------|------|------|
| (a) Case N7             |        |       |       |      |      |
| F6                      | 1.53   | 1.81  | 0.07  | 0.03 | 1.82 |
| F5                      | 4.27   | 0.73  | 0.14  | 0.04 | 3.46 |
| F4                      | 7.18   | 0.55  | 0.15  | 0.03 | 3.73 |
| F3                      | 14.22  | 0.58  | 0.14  | 0.09 | 5.37 |
| F2                      | 27.63  | 0.75  | 0.12  | 0.06 | 10.35 |
| F1                      | 58.17  | 100.00| 0.46  | 0.14 | 13.41 |

| (b) Case N8             |        |       |       |      |      |
| F6                      | 2.89   | 0.99  | 0.03  | 0.03 | 2.06 |
| F5                      | 12.34  | 0.53  | 0.03  | 0.03 | 2.49 |
| F4                      | 17.13  | 0.46  | 0.05  | 0.03 | 5.35 |
| F3                      | 31.10  | 0.51  | 0.09  | 0.10 | 9.61 |
| F2                      | 49.01  | 100.00| 1.21  | 0.33 | 18.41 |
| F1                      | 54.05  | 69.02 | 0.31  | 0.11 | 9.98 |

| (c) Case N9             |        |       |       |      |      |
| F6                      | 6.25   | 0.40  | 0.04  | 0.04 | 1.16 |
| F5                      | 10.84  | 0.28  | 0.04  | 0.05 | 2.05 |
| F4                      | 36.18  | 1.05  | 0.03  | 0.04 | 3.84 |
| F3                      | 58.36  | 100.00| 1.65  | 0.23 | 6.59 |
| F2                      | 52.93  | 56.90 | 1.36  | 0.13 | 2.28 |
| F1                      | 21.33  | 7.93  | 0.79  | 0.51 | 1.45 |

| (d) Case N10            |        |       |       |      |      |
| F6                      | 16.05  | 0.94  | 0.10  | 0.03 | 4.00 |
| F5                      | 28.66  | 2.03  | 0.13  | 0.03 | 8.81 |
| F4                      | 39.27  | 100.00| 1.00  | 0.41 | 13.69 |
| F3                      | 25.32  | 86.94 | 0.52  | 0.18 | 11.93 |
| F2                      | 12.40  | 6.67  | 0.26  | 0.11 | 5.75 |
| F1                      | 5.48   | 1.34  | 0.19  | 0.03 | 2.05 |

| (e) Case N11            |        |       |       |      |      |
| F6                      | 35.21  | 18.29 | 0.07  | 0.03 | 9.54 |
| F5                      | 56.91  | 100.00| 0.61  | 0.22 | 49.19 |
| F4                      | 16.24  | 10.63 | 0.13  | 0.14 | 6.88 |
| F3                      | 3.79   | 1.37  | 0.04  | 0.05 | 3.42 |
| F2                      | 1.36   | 0.37  | 0.05  | 0.04 | 1.41 |
| F1                      | 0.47   | 0.17  | 0.06  | 0.07 | 0.83 |

| (f) Case N12            |        |       |       |      |      |
| F6                      | 55.91  | 100.00| 0.18  | 0.08 | 49.31 |
| F5                      | 10.44  | 6.31  | 0.13  | 0.07 | 7.43 |
| F4                      | 3.54   | 1.35  | 0.16  | 0.10 | 3.03 |
| F3                      | 1.00   | 0.75  | 0.13  | 0.14 | 1.78 |
| F2                      | 0.48   | 0.64  | 0.21  | 0.08 | 1.08 |
| F1                      | 0.41   | 0.38  | 0.10  | 0.10 | 0.65 |
the concentration values at other flats decreased with the distance from the releasing flat along the UR column. A sharp decrease of concentration was observed in the upward direction of UR column, while the concentration descended gradually by one order of magnitude for every lower vertical flat. On the leeward side, all of the concentrations were approximately one order of magnitude lower than the source floor, and their variation with floor and column was quite small. The signal intensity feature on the sideward façade was similar to the former case. For condition of Case N10 shown in Fig. 7(d), the tracer gas transmission route was analogous with Case N9.

The concentration distributions illustrated in Fig. 7(e) and (f) were alike, the concentrations could be divided into three groups according to the distribution characteristics. Group one includes the profiles of UR, CR and CL column with each summit point at the source floor. The values at other units decayed with the distance to the source floor. Group two refers to the concentration profile for the leeward units with almost all of the values falling in the range of 1–10. Group three covers the character of UM and UL column, which were least infected with most values were close to 0.1.

In general, when the pollutant was released from unit below the stagnation zone at the lateral column on the windward side, tracer gas was more likely to move vertically downward rather than upward or horizontally. Normally for windward units, only a part of them on UR column could be infected obviously. The tracer gas generated quite high concentrations at the corridor window horizontally closest to the source column. The CR column was more likely to be infected than CL column in most cases. For units on the leeward side, the situations were almost the same as that when source positions were at the windward middle column.

3.2.3. Source units on the windward façade of Model B

In our previous paper [38], the airflow patterns in Model B at a horizontal section under normal wind direction have been revealed. The wind blowing perpendicularly to the windward units straightly cross over the building through open windows and doors, generating several vortexes in the corridor and around the openings. So the tracer gas releasing from a certain windward unit mainly moves to the sideward and leeward testing points at the source floor, as shown in Fig. 8. Except for the source unit, the highest signal intensity normally appeared in the leeward unit immediately opposite to the source one.

| Normalized Concentration |
|--------------------------|
| ![Normalized Concentration Table](image) |

Fig. 8. Signal intensity and color level of normalized concentration, Model B Cross ventilation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
4. Conclusions

The inter-flat pollutant transmission characteristics in a rectangular multi-storey building with natural ventilation under wind effect were further explored by wind tunnel tests in the present work. The results revealed that the gaseous pollutant has the possibility to travel vertically and horizontally along the source façade and from upstream unit to downstream unit due to the wind effect. The pollutant dispersion routes are strongly affected by the source location.

The pressure coefficient distributions were measured to assist the interpretation of surface airflow patterns. The results showed that the stagnation zone in this building approximately formed around the fifth floor of middle column on the windward side. The mean tracer gas concentration distributions at different points of each façade were monitored to reveal the dispersion characteristics and compare the different performance among various cases with distinct source position. Generally, for cases with source positions at the windward middle column, the concentrations showed good symmetric features due to the geometric symmetry, the same tendency appeared as well for the pressure coefficient. In overall cases in single-sided ventilated building, the variation of concentration values on the leeward side with column was negligible, possibly due to the fluctuant wake flow of the building. The leeward units got high risks of infection because their concentrations approximate one order of magnitude lower than the source unit, and even higher than some windward units. Moreover, the concentration profile at the leeward side presented an approximate linear variation with the height in each single-sided case, and the concentration values in lower units were firstly higher than upper ones and then smaller than upper units as the source location changed from 1st floor to 6th floor. Besides, the concentrations on the sideward façades were also remarkable in most cases. Due to the pass-through airflow patterns in the cross ventilated building, the vertical transmission was suppressed and the horizontal spread was enhanced by this ventilation mode.

Exploring the wind driven pollutant dispersion routes within a building is helpful to design effective ventilation mode for the spread control of infection, atmospheric contaminants, hazardous gases, etc. The results obtained from current experiments could be used as a reference for the validation of numerical simulation. Nevertheless, the present work is still limited, which mainly focused on the wind induced inter-flat cross contamination phenomenon, without considering the buoyancy effect. The dispersion characteristics dominated by combined effects of wind and buoyancy could be more complicated and need to be investigated in the further study.

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References

[1] UNFPA, State of World Population 2007: unleashing the potential of urban growth.  http://www.unfpa.org/publications/state-world-population-2007-2007.
[2] J. Robinson, W.C. Nelson, National Human Activity Pattern Survey Data Base, USEPA, Research Triangle Park, NC, 1995.
[3] N.E. Klepeis, W.C. Nelson, W.R. Ott, et al., The National Human Activity Pattern Survey (NHAPS); a resource for assessing exposure to environmental pollutants, J. Expo. analysis Environ, Epidemiol. 11 (3) (2001) 231–252.
[4] R.J. Heinsohn, J.M. Cimbala, Indoor Air Quality Engineering: Environmental Health and Control of Indoor Pollutants, CRC Press, 2003.
[5] J. Sundell, On the history of indoor air quality and health, Indoor air 14 (5) (2004) 51–58.
[6] R.Z. Homod, K.S.M. Sahari, Energy savings by smart utilization of mechanical and natural ventilation for hybrid residential building model in passive climate, Energy Build. 60 (2013) 310–329.
[7] T. Schulze, U. Eicker, Controlled natural ventilation for energy efficient buildings, Energy Build. 56 (2013) 221–232.
[8] Y. Tominaga, T. Stathopoulos, Ten questions concerning modeling of near-field pollutant dispersion in the built environment, Build. Environ. 105 (2016) 305–322.
[9] Y. Li, C.M. Leung, J.W. Tang, et al., Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review, Indoor air 17 (1) (2007) 2–18.
[10] I. Eames, J.W. Tang, Y. Li, et al., Airborne transmission of disease in hospitals, J. R. Soc. Interface 6 (2009) S597–S602.
[11] M. Perino, Short-term airing by natural ventilation-modeling and control strategies, Indoor air 19 (5) (2009) 357–380.
[12] Y. Si, A.K. Skidmore, T. Wang, et al., Spatio-temporal dynamics of global H1N1 outbreaks match bird migration patterns, Geospatial Health 4 (1) (2009) 65–78.
[13] R. Tellier, Review of aerosol transmission of influenza A virus, Emerg. Infect. Dis. 12 (11) (2006) 1657–1662.
[14] J.W. Tang, Y. Li, I. Eames, et al., Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises, J. Hosp. Infect. 64 (2) (2006) 100–114.
[15] J.H. Wang, Y. Yu, Evidence of airborne transmission of the severe acute respiratory syndrome virus, N. Engl. J. Med. 350 (17) (2004) 1731–1739.
[16] K.H. Yeung, I.T.S. Yu, Possible meteorological influence on the severe acute respiratory syndrome (SARS) community outbreak at Amoy Gardens, Hong Kong, J. Environ. health 70 (3) (2007) 39–46.
[17] Y. Li, S. Duan, I.T.S. Yu, et al., Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens, Indoor Air 15 (2) (2005) 96–111.
[18] Niu J, Tung C, Wan J, et al. CFD Simulation of Interflat Air Flow for the Study of the Spread of Aerosol Transmitted Infectious Diseases. Proceedings of the 9th International IBPSA Conference, Montréal Canada, 2009: 853–857.
[19] J. Niu, C.W. Tung, On-site quantification of re-entry ratio of ventilation exhausts in multi-family residential buildings and implications, Indoor Air 18 (1) (2008) 12–26.
[20] N.P. Gao, J.L. Niu, M. Perino, et al., The airborne transmission of infection between flats in high-rise residential buildings: tracer gas simulation, Build. Environ. 43 (11) (2008) 1805–1817.
[21] X.P. Liu, J.L. Niu, M. Perino, et al., Numerical simulation of inter-flat air cross-contamination under the condition of single-side natural ventilation. J. Build. Perform. Simul. 1 (2) (2008) 133–147.
[22] Y. Wu, J.L. Niu, Assessment of mechanical exhaust in preventing vertical cross-household infections associated with single-sided ventilation, Build. Environ. 105 (2016) 307–316.
[23] X.P. Liu, J.L. Niu, K.C.S. Kwok, et al., Investigation of indoor air pollutant dispersion and cross-contamination around a typical high-rise residential building: wind tunnel tests, Build. Environ. 45 (8) (2010) 1769–1778.
[24] X.P. Liu, J.L. Niu, K.C.S. Kwok, et al., Local characteristics of cross-unit contamination around high-rise building due to wind effect: mean concentration and infection risk assessment, J. Hazard. Mater. 192 (1) (2011) 160–167.
[25] J.H. Wang, J.L. Niu, X.P. Liu, et al., Assessment of pollutant dispersion in the re-entrance space of a high-rise residential building, using wind tunnel simulations, Indoor Built Environ. 19 (19) (2010) 638–647.
[26] X.P. Liu, J.L. Niu, K.C.S. Kwok, Analysis of concentration fluctuations in gas dispersion around high-rise building for different incident wind directions, J. Hazard. Mater. 192 (3) (2011) 1623–1632.
[27] X. Liu, J. Niu, K.C.S. Kwok, Evaluation of RANS turbulence models for simulating wind-induced mean pressures and dispersions around a complex-shaped high-rise building, Build. Simul. 6 (2) (2013) 151–164.
[28] Z.H. Zhang, K.C.S. Kwok, et al., Characteristics of air pollutant dispersion around a high-rise building, Environ. Pollut. 204 (2015) 280–288.
[29] C.K.C. Cheng, K.M. Lam, Y.T.A. Leung, et al., Wind-induced natural ventilation of re-entrant bays in a high-rise building, J. Wind Eng. Industrial Aerodynamics 99 (23) (2011) 75–90.
[30] W.W. Yang, N.P. Gao, The transport of gaseous pollutants due to stack effect in high-rise residential buildings, Int. J. Vent. 14 (2) (2015) 191–208.
[31] J. Mao, W. Yang, N. Gao, The transport of gaseous pollutants due to stack and wind effect in high-rise residential buildings, Build. Environ. 94 (2015) 543–557.
[32] Z.T. Ai, C.M. Mak, J.L. Niu, Numerical investigation of wind-induced airflow and interunit dispersion characteristics in multi-story residential buildings, Indoor Air 23 (5) (2013) 401–425.
[33] Z.T. Ai, C.M. Mak, A study of interunit dispersion around multi-story buildings with single-sided ventilation under different wind directions, Atmos. Environ. 88 (5) (2014) 1–13.
[34] Z.T. Ai, C.M. Mak, Large eddy simulation of wind-induced interunit dispersion
around multistory buildings, Indoor Air 26 (2) (2016) 259–273.

[35] I. Mavroidis, R.F. Griffiths, D.J. Hall, Field and wind tunnel investigations of plume dispersion around single surface obstacles, Atmos. Environ. 37 (21) (2003) 2903–2918.

[36] I. Mavroidis, S. Andronopoulus, J.G. Bartzis, R.F. Griffiths, Atmospheric dispersion in the presence of a three-dimensional cubical obstacle: modelling of mean concentration and concentration fluctuations, Atmos. Environ. 41 (3) (2007) 2740–2756.

[37] M.F. Yassin, M. Ohba, H. Tanaka, Experimental study on flow and gaseous diffusion behind an isolated building, Environ. Monit. Assess. 147 (1–3) (2008) 149–158.

[38] Y. Tominaga, T. Stathopoulos, Numerical simulation of dispersion around an isolated cubic building: model evaluation of RANS and LES, Build. Environ. 45 (10) (2010) 2231–2239.

[39] D. Mu, N. Gao, T. Zhu, Wind tunnel tests of inter-flat pollutant transmission characteristics in a rectangular multi-storey residential building, part A: effect of wind direction, Build. Environ. 108 (2016) 159–170.

[40] AHRAE, ASHRAE Handbook, Fundamentals (SI), American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA, 2009. section 10.4.

[41] W.H. Snyder, Similarity criteria for the application of fluid models to the study of air pollution meteorology, Boundary-Layer Meteorol. 3 (1) (1972) 113–134.

[42] K. Uehara, S. Wakamatsu, R. Ooka, Studies on critical Reynolds number indices for wind-tunnel experiments on flow within urban areas, Boundary-Layer Meteorol. 107 (2) (2003) 353–370.

[43] R.N. Meroney, Wind Tunnel and Numerical Simulation of Pollution Dispersion: a Hybrid Approach, Invited Lecture, Croucher Advanced Study Institute on Wind Tunnel Modeling, Hong Kong University of Science and Technology, December, 2004.

[44] ASHRAE, ASHRAE Handbook, HVAC Applications, GA. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 2015. section 45.3.