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Wind tunnel tests of inter-flat pollutant transmission characteristics in a rectangular multi-storey residential building, part A: Effect of wind direction

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Abstract

The inter-flat dispersion of hazardous air pollutants in residential built environment has become a growing concern, especially in crowded urban areas. The purpose of present study is to investigate the wind induced air pollutant transmission and cross contamination routes in typical buildings. In this paper, a series of experiments was carried out in a boundary layer wind tunnel using a 1:30 scaled model that represented the typical configuration of rectangular multi-storey residential buildings in Shanghai. Sulfur hexafluoride (SF6) was employed as tracer gas in the wind tunnel tests. The conditions under two ventilation modes, i.e. single-sided natural ventilation and cross natural ventilation, were compared. The tracer gas concentration distributions under four approaching wind angles were monitored and analyzed. Computational Fluid Dynamics (CFD) method was adopted to assist in analyzing airflow patterns. The experiment results elucidated that in the two ventilation scenarios, both of the vertical and horizontal inter-flat airborne transmission could proceed. The wind direction played a key role on the pollutant concentration distribution. Compared with the single-sided ventilation mode, cross ventilation could weaken the air pollutant dispersion along the vertical direction when the contamination source was on the windward or on the leeward unit. When the wind blowing parallelly to the source unit window, namely the source room was on the sideward, cross ventilation would not suppress the vertical transport on one hand, but reinforce the horizontal transmission on the other hand. The study is helpful for the analysis of infection risk of respiratory diseases in the residential buildings.

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1. Introduction

During the past few decades, there have been increasing interests in the influences of poor indoor air quality (IAQ) on human health because people spend 80%–90% of their time in indoor space [1,2]. Moreover, the outbreaks of severe acute respiratory syndrome (SARS) [3], bird flu [4], influenza (H1N1 and H5N1) [4,5] and Middle East respiratory syndrome (MERS) [6] have attracted growing concerns on the airborne transmission within the surroundings of buildings, particularly in crowded urban areas. In order to establish effective indoor air pollution control strategies, it is quite beneficial to have a profound understanding of the mechanism and characteristics of airborne pollutant transmission and dispersion in and around buildings.

Many previous researches performed on the airflow and contaminant distributions around buildings have laid a good foundation for the study of pollutant transmission. Field tests [7–9], wind tunnel experiments [10–12] and computational fluid dynamics (CFD) methods [13–15] have been carried out on the investigations of contaminant dispersion in and near street canyons, building arrays and an isolated building. During the outbreak of SARS epidemic in Hong Kong, the inter-flat cross contamination was identified as an important airborne transmission path and started to be examined. Using CFD and multizone modeling, Yu and Li et al. [16,17] provided the identification of the airborne transmission of the SARS virus by analysing the distribution of infected cases in the Amoy Gardens in 2003. On this basis, on-site tracer gas measurements conducted by Niu and Tung [18] at Hong Kong primarily focused on the pollutant transmission path through windows dominated by buoyancy effect under single-sided natural ventilation, and they found out that the indoor air of the immediate upper unit contained up to 7% of the exhaust air from lower unit.
and concluded that the windows on the same façade can be a major route for the vertical spread of air contaminants. Gao et al. [19] numerically investigated the combined effect of wind and buoyancy on the airborne transmission of infection between flats. It was discovered that the wind blowing orthogonally to the building openings could either enhance or restrain the upward transport. Both of their studies only focused on the upward cross-contamination between two vertically adjacent flats. Later, wind tunnel studies performed by Liu et al. [20,21] and Wang et al. [22] explored the wind effect on the pollutant dispersion around cross (#) shape buildings. The experiment results illustrated that the pollutant could spread along both upward and downward direction in the re-entry space. Horizontal dispersion was also found by analysing the tracer gas concentration. It was stated that the dispersion characteristics can be affected by source location and wind directions. Their findings are limited to the complicated shape buildings with re-entry space. More recently, Ai et al. [23–25] numerically studied the wind induced inter-unit dispersion mechanism of gaseous pollutants in two five-storey hypothetical slab-like buildings. The tracer gas dispersion characteristics on the windward and leeward sides were revealed and compared with the cross (#) shape buildings. The results showed that the tracer gas had quite different dilution speeds in both horizontal and vertical directions for the two different shapes. Wu [26] carried out on-site measurement to investigate the internal spread route between horizontal adjacent units induced by air infiltration and found that the cross-infection risk through this route could be 9%, even higher than that through single-sided open windows. Wu [27] also made effort on the prevention of vertical cross-unit infections dominated by single-sided ventilation. Such inter-flat transmission cases through building façade openings with single-sided ventilation or by air infiltration have been paid attention to, while the transmission through internal openings under cross ventilation mode which was dominated by the wind effect as well is less studied.

Generally, in the residential buildings, one of the main purposes of cross natural ventilation is to dilute the hazardous air pollutants in order to improve the indoor air quality. Many studies have been conducted to reveal the cross ventilation flow patterns. However, there have been only several attempts to analyze the air pollutant distribution in cross ventilated buildings [28,29], and no systematic attempts to explore the inter-flat cross contamination in a building with cross ventilation.

In the present study, the inter-flat dispersion characteristics of pollutants within the building under the effect of natural ventilation were investigated. Both single-sided and cross ventilation mode were considered. A rectangular multi-storey residential building was set as the research object in wind tunnel tests. Tracer gas technique was adopted to simulate the gaseous pollutant or fine particles. Previous research [30–32] found that particles with sizes of 1–20 μm could suspend and spread in the air, small-size particles less than 1.0 μm transport like gaseous pollutants. The wind induced inter-flat spread of contamination has an inalienable relationship with the airflow patterns inside and around the building. Hence, different wind directions could lead to diverse pollutant concentration distributions. The approaching wind angle was set as one of the key factors in the experiments. The results will not only be helpful for respiratory disease control, but also be used in relative fields, such as dispersion of atmospheric pollutants, hazardous releases, flue gases, etc.

2. Methodology

2.1. Atmospheric boundary layer simulation

The experiment was carried out in the TJ-1 boundary layer wind tunnel in the State Key Laboratory of Civil Engineering for Disaster Prevention, Tongji University, China. The TJ-1 wind tunnel is a low-speed open-circuit one, so the background concentration can be constant at an ignorable value during the gas dispersion experiment. The dimension of the test chamber in this boundary layer wind tunnel is 12 m in length, 1.8 m in width and 1.8 m in height. The experimental settings are shown in Fig. 1.

The following power law was used as the velocity profile \( U(h) \) of atmospheric boundary layer

\[
U(h) = \frac{U_{ref}}{h^{\alpha}}
\]

where \( h \) is the height, \( h_{ref} \) is the reference height, which refers to the building model height, \( H_b \); \( U_{ref} \) is the mean velocity at the reference height, and \( \alpha \) is the power exponent, which is given as 0.22 for creating an urban terrain [33].

To obtain such a velocity profile, two spires, two grilles and eleven uniform arrays of roughness elements, including two rows of stone cubes and nine rows of wooden cubes, were arranged as shown in Fig. 1(a). The velocity profiles and turbulence intensities of the approaching wind were measured by the 3-D Cobra probe. The test data were real-time monitored by a computer. A Pitot-tube anemometer was used to examine the immediate wind velocity at building height, namely the characteristic velocity \( U_{ref} \). The vertical profile of the dimensionless mean velocity \( U/h_b \), i.e. \( U(h)/U_{ref} \) and measured turbulence intensity were presented in Fig. 2. The height was normalized as \( h/H_b \).

For a precise modeling of atmospheric airflows, a number of similarity requirements between the prototype and the scaled model must be examined carefully. Snyder [34] pointed out that five non-dimensional parameters, i.e. Rossby (Ro), Reynolds (Re), Schmidt (Sc), Peclet (Pe) and Froude (Fr) numbers should be paid attention to. However, it is impractical and impossible to duplicate all the non-dimensional parameters in wind tunnel tests. Some of these parameters can be ignored in view of their poor relative importance when simulating pollutant dispersion in and around buildings without thermal effect. The Reynolds number independence should be considered as in several previous publications [35]. Meroney [36] suggested that the wind speed in a laboratory should be high enough, so that the obstacle Reynolds number exceeds \( 1.5 \times 10^4 \). In this study, the building Reynolds number is defined as \( Re = U_{ref} H_b / \nu \), where \( \nu \) refers to kinematic viscosity and \( H_b \) is the building height, i.e. 0.59 m. The measured velocity \( U_{ref} \) was 2.89 m/s, and the corresponding Reynolds number was 1.15 \( \times 10^5 \), which was high enough to ensure the experiment results to be independent of the Reynolds number.

2.2. Experiment setup

Since the rectangular building is one of the most representative configurations of multi-storey residential buildings in Shanghai, China, a 1:30 scaled hypothetical model was built by considering both the blockage ratio in the wind tunnel and the capability to capture the airflow patterns and tracer gas dispersion behavior. The building contains six floors and each floor contains a corridor with three rooms at each hand. All rooms are the same dimensions with length \( x \) \times height \( y \) \times width \( z \) = 3.0 m \times 2.9 m \times 3.6 m and the window \( \text{dimension of each room is height}(y) \times \text{width}(z) = 1.5 m \times 1.5 m \). Besides, the dimension of windows on either side of the corridor is width \( x \) \times height \( y \) = 0.9 m \times 1.5 m. The bottom of window frame is 0.9 m above the room floor. These sizes were according to the common settings in real residential buildings in Shanghai. All the
building dimensions are shown in Fig. 3. Geometric similarity was satisfied and the blockage ratio was 5.46%.

Given that the influence of natural ventilation modes and approaching wind directions on the wind-induced inter-flat pollutant dispersion phenomena, eight cases were designed, as listed in Table 1. Two common natural ventilation modes, single-sided and cross ventilation, were considered. Model A referred to single-sided ventilation with all windows open and doors closed, while all windows and doors were open in Model B forming cross ventilation. The approaching wind direction, $\beta$, was defined as the angle between the wind direction and coordinate axis $z$ of the building plan, as shown in Fig. 4. In the present study, the pollutant dispersion characteristics under four wind directions were investigated, $\beta = 0^\circ$, $\beta = 45^\circ$, $\beta = 90^\circ$ and $\beta = 180^\circ$ respectively (see Fig. 4).

To explore the inter-flat pollutant dispersion features, the tracer gas sulfur hexafluoride (SF$_6$) was used to simulate the pollutant. The release and detection of SF$_6$ were separately controlled by INNOVA 1303 and 1412i, manufactured by LumaSense Technologies, Inc. The releasing and sampling were through Teflon tubes with an inner diameter of 3 mm, while the dosing outlet was using a tube with an inner diameter of 6 mm. The tracer gas was emitted
at a constant flow rate of 15 ml/s, corresponding to a releasing velocity \( U_s \) of 0.53 m/s, thus the releasing velocity ratio \( U_s/U_{ref} \) was 0.18 during a series of concentration tests. The pollutant source location was set at the third floor of UR column. The concentration measuring points were located at the middle of all windows’ lower frame, as shown in Fig. 4(b). For each measuring point, the sampling time interval was 180s. For each case, the experiments were repeated three times to obtain the mean concentration value.

The accuracy of instrument mentioned above is listed in Table 2. For the analysis and comparisons of pollutant concentrations, the measured tracer gas concentration was non-dimensionalized by the following equation,

\[
K = \frac{C U_{ref} H^2}{Q_s}
\]  

(2)

where \( K \) refers to the dimensionless concentration, \( C \) is the measured tracer gas mean concentration of SF6 and \( Q_s \) is the tracer gas volumetric flow rate. The dimensionless index implies the absolute differences of tracer gas concentrations under different experiment conditions.

2.3. Simulation of the airflow patterns

The surface airflow patterns for a solid rectangular building have been given by ASHRAE [37], as shown in Fig. 5. For cases under normal wind direction, on the windward side (Fig. 5(a)), the airflow pattern generally contains an upwash region, a stagnation zone, a downwash region and an upwind vortex near the ground. The stagnation zone is at about 1/2 to 2/3 of the building height, and the outflowing air from the stagnation area spreads to all around. On the leeward side (Fig. 5(b)), a large recirculation flow along the building height and a small vortex at the bottom corner are formed. On the sideward (Fig. 5(c)), the flow pattern comprises a reverse flow, a fluctuating reattachment flow and a sweeping flow. Under the condition of oblique wind direction, on the windward façade.
The air flow pattern is fairly characterized by a distinct upstream-to-downstream sweeping flow. On the lower 2/3 to 1/4 of the building upwind façade, the surface air flow has a downward velocity component. On the leeward façade (Fig. 5(e)), the airflow pattern is mainly formed by the integration of an upwash flow, a horizontal downstream-to-upstream reverse flow and sometimes a slight reattachment flow. Since the building openings, such as windows and doors, could affect the stream patterns in and around the building to some extent, in present wind tunnel experiments the building model includes windows and doors to take the internal airflows into account.

To assist the analysis of the experimental data, a small portion of

| Measure object     | Instrument                                      | Accuracy |
|--------------------|-------------------------------------------------|----------|
| Velocity           | 3-D Cobra probe                                 | ±0.5 m/s |
| Reference velocity | Pitot-tube and Micro-manometer (DMP301N22)      | ±0.1 Pa  |
| SF6 concentration  | INNOVA 1303 and 1412i, 7620 software            | ±2%      |

* For the reference velocity, the corresponding accuracy in “m/s” is ±0.03 m/s.

Fig. 5. Surface flow patterns around a rectangular building for normal and oblique winds. (Mainly from ASHRAE Handbook, 2015, Section 45.3).

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numerical simulation was carried out to reveal the visualized airflow patterns in and around the building. The CFD method was employed by using a commercial program, Fluent 14.5. The computational domain is shown in Fig. 6. The dimension sizes of height and width were the same with wind tunnel. A mesh system with $3.6 \times 10^6$ grids was used. The renormalization group (RNG) $k-\varepsilon$ model was adopted to simulate the turbulent effect. The standard wall function was used with $30 < y^+ < 60$. The approaching wind profile obtained from the experiment was used as numerical inflow condition. To validate the reliability of simulation results, the mean
velocity distributions along four vertical lines in single-sided ventilation building under normal wind direction are shown in Fig. 7. It can be seen that the present setting for CFD method is accurate enough to predict the air flow around the building model, except for the reverse flow above the building roof and the downstream wake flow. According to a large number of researches on the comparisons and verifications of CFD results from Architectural Institute of Japan [38, 39], despite the inaccuracies of RNG k-ε model in predicting the vortex-shedding effects especially in the building wake, the detailed and overall spatial flow patterns obtained by RNG k-ε model can be identified and as a reference qualitatively.

3. Results and discussion

3.1. Tracer gas concentration distributions under 0° wind direction

Fig. 8 shows the normalized concentration in Model A and Model B at all measuring points under normal wind direction (β = 0°) when the source location was in the third floor of UR column, which was the side column on the windward side and below the stagnation zone.

Fig. 8(a) shows the tracer gas dispersion in Model A. There's no doubt that the highest normalized concentration value appeared at the source unit, which was between 10^1 and 10^2. On the windward façade, 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 vertical direction of UR column, while the concentration descended slowly for lower flats. The concentrations along the other two columns were also very low, which were two orders of magnitude lower than that in the source flat. The results indicated that the tracer gas was more likely to move vertically downward rather than upward or horizontally, according with the qualitatively consistent air flow patterns shown in Figs. 5 and 9(a). On the leeward façade, all of the concentration values were only one order of magnitude lower than the source floor, and their variation with floor and column was negligible. Besides, tracer gas generated quite high concentrations at the corridor window horizontally closest to the source column. For leeward and sideward surfaces, due to the fluctuating stream and reverse flow near the façades, the tracer gas could not easily be evacuated, resulting in high risks of being contaminated at these points.

Fig. 8(b) gives the tracer gas dispersion characteristics in Model B. The situation was obviously different from Model A. Most of the flats at the third floor got remarkable tracer gas concentrations, while the concentration at other floors rapidly decayed to a weak level, below 10^-1. Therefore, in the vertical direction, the concentration profile shows a symmetrical shape. The concentrations were at the same order of magnitude with or only one order of magnitude lower than that in the same floor of UR column, except unit UM3rd and UL3rd. In cross natural ventilation mode under normal wind direction, the air flow patterns were more complicated if compared with Model A, especially in the indoor space and on the leeward side of the building. The airflow directly passed through windows and doors of the units, forming several vortexes in the corridor and on the leeward side around the openings, as shown in Fig. 9(b). Consequently, the tracer gas released from UR3rd is mainly transported to the inner space of Model B at the third floor. Contributing to the vortexes in the corridor and near the downwind windows, the tracer gas dispersed to leeward flats, leading to high concentration levels. The results indicated that the vertical inter-
3.2. Tracer gas concentration distributions under 45° wind direction

Fig. 10(a) illustrates the normalized concentration in Model A at all measuring points under oblique wind direction. On the windward façade, the tracer gas concentrations at each floor were at the same magnitude level for column UR, UM, and UL. This implied that the tracer gas tended to quickly move in the horizontal direction from UR to UM and UL column, namely from upstream to downstream, which was quite different from the distribution feature under normal wind direction (as shown in Fig. 8(a)). Along the vertical direction, the tracer gas concentrations at the lower flats were generally higher than those in the upper flats, caused by the downwash flow in the front of the building (see the qualitatively similar airflow in Figs. 5 and 11(a1)). For flats on the leeward façade, the concentrations were only one order of magnitude lower than that in the source flat as well, and again they seemed to be not sensitive to the height. It should be noticed that the leeward concentration level was significant even compared with the windward concentration. Especially for the floor 4, 5, and 6, the concentration was higher than the one in the corresponding windward floor. It was interesting that the concentration at CR and CL was lower than that at the three leeward columns although they were closer to the pollutant source. As shown in Fig. 11(a2), the air moved along the wall surface of CR, UR, UM, and UL and then detached at the building edges. Next the air from “U” side reattached at the downstream part of “CL” side and then flowed to “D” side. So the pollutant released from UR3rd unit would not tend to move to CR and CL column, but rather spread to “D” side with the reverse flow.

The tracer gas dispersion in Model B under oblique wind direction is given by Fig. 10(b). The normalized concentration varied in a similar way with that in Fig. 8(b). The tracer gas mainly spread at the source floor along the flow direction. The cross-
contamination risks for flats at other floors were not so significant. The concentrations of different unit were almost the same except UM and UL column. According to the stream flow direction as shown in Fig. 11(b), the tracer gas released from the windward façade was transported to the indoor space and corridor, and then spread to the leeward flats, showing a path of UR→corridor→DR, DM and DL. Therefore, the flats located at the column of UM and UL were rarely affected. The contamination risks of downwind flats were slightly higher than those in Fig. 8(b) where the wind direction was 0°.

3.3. Tracer gas concentration distributions under 90° wind direction

For conditions when the wind direction was 90°, the tracer gas normalized concentrations were shown in Fig. 12. The pollutant source unit was located at one of the side façades of the building. The corridor windows lined on the windward side and leeward side separately, as shown in Fig. 13.

For the single-sided ventilation case, the concentrations in Fig. 12(a) could be divided into three levels. Columns UR, UM, and UL had a high concentration level. The windows at CL and CR had the lowest concentration level while columns DR, DL, and DM had a medium one. On the other hand, the concentration in every column is not susceptible to the height, especially the "D" and "C" sides. Fig. 13(a) suggests the airflow patterns at the source location height in Model A. A reverse flow from downstream to upstream along the side façade was observed. According to such a flow direction, if the tracer gas was released from UR3rd unit, there should be a small chance for the tracer gas to be transported to UM and UL flats. However, the experimental data proved that due to the diffusion effect, velocity fluctuation, and the large circulation at the side façade, all the flats on the source façade were affected evidently. For the units at the opposite side to the source unit, the concentrations were almost lowered by one order of magnitude. It might be contributed to the reverse flow from leeward area to side area. Since CR column was on the windward side and CL was on the leeward side, the approaching wind blew from CR to CL through the corridors, the tracer gas released from side façades could hardly be monitored at these two columns.

Fig. 12(b) shows the normalized concentration in Model B. Except for the CR column on the windward side, it is found that most of measuring points got a high normalized concentration level, especially the units located at the third floor. In each column, the concentration values at other flats decreased with the distance from the releasing floor. The profile showed a mountain shape as
well. The airflow patterns were similar to Model A, as shown in Fig. 13(b). The flow tended to fluctuate and formed small vortexes around the openings in the experiment, while the numerical simulation could only give a steady flow result. As a consequence of the fluctuating flow in the corridor, the tracer gas might spread from “U” side to “D” side through opened doors. Moreover, column CL on the leeward side was also affected.

3.4. Tracer gas concentration distributions under 180° wind direction

If the wind direction was 180°, the “U” façade was on the leeward side while “D” façade on the windward side. It was in contrast to the scenario under β = 0°. For the airflow patterns in and around the building readers can refer to Fig. 9.

As shown in Fig. 14(a), in the single-sided natural ventilation building, the normalized concentrations in the flats on the windward side were generally lower than 10⁻¹, which were two to three orders of magnitude lower than the source level. On the leeward side, the measuring point at the source unit got the highest concentration. Both vertical and horizontal cross contamination phenomena could be observed, resulting from the fluctuating flow and vortexes around the openings. The concentrations in the vertically adjacent units were higher than those in the horizontally adjacent units. As a consequence of reverse flow from the leeward façade to the side façades, the sampling concentrations located at the corridor windows were as high as that in column “U”.

For cross natural ventilation as illustrated in Fig. 14(b), it is observed that the concentrations were mostly lower than 10⁻¹, the highest value was still the source unit. The mountain shape of the vertical concentration profile is not obvious, except the column UR. The flats on the windward side could be considered as relatively safe, the same as in Model A. The side façade adjacent to the source unit
the air pollutants was released from a specific unit of the building model. The results indicated that under both single-sided and cross natural ventilation modes, the gaseous pollutant has the feasibility to travel vertically and horizontally in the building due to the wind effect. Since the airflow patterns around and inside the building are unsteady and the pollutant dispersion paths. However, it should be noticed that during the experiments, the approaching stream was inherently unsteady and the flow patterns were fluctuant, so there was deviation between steady numerical flow field and real flow field.

After all, exploring the pollutant transmission routes under wind effect in a building is helpful to design effective ventilation modes for the control of respiratory infectious diseases. The proper opening locations in the building could be adopted for the prevention of cross-contamination and optimization of ventilation strategies. Moreover, the investigation method could be used to predict the transmission of atmospheric contaminants, hazardous gases, etc. Besides, the present work paid attention to the steady wind-induced inter-flat cross contamination phenomenon by using the mean concentration, without considering the effect of inherent fluctuation of concentrations in natural ventilation. The unsteady dispersion characteristics could be more complex and worth of further investigations.

4. Conclusions

In the present study, the inter-flat pollutant dispersion characteristics in a rectangular multi-storey building under wind effect were explored by wind tunnel tests. The tracer gas used to simulate the air pollutants was released from a specific unit of the building model. The results indicated that under both single-sided and cross natural ventilation modes, the gaseous pollutant has the feasibility to travel vertically and horizontally in the building due to the wind effect. Since the airflow patterns around and inside the building are quite sensitive to the approaching wind angle, the pollutant dispersion routes are strongly affected by the wind direction. The mean tracer gas concentrations at different points of each façade were monitored to reveal the dispersion characteristics and compare the performances of the two kinds of natural ventilation modes. It is obvious that in single-sided natural ventilation, the dispersion behavior can occur in both vertical and horizontal direction no matter what the approaching wind angle was. However, in the cross natural ventilation, when the wind direction was 0°, 45° or 180°, the potential risk of inter-flat cross-contamination between vertical nearby units could be reduced, while the horizontal adjacent units got higher probability of being infected. In addition, the worst case appeared in the cross ventilated building when the wind direction was 90°. In addition, under normal and oblique wind directions, for cases in single-sided ventilation building, the concentrations of the leeward units were generally only one order of magnitude lower than the source unit, while for cases in cross ventilation building, the concentrations of infection units along the horizontal direction were at the same order of magnitude with or only one order of magnitude lower than the source floor.

The steady flow patterns reflected by the numerical simulation could be a qualitative reference to help analysing the gaseous pollutant dispersion paths. However, it should be noticed that during the experiments, the approaching stream was inherently unsteady and the flow patterns were fluctuant, so there was deviation between steady numerical flow field and real flow field.

After all, exploring the pollutant transmission routes under wind effect in a building is helpful to design effective ventilation modes for the control of respiratory infectious diseases. The proper opening locations in the building could be adopted for the prevention of cross-contamination and optimization of ventilation strategies. Moreover, the investigation method could be used to predict the transmission of atmospheric contaminants, hazardous gases, etc. Besides, the present work paid attention to the steady wind-induced inter-flat cross contamination phenomenon by using the mean concentration, without considering the effect of inherent fluctuation of concentrations in natural ventilation. The unsteady dispersion characteristics could be more complex and worth of further investigations.

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