buildings have laid a good foundation for the study of vertical transmission. However, studies on inter-flat interaction are limited. On-site tracer gas measurements carried out by Niu and Tung(2008) studied the buoyancy-driven transmission path of single-sided natural ventilation through openings, they discovered that the indoor air of upstairs room contained up to 7% of exhaust air directly from downstairs room and concluded that the windows flushed with a flat façade can be a major route for vertical spread of air pollutants. Gao et al.(2008) numerically investigated the combined effect of wind and buoyancy on the airborne transmission of infection between flats. The study discovered that wind blowing perpendicularly to the building could either reinforce or suppress the upward transport. Wind tunnel studies by Liu et al.(2010) and Wang et al.(2010) illustrated that the pollutant vertical dispersion can be influenced by wind directions and source location. Studies above didn't focus on the airflow vertical transmission driven by both wind and buoyancy in high-rise residential buildings with single-sided natural ventilation, which is numerically analyzed in this study.

RESEARCH METHODS

The computational fluid dynamics (CFD) method is employed in this study by using a commercial program, Fluent. The turbulent effect is simulated by the renormalization group (RNG) k-ε model (Gao et al. 2008). In order to study the combined effect of wind and buoyancy via open windows in a high-rise residential building, a ten-story hypothetical model is constructed. The room dimension is height(y) × length(x) × width(z) = 3.0m × 4.5m × 3.6m and the window dimension of each floor is height(y) × width(z)=1.5m ×1.8m. The window bottom is 0.9m above the room floor (Figure 1). This treatment is based on the common configuration of bedrooms in residential buildings in Shanghai, due to the fact that single-sided ventilation through closed door and open window is generally adopted in bedrooms. To simplify the calculation, the influence of other rooms is disregarded.

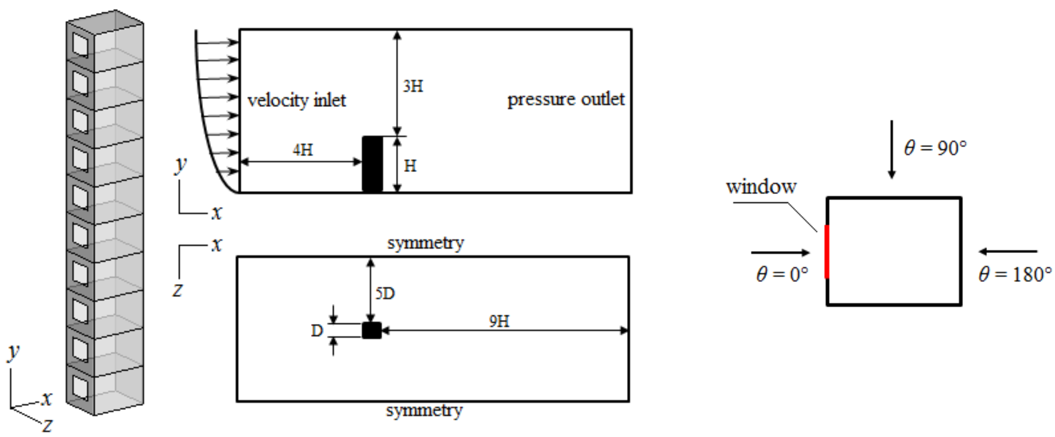


Figure 1. *Geometry of the building model and the computational domain*

The building model is placed in a computational domain, as shown in Figure 1. This domain is large enough to generally avoid the intervention of physical boundaries according to the experiences by previous works (Jiang et al. 2003 and Allocca et al. 2003). As to the buoyancy effect, heat is released from the internal walls of each floor. The outdoor temperature is 20℃ while the indoor wall surface temperature is 25℃. Based on researches of Niu and Tung (2008) and Gao et al. (2008), for current building configurations and an indoor-outdoor temperature difference of 5℃, the wind force with a speed as low as 0.16 m/s is comparable with buoyancy force. Previous measurements (Georgakis and Santamouris 2006) illustrate that the most common range of wind speeds in urban environment is 1.0 to 2.0 m/s. Therefore, four reference wind speeds, U_{ref}, at 10m above the ground level, at 0.1, 0.5, 1.0 and 2.0 m/s is considered. The wind profile at the inlet of the computational domain in urban environment is determined by the following equation (Gao et al. 2008):

$$U_y = 0.35 U_{ref} y^{0.25} \tag{1}$$

Three different wind directions θ are considered in this simulation, which are 0°, 90°and 180°, respectively. The tracer gas propane as pollutant is released at a rate of 8 mg/s in the center of the source floor and the concentrations in each flat are checked when solution is converged. At each wind speed and wind direction, tracer gas is generated at three different flats, separately at the 3rd floor, the 5th floor and the 8th floor, to respectively represent the low, middle and high layers of the building model. Considering all the wind conditions and source locations above, a total of twenty-one typical and practical cases are conducted.

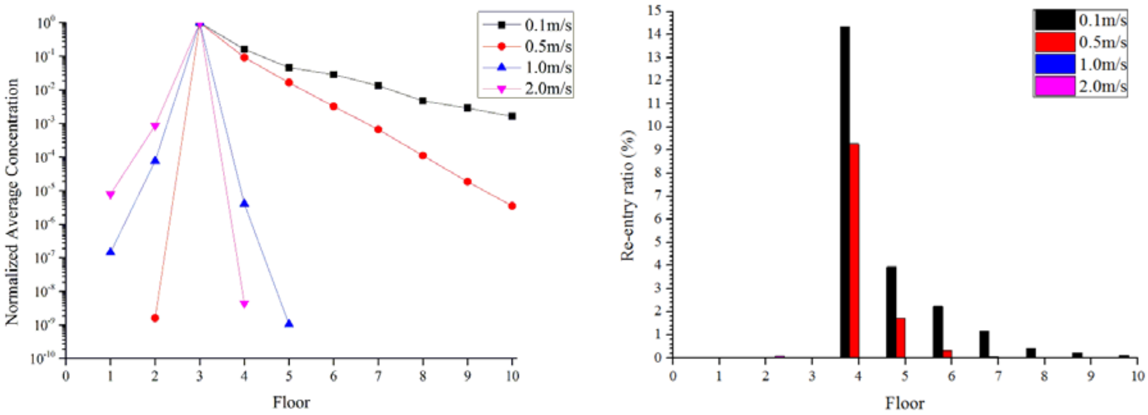
In order to evaluate the inter-flat cross-contamination risk, the reentry ratio K_{re} proposed by Niu and Tung (2008) is used. It is defined as the fraction of the exhaust air from the source flat i which re-enters another flat j. The calculated equation of K_{re} is as following:

$$K_{re} = M_{i-j} \frac{V_j (\mathrm{ACH})_j}{V_i (\mathrm{ACH})_i} \tag{2}$$

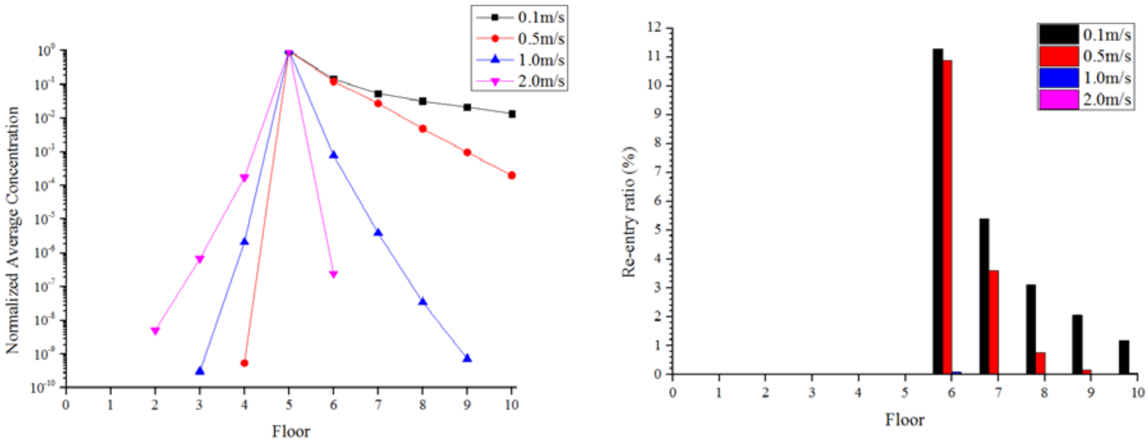
Where V_i and V_j are the flat volumes, which are the same for all rooms. M_{i-j} is the mass fraction of air that originates from the source flat i and is present in another flat j, which can be calculated directly from the average concentrations of the tracer gas in two flats, $M_{i-j} = C_j/C_i$. $(\mathrm{ACH})_i$ and $(\mathrm{ACH})_j$ are the air change rates per hour, which can be carried out by an integral method (Jiang et al. 2003), $\mathrm{ACH} = \left(0.5\int_0^A |U_x| \, dA\right) / V$, where A is the opening area and U is the wind velocity.

RESULTS AND DISCUSSION

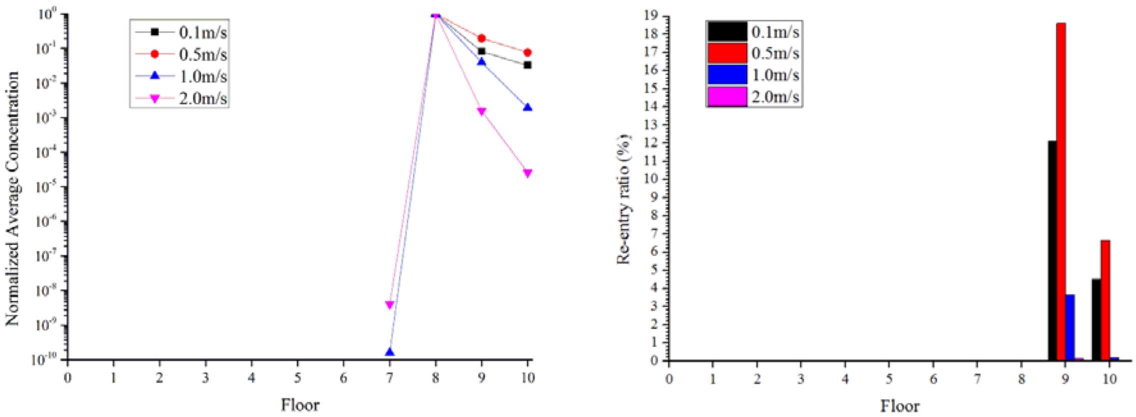
Tracer gas dispersion under different wind speeds



Source location is 3rd floor



Source location is 5th floor



Source location is 8th floor

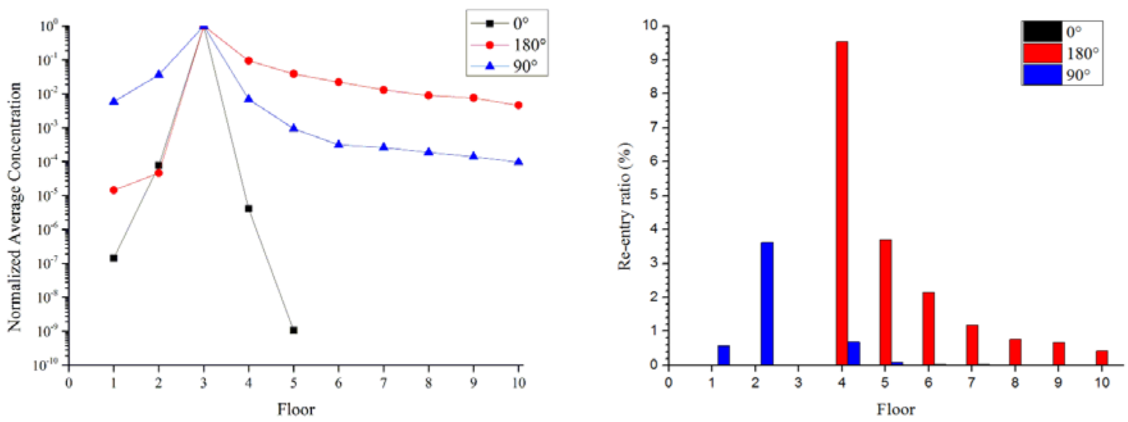
Figure 2. *Normalized average concentration ($M_{i\text{-}j}$) and reentry ratio (%) when the window openings at the windward side*

Tracer gas concentration distributions under different wind speeds are compared on the windward side. When wind is blowing normally to the upwind wall, the airflow divides into upward flow and downward flow, meanwhile a stagnation zone is formed at about two-thirds height of the building (ASHRAE 2007), which is located at the 7th floor in this study.

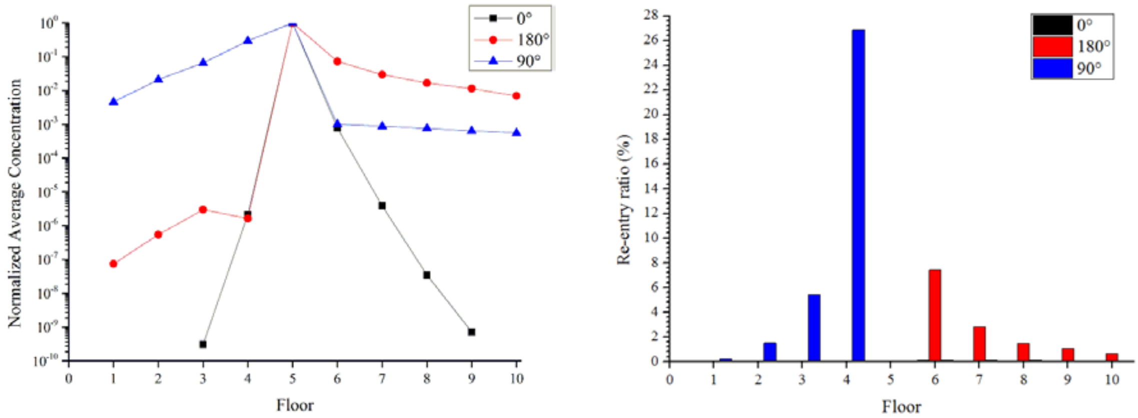
$M_{i\text{-}j}$ can be seemed as the normalized average concentration, only those greater than 10^{-10} are shown in Figure 2. At a quite low wind speed of 0.1m/s, which can be seen as pure buoyancy effect condition, for floors above the source floor, the average concentration of tracer gas in the lower flat is 1.5~6.1 times that in the immediate upper flat. The reentry ratios in the direct upper flat of the source floor are 14.3%, 11.3% and 12.1%, respectively, considering of different source locations from low layer to high layer. While at a wind speed of 0.5m/s, in the case that tracer gas is released from the 3rd floor or the 5th floor, for flats above the source floor, the average concentration of tracer gas in the upper flat is lower by almost one order of magnitude than that in the immediate lower floor. This is because that when the source floor is below the stagnation zone, the upward transmission driven by buoyancy lift could be weakened by the downward flow. The dispersion to upper flats can be totally decreased, which results in lower reentry ratios than those under pure buoyancy effect. However, when the source location is 8th floor, the upward flow driven by both wind force and buoyancy lift can effectively enhance the tracer gas dispersion between flats, and the highest reentry ratio on windward side in present study shows, which is 18.6%. When the wind speed is up to 1.0m/s，the upward spread is significantly restrained since that the wind and buoyancy effects offset each other, and the wind force can be even over the buoyancy lift.

It should not be neglected that with the increase of wind speed, the downward cross-contamination trend is more and more obvious resulting from that the effect of near-wall downward airflow below the stagnation zone is getting stronger step by step.

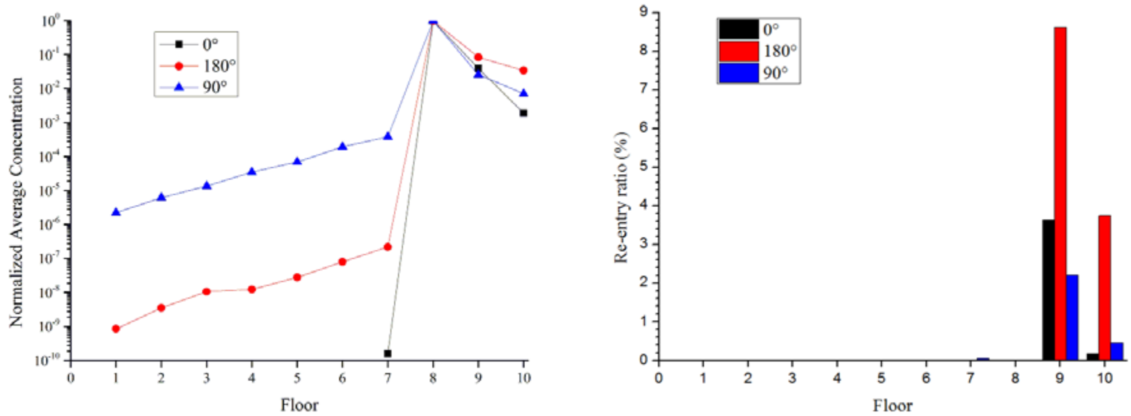
Tracer gas dispersion under different wind directions



Source location is 3rd floor



Source location is 5th floor



Source location is 8th floor

Figure 3. *Normalized average concentration ($M_{i\text{-}j}$) and reentry ratio (%) at the different wind directions with a constant speed of 1.0 m/s*

A wind speed of 1.0m/s is employed in the comparison of tracer gas dispersion under different wind directions. It is observed that when the wind direction θ is 90° or 180°, all flats except the source flat are influenced more distinctly than that is 0°, wherever the source location is (see Figure 3). It should be paid attention that, at a wind direction of 90°, which is parallel to the window façade, floors below the source flat can be more affected than that under the condition of 180°, while the tendency of floors above the source flat is on the contrary.

Firstly, when the wind direction is 180°, the open window façade is on the leeward side. The downstream airflow pattern contains two vortexes (ASHRAE 2007), in present study namely a large vortex from the third floor to the top and a small vortex across the lowest two flats. The large vortex could reinforce the tracer gas upward dilution to some extend on the base of buoyancy effect. Since the source locations are all above the third floor in this research, the upward cross-contamination could be obvious under this wind condition. The high reentry ratios of flats above the source floor cannot be ignored (see the reentry ratio columns in Figure 3), which imply a high infection risk. The small bottom vortex could contribute to the downward

dispersion to the lowest two floors, as the normalized average concentration shown in Figure 3, the concentration levels discrepancy between the bottom two floors are no more than an order of magnitude.
Secondly, when the wind direction is 90°, the downward cross-contamination risk is relatively high. Even a reentry ratio up to 26.8% is examined in the fourth floor when the source is located at 5^{th} floor. For flats below the source floor, generally the difference of the concentration levels is only several times. Meanwhile, the infection of upper floors above the source floor also cannot be neglected. These results are supported by Liu et al.'s (2010) wind tunnel experiments. In this wind condition, the wind flows from the upstream directly travels to the downstream, the air inside has little exchange with outside in the direction normal to open window. The dispersion of pollutant is intensive due to the natural diffusion. As a consequence, the serious cross-contamination happens.

CONCLUSIONS

This study has numerically examined the inter-flat pollutant dispersion routes in a high rise residential building using CFD method. The cross-contamination risk has been quantified by reentry ratio. The conclusions are listed as following:

1. Under single-sided open-window natural ventilation conditions with combine effect of wind force and buoyancy lift, the pollutant could spread both upward and downward between flats. The flat immediately above or below the source floor is generally the most vulnerable to infections.
2. The dispersion route is responsive to the wind condition and source location. The wind condition can decide different combined effects of wind force and buoyancy force and the source location can impact on the infection risks of other flats.
3. On the leeward side, flats above the source floor are quite susceptible. High infection risks, especially the unignorable downward transmission, also show under a wind direction of 90°.

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