Respiratory infectious diseases transmission in high-rise residential environment: abridged secondary publication

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KEY MESSAGES

1. Characteristics of two possible airborne infection transmission routes—intra-building transmission and cross-building transmission—were investigated in high-rise residential environments.
2. Infection risks and their factors associated with the two transmission routes were assessed.
3. A reliable computational fluid dynamics model was developed for predicting the air movement and pollutant dispersion in high-rise residential environments.

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Introduction

Airborne transmission may be responsible for the spread of various respiratory infectious diseases.[1,2] Identifying possible airborne transmission routes and their infection risks are essential for formulating effective control strategies. In a hospital environment, or in an enclosed environment such as an aircraft cabin, relevant guidelines to prevent cross-infection have been provided. However, in densely populated high-rise residential environments, the mechanism of airborne spread routes and the related risk levels are lacking.

In 2003, an outbreak of severe acute respiratory syndrome (SARS) in the Amoy Gardens estate, Hong Kong, infected 321 residents in a period of weeks. Epidemiological examination revealed that both intra-building spread and cross-building spread had occurred. Windows flush with the façade can be a major route for vertical upward spread of pathogen-containing aerosols under the buoyancy effect.[3-5] We aimed to identify possible horizontal transmission mechanisms in high-rise residential buildings under the wind effect.

Methods

From March to May 2015, on-site measurements were carried out to investigate intra-building transmission in three horizontal adjacent units on the same floor of a slab-type 16-story public housing block in Pak Tin Estate, Hong Kong (Fig 1). Four measurement scenarios were carried out: closed window mode, open window mode, corridor dosing mode, and 2-room mode. In closed window mode, all the doors and windows in the three flats were closed, which is in conformity with the occupant behaviour in cool seasons. In open window mode, the windows on external facades and on the partitions were open at an angle of 45°, which conforms to the occupant behaviour in warm seasons. For corridor dosing mode and 2-room mode, the tracer gas dosing locations were in corridor to investigate the transmission characteristics in the semi-open corridor.

Dual tracers SF_6 and CO_2 were used at low concentrations. SF_6 was used as tracer for pollutant dispersion analysis, whereas monitored CO_2 concentrations were used to calculate the ventilation rates. B&K Multi-gas Monitor 1302 and B&K Multipoint Sampler and Doser 1303 were used for SF_6 dosing and sampling. The CO_2 concentrations were monitored in three units using two sets of TSI Q-Trak and one set of Telaire CO_2 Sensor. The wind conditions on the roof were measured at the same time using Young UVW Anemometers.

Computational fluid dynamics simulation program FLUENT was used to model the cross-building tracer gas dispersion. To accurately reproduce the unsteady vortex shedding flows downstream of building blocks, great efforts were made in evaluating and validating the turbulence models, and the unsteady RANS (URANS) RNG k-ε model and delayed discrete-event simulation turbulence model were compared. In particular, the Strouhal number of the vortex shedding behind the building group predicted by the URANS model is in the range of 0.02 to 0.03, whereas the value predicted by discrete-event simulation model is approximately 0.15, which is more consistent with the value reported in the literature. Thus, the discrete-event

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simulation model is more accurate than the URANS model in reproducing the vortex shedding frequency in the wake region of the building group.

A geometry model of a building array with seven cross-type building blocks was built, based on the detailed structures of Amoy Gardens. The computational domain was large enough so that the blockage ratio was <3% as recommended in the Architectural Institute of Japan guidelines. The inflow boundary conditions were determined based on the site wind environment near the Amoy Gardens, available from the *Consultancy Study on Establishment of Simulated Site Wind Availability Data for Air Ventilation Assessments in Hong Kong.*

Results

The daily mean concentrations and concentration profiles of SF_6 in one sampling day for each measurement scenario are presented in Fig 2. All concentrations at the monitored points P-1 to P-6 increased exponentially after the start-up of dosing but reached equilibrium within 1.5 hours. The SF_6 concentrations in the receptor units were about one order lower than that in the index unit in both closed window mode and open window mode.

The simulated cross-building transmission characteristics of tracer gas are presented in Fig 3. The tracer gas was released from the window of a unit on the 16th floor facing the semi-open re-entrance space. The concentration decreased by one order of magnitude at the adjacent floors. On the more upper part of the re-entrance space, the concentration decreased by two orders of magnitude. The tracer gas then dispersed downstream following the prevailing wind. The tracer gas concentrations around blocks A and B, which were situated exactly downstream of the index unit building, were four orders lower than the source room concentration but relatively higher than those around the lateral blocks.

Discussion

The intra-building transmission route of the tracer gas from the index unit to receptor units is across the internal window leakage and the corridor. Along the routes, tracer gas is diluted, especially when passing through the ventilated corridor. Well mixing of air in the measurement units was observed for all four scenarios, when the concentration profiles measured at two different points in each unit were compared.

In cross-building transmission, the tracer gas concentration decreased rapidly when the air moves through the vertical re-entrance space of the index block, and it decreased by three orders of magnitude at the rooftop. However, from the roof of the source block to the downstream blocks, the concentration decreased only by one order of magnitude, so that the cross-infection risk via cross-building airborne transmission was almost comparable with that of the intra-building transmission. The iso-surface of the normalised concentration level 2 penetrated downstream of the building array to a distance of five times of the array dimension, indicating that the tracer gas dispersion downstream of the buildings arrays was relatively slow (presumably owing to the recirculation effects of the wake flow) and that there were risks of cross-building transmission between closely located high-rise building blocks.

FIG 1. Sampling site and the building plan (unit R1310 and the corridor)

The infection risk of a disease was assessed using the Wells-Riley model in terms of the infection probability *P*. The mean infection risks in the receptor units were one order lower than that in the index unit, with a maximum infection risk of 9% corresponding to the maximum mass fraction of 0.28 polluted air from the index room. The cross-infection risk was related to the air leakage of the doors and windows facing the corridoor. This risk is higher when compared with our previous study[3,4] on the vertical transmission through the open windows induced by the single-sided natural ventilation, in which the maximum value of infection probability is 6.6% and the maximum mass fraction is <0.09.

Two driven forces of the airflow and dispersion, wind force and thermal buoyant force, were compared by estimating the contribution of thermal flow in total air change rate. The wind force was more dominant than the thermal buoyant force. The characters of tracer gas dispersion and distribution indicate that the wind condition and the geometric feature of the corridor significantly affected the inter-unit transmission. Higher wind speed resulted in more tracer gas inter-unit transmission under the low-wind condition during the measurements. The effect of wind direction on the tracer gas dispersion was more significant than the wind speed. The source in windward side had a higher risk of inter-

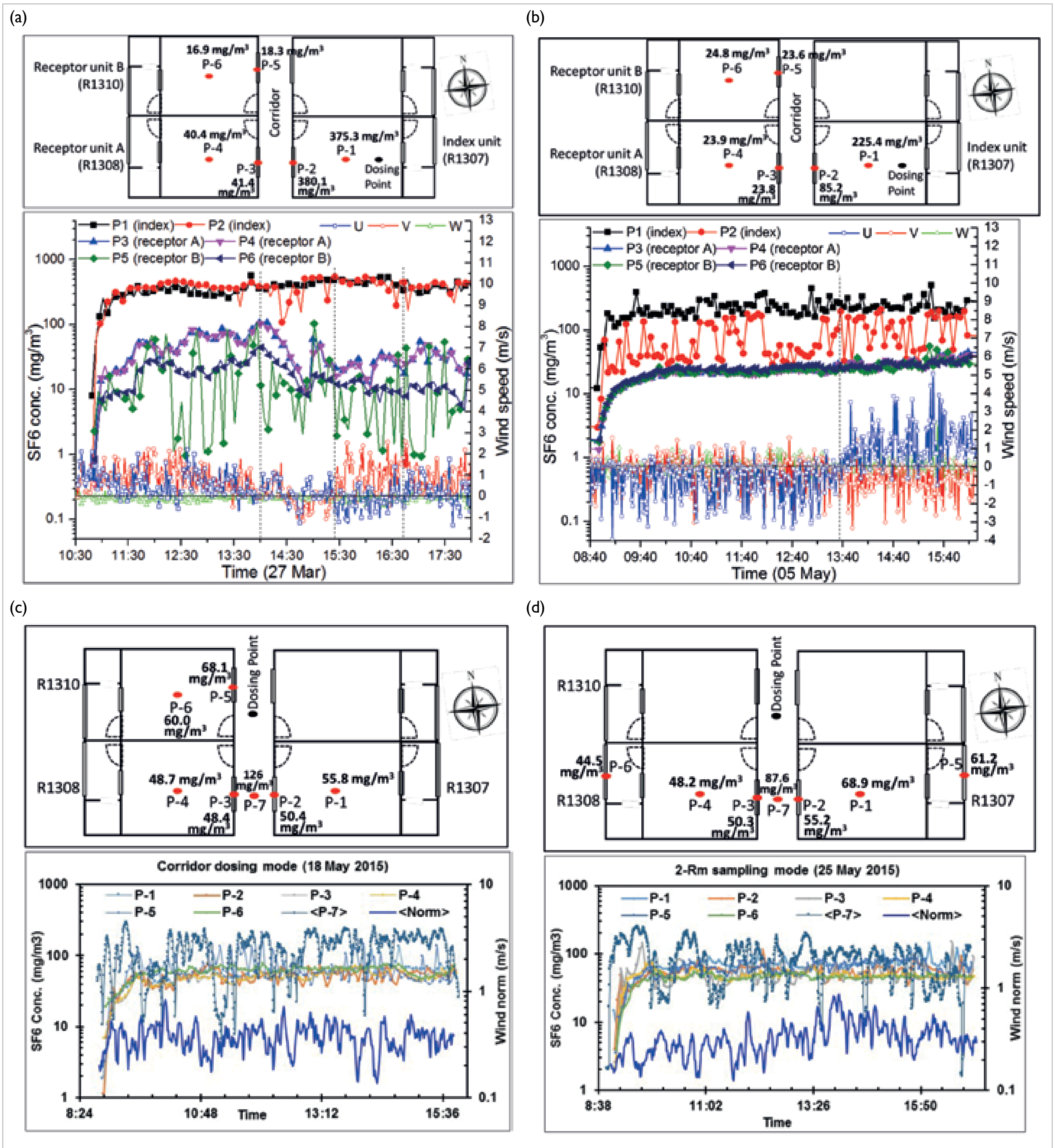

FIG 2. Mean SF_6 concentrations and concentration profiles: (a) closed window mode, (b) open window mode, (c) corridor dosing mode, and (d) 2-room mode

unit dispersion in slab-typed building than the source in leeward side. The rapid dilution of tracer gas in the semi-open corridor indicates that semi-open corridor can prevent the accumulation of contaminants and reduce the inter-unit transmission in slab-typed building.

Conclusion

Tracer gas concentrations in adjacent units are one order lower than that in the source unit, and the infection risks are also one order lower. The intra-building transmission risk through the internal route can be 9%, which is higher than the external spread through open windows induced by the single-sided natural ventilation airflow. Practically, in residential building design, the internal windows open to closed corridor should be avoided, and the airtightness of individual entrance doors to public spaces should be improved. These strategies also conform to the privacy requirements and fire control in modern constructions.

With regard to the computational fluid dynamics model, the discrete-event simulation model reproduced the unsteady fluctuations of airflow around the building array more accurately than the URANS model. The tracer gas travelled a long distance downstream of the building array with slow concentration decrease. The concentrations near the downstream buildings are only one order of magnitude lower than that at the rooftop of the source building, indicating an infection risk of cross-building in high-density high-rise residential environment.

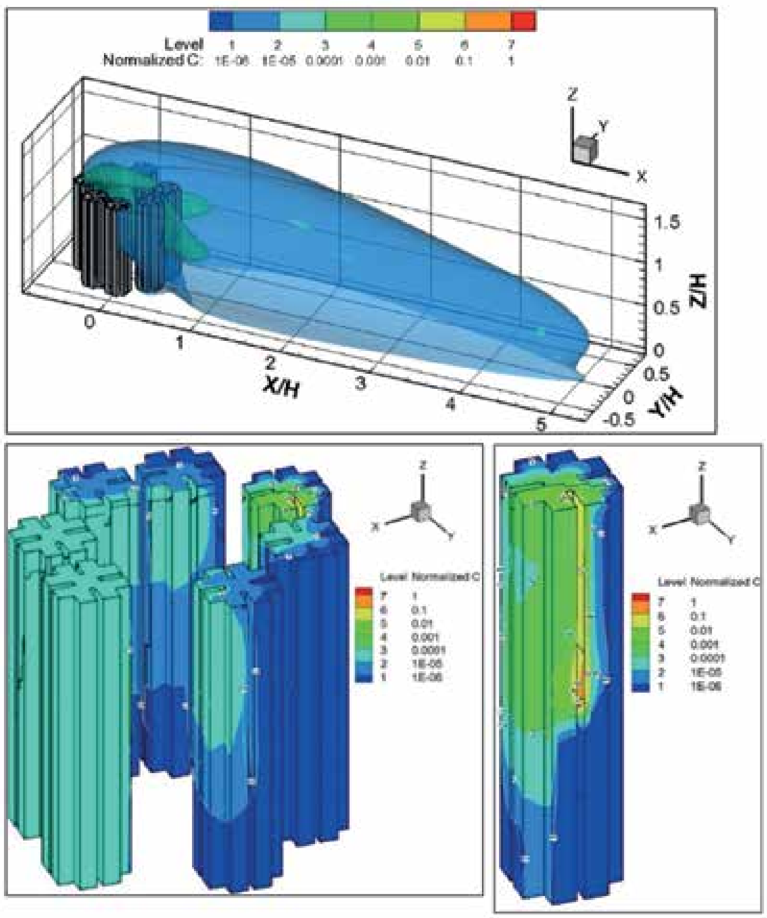

FIG 3. Dispersion and distribution of tracer gas around a group of buildings

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Disclosure

The results of this research have been previously published in:
1. Wu Y, Niu JL. Numerical study of inter-building dispersion in residential environments: prediction methods evaluation and infectious risk assessment. Build Environ 2017;115:199-214.
2. Wu Y, Niu JL. Assessment of mechanical exhaust in preventing vertical cross-household infections associated with single-sided ventilation. Build Environ 2016;105:307-16.
3. Wu Y, Tung TCW, Niu JL. On-site measurement of tracer gas transmission between horizontal adjacent flats in residential building and cross-infection risk assessment. Build Environ 2016;99:13-21.

References

1. Yu IT, Li Y, Wong TW, et al. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N Engl J Med 2004;350:1731-9.
2. Li Y, Leung G, Tang J, et al. Role of ventilation in airborne transmission of infectious agents in the built environment–a multidisciplinary systematic review. Indoor air 2007;17:2-18.
3. Niu J, Tung TC. On-site quantification of re-entry ratio of ventilation exhausts in multi-family residential buildings and implications. Indoor air 2008;18:12-26.
4. Gao NP, Niu JL, Perino M, Heiselberg P. The airborne transmission of infection between flats in high-rise residential buildings: tracer gas simulation. Build Environ 2008;43:1805-17.
5. Liu XP, Niu JL, Kwok KC, Wang JH, Li BZ. Investigation of indoor air pollutant dispersion and cross-contamination around a typical high-rise residential building: wind tunnel tests. Build Environ 2010;45:1769-78.