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# A study of interunit dispersion around multistory buildings with single-sided ventilation under different wind directions

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## HIGHLIGHTS

- Interunit dispersion in multistory buildings is studied using CFD method.
- Transport of gaseous pollutants and fine particles is indicated by tracer gas.
- Reentry ratios between units under prevailing wind directions are quantified.
- Dispersion routes under different wind directions are compared.
- The effects of balconies on interunit dispersion characteristics are discussed.

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## ABSTRACT

This study examines the interunit dispersion characteristics in and around multistory buildings under wind-induced single-sided ventilation conditions using computational fluid dynamics (CFD) method, under the hypothesis that infectious respiratory aerosols exhausted from a unit can reenter into another unit in a same building through opened windows. The effect of balconies on the interunit dispersion pattern is considered. The RNG $k - \varepsilon$ model and the two-layer near-wall model are employed to establish the coupled indoor and outdoor airflow field, and the tracer gas technique is adopted to simulate pollutant dispersion. Reentry ratios from each unit to other units under prevailing wind directions are quantified and the possible interunit dispersion routes are then revealed. It is found that many reentry ratios appear to reach around 10.0%, suggesting that the interunit dispersion is an important pollutant transmission route. The interunit dispersion pattern is highly dependent on the incident wind direction and the fact whether the building has protrusive envelope features. On average, the strongest dispersion occurs on the windward wall of the buildings under oblique wind direction, owing to high ACH (air change per hour) values and unidirectional spread routes. Except under a normal incident wind, the presence of balconies intensifies the interunit dispersion by forming dispersion channels to increase the reentry ratios.

## 1. Introduction

Natural ventilation through open windows is a common ventilation strategy in residential buildings, especially during the mild season. People use this natural ventilation to condition the indoor environment not only due to its excellence in improving building sustainability (Homod and Sahari, 2013; Schulze and Eicker, 2013), but also due to increased health awareness regarding exposure to outdoor fresh air (Chau et al., 2008; Finnegan et al., 1984). However, it is probably during this ventilation process that outdoor pollutants make their incursion into the interior (Santos et al., 2011). Generally speaking, pollutants entering from outdoors due to natural ventilation or envelope infiltration are mainly traffic exhaust, dust, and pollen (ASHRAE Handbook, 2009). There are also suspended aerosols in the air, such as smoke, fumes, and mist (ASHRAE Handbook, 2009), carried by the airflow and transported from the vicinity into the building. Apart from this common route, however, there is another important pollutant transport route: cross transmission between units within the same building, called "interunit dispersion" in the present study. This interunit dispersion is dangerous, essentially because it is likely to involve the transport of infectious aerosols, such as virus-laden respiration droplets. Another consideration is that the transport distance and time are relatively short. Since interunit dispersion was actually observed in Hong Kong during the outbreak of SARS in 2003

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(Health, Welfare & Food Bureau, Government of the Hong Kong Special Administrative Region, 2003), it has begun to attract more and more attention. Understanding the mechanisms and routes of interunit dispersion thus becomes critically important in developing control measures and ventilation strategies.

With regard to the interunit dispersion, previous on-site measurement (Niu and Tung, 2008) and numerical simulations (Gao et al., 2008) have calculated that, under buoyancy-dominated conditions, the reentry ratio of gaseous pollutants from a lower room to an adjacent upper room (i.e., upward transmission) can reach up to 7%. This is equivalent to nearly 2% infectious risk, according to the classic Wells–Riley infection risk assessment model (Riley et al., 1978), based on an assumed condition (Gao et al., 2008). Later, using the wind tunnel technique, it was found that, due to wind effect, this interunit transmission could occur horizontally as well as vertically (Liu et al., 2010, 2011; Wang et al., 2010). However, due to the limitations of the experimental resolution of the coupled outdoor and indoor flow in highly reduced-scale models (Mfula et al., 2005; Stathopoulos, 1997), previous studies did not discuss the indoor concentration level and reentry ratio of pollutant from a source unit to other units of interest.

Some recent studies (van Hooff and Blocken, 2010, 2013; Chen, 2009) have shown that CFD modeling is particularly suitable for the study of natural ventilation and is currently the most widely used model. However, one must carefully verify and validate the accuracy and reliability of CFD modeling on a given physical problem. In the present study, only single-sided ventilation is considered, in view of the fact that it is the most common ventilation mode in the residential buildings in a densely urban environment (Caciolo et al., 2011, 2013; Freire et al., 2013; Wang and Chen, 2012). The CFD modeling of single-sided natural ventilation has been compared with experiments in a number of studies (Caciolo et al., 2012; Evola and Popov, 2006; Jiang et al., 2003; Papakonstantinou et al., 2000). Some researchers (Caciolo et al., 2012) have concluded that the Large Eddy Simulation (LES) can potentially produce more accurate results than the two-equation Reynolds-Averaged Navier–Stokes (RANS) models, but the cost of LES is at least one order of magnitude higher than that of RANS. In addition, the renormalization group (RNG) $k-\varepsilon$ turbulence model (Evola and Popov, 2006) has shown acceptable performance in the study of wind-driven single-sided natural ventilation, especially in the prediction of ventilation rate and internal air movement. It was noted, in the previous studies using RANS models (Caciolo et al., 2012; Evola and Popov, 2006; Papakonstantinou et al., 2000), that near-wall regions were bridged by standard wall functions, and thus the low-Reynolds effect of the near-wall region on the whole wall-bounded turbulent flow was not considered. Given that interunit dispersion routes are mainly embedded in the flows near the building's surfaces, accurate near-wall treatment is believed to be essential to the successful prediction of the reentry phenomenon. In this study, the two-layer model (Fluent, 2010) is employed as an alternative near-wall approach to directly resolve the viscosity-affected near-wall region, which is expected to be helpful in producing a more realistic wall-bounded turbulent flow. The two-layer model's performance in the prediction of single-sided ventilation against experimental data (Jiang et al., 2003) will be discussed later.

The general airflow pattern around a bluff body has been shown clearly in computational wind engineering (CWE), e.g., in reference (ASHRAE Handbook, 2011; Martinuzzi and Tropea, 1993), which involves impingement, separation, reattachment, recirculation, and vortex-shedding, etc. The present interest, however, is to explore how these flow characteristics affect interunit pollutant dispersion. Our earlier paper (Ai et al., 2013) only studied interunit dispersion under normal wind direction. Given that the airflow and pollutant dispersion around a building should be substantially different when experiencing different prevailing wind directions, this study further predicts and quantifies the reentry phenomenon in a multistory building, under oblique and parallel wind directions. The detailed pollutant dispersion patterns, under the three wind directions, are then compared and discussed. Buildings' facades are often not flush walls, but present envelope features such as balconies and sunshade devices (Joint Practice Note No. 1, 2001). In order to compare, the interunit dispersion characteristics around a building with non-flush walls (with the presence of balconies) are further examined. After being validated against published experimental data, the RNG $k-\varepsilon$ model is used with a two-layer near-wall modification to establish the airflow field in and around multistory buildings (see Section 4). The interunit dispersion pattern characterized by the airflow field is then investigated by generating tracer gas in each unit of the buildings. Passive tracer gases, such as carbon dioxide ($CO_2$) and sulfur hexafluoride ($SF_6$), are widely and successfully used in experimental and numerical investigations of pollutant dispersion (Gao et al., 2008; Liu et al., 2010, 2011; Niu and Tung, 2008; Riley et al., 1978; Wang et al., 2010) owing to the similarity of their aerodynamic characteristics to those of various gaseous pollutants and fine aerosols. The present study uses carbon dioxide as a tracer of indoor pollutants. Dispersion routes can be visualized and reentry possibilities can be quantitatively estimated by analyzing the tracer gas concentration distribution in adjacent units. The results from this study are expected to be useful in understanding the pollutant dispersion mechanisms around the built environment and in assisting the building officials and designers to formulate effective strategies in the control of infectious respiratory diseases.

## 2. CFD models

Numerical solutions are obtained for an isothermal condition by resolving the governing equations describing the fluid field, namely the equations for the conservation of mass and momentum. Turbulence effects are taken into consideration using the RNG $k-\varepsilon$ turbulence model, and the two-layer approach is applied to the near-wall region. The species transport model is used to reveal the pollutant dispersion process. For incompressible flow, the time-averaged governing equations can be written generally as:

$$\frac{\partial}{\partial t}(\varphi)+\nabla\cdot(\overline{u}\varphi) = \nabla\cdot(\Gamma_{\varphi}\nabla\varphi)+S_{\varphi} \tag{1}$$

where $\varphi$ represents the scalars: the velocity components, $u$, $v$, $w$, the turbulent kinetic energy $k$, its dissipation rate $\varepsilon$, and the mass fraction $M_i$; term $\overline{u}$ is the mean velocity, $\Gamma_{\varphi}$ the effective diffusion coefficient for each variable, and $S_{\varphi}$ the source term of an equation. The effective exchange coefficient and the source rate for each scalar are given in Table 1, where $\mu_{eff}$ represents the effective turbulent viscosity, $\mu$ the fluid viscosity, $\mu_t$ the turbulent viscosity, $\alpha_k$

**Table 1**
Effective exchange coefficient and source rate for each scalar.

| Equation | $\varphi$ | $\Gamma_{\varphi}$ | $S_{\varphi}$ |
|---|---|---|---|
| Continuity | 1 | 0 | 0 |
| $x$-momentum | $u$ | $\mu_{eff}=\mu+\mu_t$ | $-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial x}\right)$ |
| $y$-momentum | $v$ | $\mu_{eff}=\mu+\mu_t$ | $-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial y}\right)$ |
| $z$-momentum | $w$ | $\mu_{eff}=\mu+\mu_t$ | $-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial z}\left(\mu_{eff}\frac{\partial w}{\partial z}\right)$ |
| Turbulence kinetic energy | $k$ | $\alpha_k\mu_{eff}$ | $G_k-\rho\varepsilon$ |
| Turbulence dissipation rate | $\varepsilon$ | $\alpha_{\varepsilon}\mu_{eff}$ | $\varepsilon/k(C_{1\varepsilon}G_k-C_{2\varepsilon}\rho\varepsilon)-R_{\varepsilon}$ |
| Mass fraction | $M_i$ | $D_{i,m}+\mu_t/Sc_t$ | Based on the generation rate |