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Gaseous pollutant transmission through windows between vertical floors in a multistory building with natural ventilation

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Article history:
Received 24 May 2017
Received in revised form 25 July 2017
Accepted 9 August 2017
Available online 12 August 2017

Natural ventilation is an effective strategy to control thermal comfort in buildings, and can be enhanced depending on the window style. The combination of natural ventilation and window can also facilitate the removal or dilution of gaseous pollutants from indoor sources in newly decorated buildings. However, the windows on the same facade may cause gaseous pollutant cross-transmission during single-sided ventilation between households on different floors close to the source. Although some research has focused on the pollutant cross-transmission in buildings, the simplification of windows into rectangular openings often affects accurate knowledge of pollutant transmission characteristics. Therefore, this investigation explored gaseous pollutant cross-transmission through real windows during single-sided, buoyancy-driven ventilation in a multistory building. Six types of windows were modeled for the indoor pollutant of gaseous formaldehyde (HCHO). Computational fluid dynamics (CFD) was utilized to solve characteristics of pollutant transmission inside and outside the multistory building. The results indicated that the ventilation rates, thermal profiles and pollutant transmission inside and outside the building varied according to each window type, although the open window areas were identical. The re-entry ratio of exhausted air entering upper floors and the infection risk of epidemic viruses caused by airborne cross-transmission was sensitive to ventilation rates and window configurations, while the sensitivities for window configurations varied case by case. The comparisons also revealed that the specification of ambient temperature and pollutant release rate ultimately did not affect the evaluation of pollutant cross-transmission using CFD.

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1. Introduction

The rapid urbanization and population growth makes China the world’s largest market for new construction [1]. According to statistical data, construction and expansion are expected to continue through 2050 with 1.8–2.0 billion m² of floor space every year [2]. These new buildings raise public concerns regarding indoor air quality (IAQ) associated with higher levels of pollutants such as volatile organic compounds (VOCs) [3]. A field survey in Hangzhou, China revealed that the average concentration of formaldehyde (HCHO) in new residential buildings after decoration is 9 times higher than the threshold from World Health Organization (WHO) [4]. The dramatic increase of HCHO in indoor environment greatly enhances the risk of exposure risk to human beings that reside in the dwelling. It is hypothesized that significant exposure to high levels of HCHO has contributed to childhood leukemia incidents in China [5,6]. As an ordinary but effective solution, natural ventilation is being applied to remove or dilute gaseous pollutants in new decorated buildings [7]. In particular, single-sided natural ventilation is more common than cross-ventilation in practice, and can readily satisfy fire codes, security issues and privacy concerns [8].

Single-sided natural ventilation uses openings in the form of windows or ventilation devices on the facade to allow outdoor air to enter and indoor air to leave from the same or different opening [9]. Due to the unique airflow paths created by single-sided ventilation, air can flow between households on different floors in multistory buildings [10]. As a result, there is the possibility of cross-infection via airflow between multi-story households if the IAQ of one household is not within the recommended safe limits. Cross-infection was initially found during the outbreak of SARS in China [11]. The SARS virus was found in rooms and windows where residents did not suffer...
The airborne transmission of pollutants is often driven by three forces, namely, the buoyancy force, wind force and their combination [17]. Niu and Tung [16] employed carbon dioxide (CO₂) and sulfur hexafluoride (SF₆) as tracer gases to measure the amount of the exhausted air re-entering upper floor windows due to buoyancy effects. It was found that up to 7% of the exhausted air from the lower floor transferred to the adjacent upper floor. Liu et al. [18] numerically investigated the airborne transmission in a high-rise building with buoyancy-driven ventilation. The results revealed that the windows flush with the building facade became major paths of pollutant cross-transmission. To reduce pollutant transmission between floors, Wu and Niu [19] installed a mechanical exhaust system in each room with single-sided, buoyancy-driven ventilation. It was shown that the outflow through the window was weakened when the mechanical exhaust was employed. If the mechanical exhaust rate was large enough, no indoor air escaped through the window. The two-way airflow through the window turned into one-way inflow, and thus re-entry risk was avoided. Lim et al. [20,21] further confirmed the possibility of pollutant transmission from lower floors to upper floors through buoyancy-driven airflow by means of field measurement and numerical analysis in a hospital setting. Considering the variety of indoor pollutants, Gao et al. [22] utilized Lagrangian and Eulerian models to simulate particulate (pollutant) transmission between adjacent floors. It was concluded that the upward transmission closely depended on the size of the particulate. If the particulate sizes were larger than 20 μm, the upward transmission was limited by gravitational settling effects.

Compared to pollutant cross-transmission by buoyancy-driven airflow, wind-driven airflow is more complex because of the random nature of wind. Liu et al. [23–25] measured pollutant transmission and possible cross-infection based on a 1:30 scale model of a 10-story residential building in a wind tunnel. Experimental results indicated that vertical (bidirectional) and horizontal cross-transmission between adjacent flats were both observed. Furthermore, the impacts of transient characteristics of wind on pollutant cross-transmission should be considered when evaluating the risk of cross-infection. To perform accurate numerical predictions on indoor pollutant dispersion around a building, Liu et al. [26] compared three turbulence models based on a high-rise building with 33 floors and 8 units in a prescribed wind field. Obvious differences were observed among the turbulence models, and the simulations based on the realizable k–ε model agreed best with experiments. Ai et al. [27–29] used the Reynolds-averaged Navier-Stokes (RANS) model and the large eddy simulation (LES) model to quantify the dispersion of pollutants during wind-dominated conditions inside and outside a typical multistory building. The results indicated that the incident wind and the balcony created significant changes in the route of airborne transmission and the re-entry ratio of exhaust air.

Owing to the fact that pollutant cross-transmission does not always depend on one force, i.e., buoyancy-driven or wind-driven forces, the combination of these forces may transport pollutant between floors. Gao et al. [30] considered the combination of forces for pollutant cross-transmission in a high-rise building with single-sided natural ventilation. It was found that the wind could reinforce or suppress vertical cross-transmission of pollutants between floors, which was mainly attributed to wind speed and direction. Mao et al. [31] further extended the research in a 33-story building with closed doors and windows. The pollu-
tant cross-transmission between floors was driven by buoyancy and wind effects together. The multi-zone model was developed to analyze pollutant spread in vertical and horizontal directions. The pollutant concentration on the upper floors was 3–4 orders of magnitude lower than that on the floor where the source was located. Though the research on pollutant cross-transmission via combined forces has been investigated, it is still far from being fully understood since the characteristics of airflow resulting from the interaction between buoyancy and wind has not been well explained [32].

The above review implies that most attention has focused on experimental measurements and numerical simulations to identify the possible routes of pollutant cross-transmission and quantify the amount of exhausted pollutants re-entering indoor environments. Due to the complex features of airflow inside and outside buildings, there are very few studies that investigate the impact of window configuration; real windows are simplified as rectangular openings. Our previous study demonstrated that there are significant thermal flow differences in natural ventilation with various window configurations [33], which should also affect pollutant cross-transmission accordingly. Therefore, the investigation herein aims to quantify gaseous pollutant cross-transmission in a multistory building with single-sided, buoyancy-driven ventilation through variable window types. The sensitivities of re-entry ratios and infection risks for variable windows are analyzed and compared for pollutant cross-transmission.

2. Methodologies

In this section, the geometrical model used to demonstrate gaseous pollutant cross-transmission via single-sided, buoyancy-driven ventilation in a multistory building is presented first, followed by a brief introduction of governing equations to solve airflow and pollutant transmission using CFD. Finally, the numerical solution and validation is addressed.

2.1. Geometrical model

To represent pollutant transmission between households through real windows in a multistory building, the geometrical model is illustrated in Fig. 1. The three empty cavities represent rooms on different floors of a multistory building with dimensions of 2.5 m (L) × 3.5 m (W) × 3.2 m (H). Six types of windows that are common in residential buildings are installed on the facade of the building, which include the vertical slide window (VSW), tilt window (TILT), awning window (AW), horizontal pivot window (HPW), turn window (TURN) and vertical pivot window (VPW), as shown in Fig. 2. The sizes of the window frames are identical, with dimensions of 1.23 m (w) × 1.48 m (h). The open area of each window style and corresponding open gap are summarized in Table 1, and represent typical openings in practical conditions. Fig. 2(a) shows an example of the open area A and gap δ for the VSW style; for the other window styles, the gap is the base of the isosceles triangle. Furthermore, the openings of the same window type on each floor are identical for the same case. Since the airflow and pollutant dispersion near a window is of concern, the computational domain only includes the front region of the multistory building and wind is not considered [19]. The height of the computational domain is 12.8 m (4H), which is one floor higher than the building, and its length is 12.5 m (5L) which is large enough to ensure that the computational boundaries do not affect the windows. The pollutant source is located in the center of the first floor room, which is denoted by the character * in Fig. 1. The gaseous HCHO is assumed to be released by the source with a constant mass flow rate that ranges from 10 – 100 μg/s.

2.2. Governing equations

To characterize airflow and pollutant transmission inside and outside the multistory building, the governing equations of fluid flow, heat transfer and scalar transport are solved. Since the equations are widely available from published literature, the following briefly addresses the governing equations employed in the study.

The continuity, momentum and energy equations for an incompressible fluid are written as [34],

\[
\mathbf{\nabla} \cdot \mathbf{\bar{u}} = 0
\]  

(1)

\[
\rho \left( \frac{\partial \bar{u}}{\partial t} + \bar{u} \cdot \nabla \bar{u} \right) = -\nabla p + \mu \nabla^2 \bar{u} + \rho \mathbf{\bar{g}}
\]  

(2)

\[
\frac{\partial T}{\partial t} + \bar{u} \cdot \nabla T = \frac{K}{\rho c_p} \nabla^2 T
\]  

(3)

where \(\bar{u}\) is the velocity vector, \(p\) is the pressure, \(T\) is the temperature, \(K\) is the thermal conductivity, \(\mathbf{\bar{g}}\) is the gravitational acceleration, \(\rho\) is the density, and \(\mu\) is the absolute viscosity. The Boussinesq model is
used to include buoyancy effects caused by variation of air density. It approximates the buoyancy term in Equation (2) as,
\[ \rho \frac{\partial \bar{g}}{\partial t} = \rho_{ref} \left[ 1 - \beta (T - T_{ref}) \right] \bar{g} \]
where \( \rho_{ref} \) is the reference density, \( T_{ref} \) is the operating temperature, and \( \beta \) is the thermal expansion coefficient.

In view of desirable performances in accuracy and stability when modeling turbulence, the BSL \( k-\omega \) model is used to characterize turbulent airflow [35]. The mathematical descriptions of the BSL \( k-\omega \) model are given by [36],
\[ \frac{\partial}{\partial t} \left( \rho k \right) + \nabla \cdot (\rho u k) = \nabla \cdot \left( \Gamma_k \nabla k \right) + G_k - Y_k + \rho \cdot \nabla \cdot \left( \Gamma_\omega \nabla \omega \right) + G_\omega - Y_\omega + D_\omega \]
where \( k \) is the turbulence kinetic energy, \( \omega \) is the specific dissipation rate, \( \Gamma_k \) and \( \Gamma_\omega \) represent the diffusivity of \( k \) and \( \omega \), \( G_k \) and \( G_\omega \) represent the generation of \( k \) and \( \omega \), \( Y_k \) and \( Y_\omega \) represent the dissipation of \( k \) and \( \omega \), and \( D_\omega \) represents the cross-diffusion term. More details about the BSL \( k-\omega \) model can be found in [33,36].

Based on the airflow predicted by the mathematical models introduced above, one can continue to solve another equation to obtain characteristics of pollutant transmission in indoor and outdoor environment. Generally, there are two methods for modeling pollutant transmission, i.e., the Eulerian method and the Lagrangian method. The Lagrangian method is usually applied to transiently track particle pollutants. Under steady state conditions, both methods can provide reasonable results, while the Eulerian method requires less computing time than the Lagrangian method [37]. Since the densities of air and gaseous HCHO are similar, they can be considered as a passive pollutant. Therefore, the Eulerian method is suitable to quantify passive pollutant transmission. The following scalar transport equation is utilized to model the pollutant transmission [34],
\[ \nabla \cdot (\rho \mathbf{u} \mathbf{c}) = \nabla \cdot \left( \Gamma_c \nabla \mathbf{c} \right) + S_c \]
where \( \mathbf{C} \) is the concentration of the scalar (HCHO), \( S_c \) is the source term, and \( \Gamma_c \) is the scalar diffusivity as proposed by Zhang et al. [38] where \( \Gamma_c = \left( \mu + \mu_t \right)/St \) for \( St = 1.0 \). Further details on the scalar transport equation can be found in [34].

### 2.3. Numerical solution

ANSYS Fluent (Version 16.0) is used simulate the flow through windows and predict pollutant transmission. The governing equations are discretized using the finite-volume method. The discretization for continuity, momentum, energy, turbulence and scalar are all second-order upwind schemes. The pressure staggering option (PRESTO!) scheme is employed for pressure interpolation. The pressure and velocity is coupled using the semi-
implicit pressure linked equation (SIMPLE) algorithm. Convergence criteria of $10^{-5}$ are used for all variables. Each case is solved using the steady state form of the equations except for the second validation case. When simulating the transient solution, the time step is set to 0.5 s to satisfy the Courant number of unity. The boundary conditions for the building and computational domain are summarized in Table 2. In the building, the no-slip condition is imposed on all solid surfaces. Temperatures are specified for the side walls and floor, while the front wall and ceiling are specified as adiabatic. In the computational domain, temperature and ambient pressure are
Fig. 4. Comparison of the predicted CO$_2$ concentration profiles with the experimental data.
Fig. 5. Comparison of the pollutant profiles for different ambient temperatures.

| Location   | Type/Value          | Location   | Type/Value                     |
|------------|--------------------|------------|-------------------------------|
| Ceiling    | No-slip/Adiabatic  | Top        | Ambient/12 – 24 °C, 1 atm     |
| Floor      | No-slip/28 °C      | Ground     | No-slip/Adiabatic              |
| Walls      | No-slip/28 °C      | Sides      | Symmetric (left and right side) |
| Front      | No-slip/Adiabatic  | Free-slip (other side)/12–24 °C |

specified at the topmost plane. No-slip and adiabatic boundary conditions are employed on the ground. As shown in Fig. 1, the left and right sides of the external domain in the z – y planes are symmetric boundaries, which replicate multiple dwellings on a floor. The x – y plane at the computational boundary of the ambient region is specified as a free-slip boundary with different temperatures to represent different ambient conditions.

The geometry and mesh were created using Gambit (Version 2.3.16), and hexahedral cells were generated with the ‘submap’ scheme. A grid resolution study was performed using cells with average lengths of 2.5 cm (fine), 5.0 cm (medium) and 10 cm (coarse). Changes in velocity and temperature were examined and it was found that the discretization error for the medium-to-fine was 4.25% using a Richardson extrapolation[39,40]. Hence, the simulations will use the medium grid for the analysis herein. Further details about the grid resolution can be found in [33].

2.4. CFD model validation

The study begins by validating the CFD predictions with data from two experiments. One experiment is from Jiang and Chen [41], who provided velocity and temperature profiles that we use to demonstrate the accuracy of the CFD model to predict natural ventilation. The other is an experiment by Grabe et al. [42], which provides profiles of tracer gas inside the building with buoyancy-driven ventilation and will validate the CFD model for gaseous pollutant transmission.

In the experiment by Jiang and Chen [41], two chambers represented the indoor and outdoor environments, as shown in Fig. 3(a). The buoyancy-driven ventilation was generated through a baseboard heater inside the test chamber and a rectangular window was located opposite to the baseboard heater. The air velocity and temperature at five locations (P1 – P5) inside and outside the test chamber were measured. The experimental data from two posi-
tions (P2, P5) in the test chamber were used to validate the CFD model in the study. More details on the experiment can be found in [41]. However, specific experimental uncertainty was not provided so the data will not be represented with error bars. Fig. 3(b)–(e) compare the predictions for velocity and temperature with the measured data at P2 and P5. In general, the velocity and temperature profiles are in good agreement with the experimental data. Thus, the CFD model is able to provide acceptable predictions of thermal flow profiles for buoyancy-driven natural ventilation.

In the study by Grabe et al. [42], the experiment consists of a test chamber and an environmental chamber, as shown in Fig. 4(a). The dimensions of the test chamber have a length of 2.5 m, width of 3.5 m and height of 3.2 m. The dimension of the environmental chamber exceeds that of the test chamber, but the specific size of the environmental chamber was not provided. A vertical slide window with a 1.23 m width and 1.48 m height was located on the front wall of the test chamber. Carbon dioxide (CO₂) was the tracer gas and was injected into the test chamber with the window closed before measurements were taken. The tracer gases of CO₂ and SF₆ are the most frequently applied tracer gases in ventilation measurements, which are both colorless gases with densities larger than that of air [43,44]. The test chamber was heated by an electrical heating unit. Once CO₂ concentrations reached 4000 ppm inside the test chamber and the temperature difference between the two chambers was 8 °C, CO₂ injection and electrical heating ceased, the window was opened and the measurements began. CO₂ concentration in the center of the test chamber at different heights was measured during the buoyancy-driven ventilation.

Fig. 4(b)–(e) compare the computed CO₂ concentration with the experimental data at different heights at the center of the test chamber. Due to the lack of information of the environmental chamber, two types of boundary conditions were tested with the CFD modeling. One condition assumed that the upper surface of the computational domain was open to ambient conditions and pressure was specified (BC-open). The second condition assumed that the upper surface of the computational domain was a no-slip wall (BC-close). As shown in Fig. 4(b)–(e), the CO₂ concentration generally decreases with time during ventilation. Compared to the decay of CO₂ at y = 2.8 m, the CO₂ concentration at y = 0.4 m decreases faster at the initial stage (t = 0 – 800s). The concentration of CO₂ predicted by the CFD model is in good agreement with experimental data at the initial stage. However, the CFD predictions gradually deviate from measurements as the time continues. The CFD predictions suggest that the boundary condition that specified ambient pressure is more similar to the experimental conditions. Although neither boundary condition tested perfectly agrees with the experimental data, and not knowing the exact experimental conditions, the CFD modeling can be considered reliable.

As shown in Fig. 4(b)–(e), the discrepancy may be attributed to the specification of the external domain which represents the environmental chamber. When the no-slip boundary (close) is employed at the top of the external domain, the CO₂ exhausted from the test chamber cannot be removed from the external domain, increasing the CO₂ background concentration. However, the CO₂ exhausted from the test chamber can be removed from the external domain over time if the ambient boundary (open) is specified at the top of the external domain, thus maintaining a lower CO₂ concentration. Owing to that, the size of external domain highly affects the background concentration of CO₂ entering into the test chamber. Unfortunately, the dimension of the environmental chamber was not given in the experiment [42]. Nevertheless, it is reasonable to use the scalar transport equation to predict gaseous pollutant transmission via buoyancy-driven airflow.

3. Results and discussions

The computational study continues by investigating the pollutant transmission among households in a multistory building. As shown in Fig. 1, the gaseous pollutant of HCHO is released at the center of the first floor room. The ventilation opening will change according to one of the six window styles shown in Fig. 2. The pollutant transmission under different ambient temperatures and HCHO release rates are compared first, followed by a discussion of the impact of window types and open areas on pollutant transmission and infection risk.

3.1. The effects of the ambient temperature and released pollutant

Fig. 5 compares the predicted velocity, temperature, concentration and mass flow rate profiles for different ambient temperatures; the profiles are taken along a line that runs directly through the center of the room on each floor. Since VSW is one of the most general window types and can produce the largest ventilation rate among the six windows, as discussed in [33], the impacts of the ambient temperature and released pollutant on cross-transmission are presented using the VSW as an example. The VSW configuration is
modeled with an open area of 0.8733 m$^2$ and the release rate of the target pollutant (HCHO) is 20 μg/s. The reason of setting the value of the pollutant release rate will be explained in Sect. 3.1. To improve the comparability of numerical results, the parameters are non-dimensionalized as,

\begin{align}
    y^* &= y/H \\
    u^* &= u/\sqrt{gH} \\
    T^* &= (T - T_\infty) / (T_s - T_\infty) \\
    C^* &= (C - C_{\min}) / (C_{\max} - C_{\min}) \\
    M^* &= M / (\rho GW \sqrt{R_e \Delta T})
\end{align}

where $y$ is the vertical coordinate, $H$ is the floor height, $W$ is the building width, $\Delta T$ is the indoor-outdoor temperature difference, $M$ is the mass flow rate of air passing through the window, $R_e$ is the air constant, the subscripts $s$ and $\infty$ denote the surrounding surfaces and ambient environment, respectively, and the subscripts min and max denote the maximum and minimum values, respectively.

As illustrated in the pollutant profiles of Fig. 5, the indoor velocity, concentration and mass flow rate generally increase when the ambient temperature decreases, while the indoor temperature shows an opposite variation. The pollutant distribution on the first floor and the two upper floors differ greatly because the pollutant source is located in the center of the first floor room. The concentration around the pollutant source is the largest, and the maximum concentration on each floor appears at the height of air inflow, as shown in Fig. 5(c). The comparison demonstrates that ambient temperature does not produce an obvious impact on the basic characteristics of thermal flow and concentration profiles. To compare the results with our previous research [33] and subsequently determine the best window configuration that minimizes cross-transmission, the ambient temperature is specified as 20 °C in the remainder of the study.

Fig. 6 compares the computed concentration profiles with different release rates of the HCHO source for the VSW case ($A_2 = 0.8733$ m$^2$, $T_\infty = 20$ °C). The average concentration of HCHO inside the building obviously increases with increasing release rate for each floor, as shown in Fig. 6(a). Since the HCHO source is located on the first floor, the average concentration inside shows the most drastic response to the variation of the release rate. According to the threshold for indoor HCHO suggested by WHO (81 ppb), the average concentration in the first floor room is 1.4 – 13.1 times the

![Fig. 7. Relationship of ACH versus open area for different floors.](image-url)
threshold. As introduced by Guo et al. [4], the HCHO level in new residential buildings after decoration was found to be over 9 times higher than the threshold. Therefore, modeled a pollutant source of 80 μg/s for the VSW case (A2) can best represent the real condition based on the WHO threshold. The average concentrations for the second and the third floor are 62 ppb and 11 ppb in the case of 1 = 80 μg/s, which are 0.77 and 0.15 times the threshold, respectively. If the release rate of the source pollutant increases slightly, the HCHO concentration in the second floor room may be over the threshold, and the level in the third floor room will become worse as well. Therefore, human beings on the upper floor adjacent to the first floor (with the pollutant source) in the multistory building risk cross-infection during single-sided natural ventilation.

Fig. 6(b) presents the dimensionless concentration profiles along a line through the center of the rooms and corresponds to different release rates of the HCHO source. Most notably, the profiles collapse and demonstrate that the trends do not change, irrespective of release rate; only the magnitudes change for the raw data. Therefore, it is reasonable to speculate that the specification of the pollutant release rate will not affect obtaining basic characteristics of gaseous pollutant cross-transmission in the multistory building.

Due to that, the release rate of the pollutant source is specified as 20 μg/s for the remainder of the study.

### 3.2. The impact of window types on pollutant transmission

As defined by ASHRAE Handbook [45], the air change rate per hour (ACH) compares the airflow rate Q to the volume of the corresponding space V (i.e., ACH = Q / V). As shown in Fig. 7(a) – (c), the ACH for each floor increases with increasing open area for each window type. The ventilation performances of each window type on the first and second floor are very similar, and minor differences are present on the third floor. In general, the VSW and HPW perform best in terms of ventilating the multistory building, followed by the TURN, VPW and TILT. The AW style always performs the worst among the six window types except when the window open area is less than 0.5 m² on the first floor, and then TILT performs the worst as shown in Fig. 7(a). On the second and third floor of the multistory building, the performance of the TILT is better than that of the AW owing to the upward airflow in front of the facade induced by the plane of the TILT, as shown in Fig. 7(b) and (c). On the first floor of the multistory building, the performances of the
TILT and AW are more similar and change with the open area of the window. These findings are consistent to our previous work on ventilation performances of various window types in a one-story building, as shown in Fig. 7(d) [33].

Fig. 8 presents the average HCHO concentration for each floor comparing open area. The average HCHO concentration decreases with increasing open area for each window type. Note that the maximum values along the abscissa are different in Fig. 8 because the first floor levels are significantly higher and the third floor levels are significantly lower. However, the pollutant concentrations on a particular floor with different window types show pronounced differences on the second floor, although the open window areas and release rates of HCHO are equal. This can be attributed to the window style that impacts ventilation rates. As shown in Fig. 8, the average concentration of HCHO for the HPW case in each floor is not the smallest among the six window cases. However, the corresponding ventilation rate for the HPW case is still the largest, as shown in Fig. 7. Therefore, the window configuration affects the pollutant transmission between floors in multistory buildings. The HCHO concentration decays with increasing floor level with the same window type. From the first floor to the second floor to the third floor, the average HCHO concentration can reach magnitudes of 100 to 1000, 10 to 100 and 10, respectively. Clearly, the performance of various windows on preventing airborne pollutant re-entering upper floors are different. Among the six window types, the VPW, TILT and TURN styles generally do not perform well and thus does not adequately restrict the pollutant from re-entering upper floors. In contrast, the VSW and HPW styles perform better but the AW style presents the best performance on restricting pollutant cross-transmission, although it is not able to provide larger ventilation rates.

To further illustrate the impact of window configurations on pollutant transmission between floors in the multistory building. Fig. 9 presents HCHO distributions at the central x-plane for different window types with the same open area ($A_j = 0.8733 m^2$). As shown in Fig. 9, the HCHO profiles inside and outside the building are sensitive to window styles. By considering the configurations of the VSW and HPW styles, the TILT, VPW and TILT styles present similar characteristics of HCHO distributions because similar transmission paths are created by windows. Among the six windows, the AW style performs the best with low pollutant transmission since the upward airflow is prevented by the window pane. In contrast, the TILT, TURN and VPW styles are not as effective in reducing pollutant cross transmission because the window pane does not redirect the flow. Therefore, the HCHO concentrations in the upper floor rooms for these three window cases are relatively higher. The HCHO concentration reduces by nearly one order of magnitude between the first floor (with the pollutant source) and the upper floors for each window style, while the reduction between the second floor and the third floor is much less than that between the first floor (with the pollutant source) and the upper floors.

To better understand different window performance on the pollutant transmission between floors, Fig. 10 presents thermal flow profiles at the central x-plane for three cases. Among the six window types, the AW style shows the best performance for restricting pollutant cross-transmission, although it is not able to provide larger ventilation rates. The VSW and HPW styles perform adequately, and the VPW, TILT and TURN types perform the worst. Considering the performances of each window and the characteristics of pollutant distribution, only the thermal flow profiles corresponding to VSW, AW and TURN are presented. The velocity streamlines near the windows provide a visual understanding of how the pollutant transports through the openings. The upward flow is obviously restricted by the window pane in the AW case, controlling the exhausted pollutant from re-entering the upper floors, as shown in Fig. 10(b). The TURN style directs the air toward the window opening such that the air exhausted from each floor cascades along the facade and thus enhances the air re-entering the upper floors, as shown in Fig. 10(c). Compared to the TILT case, the air path passing through each floor window is better separated in the VSW case, so the indoor pollutant cross-transmission is reduced as well, as shown in Fig. 10(a). The thermal flow profiles for the VSW provides the best ACH ventilation rates, and the overall mean velocity is higher and the temperature is lower than the other cases. The TILT case performs adequately but the velocity field demonstrates reduced circulation, and thus lower ACH but the temperatures are reasonable.

3.3. The assessment of infection risk by cross-transmission

The results presented thus far indicate that possibility of pollutants flowing between adjacent floors. Therefore, the infection risk of a pandemic virus through cross-transmission in multistory buildings with flush windows on the same facade cannot be neglected. To quantify the infection risk caused by cross-transmission, the amount of the air exhausted from the first floor (source) entering upper floors can be determined. As proposed by Niu and Tung [16], the parameter of re-entry ratio that represents the fraction of the exhausted air from the source floor to upper floors can be defined as,

$$\eta_R = \frac{C_{ave, R} Q_R}{C_{ave, S} Q_S} \text{ (13)}$$

where $\eta_R$ is the re-entry ratio, $C_{ave, S}$ is the average pollutant concentration in that floor, $Q$ is the volume flow rate, $R$ is the floor number (1, 2, 3, etc.), and $S$ is the floor with the source.

Fig. 11 presents the re-entry ratio of the exhausted air from the source floor entering the upper floors. As shown in Fig. 11, the re-entry ratio for the second floor is generally larger than that for the third floor because of the smaller transmission distance from the pollutant source. In the second floor room, the re-entry ratios for HPW and TILT cases increase progressively with ACH, while that for the VSW case exhibits a monotonic decrease. In contrast, the re-entry ratios for the TILT and VPW cases fluctuate with ACH, but the re-entry ratio for the AW case remains constant with ACH. Similarly, various window types are not able to present consistent behaviors in re-entry ratios in the third floor room. Notice that the TILT style always presents the largest re-entry ratio among the six windows, which is most likely because the upward airflow is not restricted by the structure of the window itself. Moreover, the window pane is angled toward the indoor environment and induces the pollutant to re-enter. Thus, the window configurations should be carefully considered for cross-transmission, especially in the control of cross-infection of pandemic virus via airborne transmission, as well as acceptable ventilation.

Fig. 11. Based on the re-entry ratio of the exhausted air entering the upper floors, the infection risk of a pandemic virus via airborne transmission can be estimated by the Wells–Riley equation [46]. The Wells–Riley model was initially proposed in an epidemiological study on measles outbreak, which was based on the quantum theory of infection. A quantum was defined as the number of airborne pathogens required to infect a person. By considering the intake dose of airborne pathogens in terms of the number of quanta to evaluate the probability of escaping the infection, the Wells–Riley equation is derived as [46–48],

$$P = 1 - \exp\left(-\frac{nr\xi_0}{Q}\right) \text{ (14)}$$

where $P$ is the infection risk, $n$ is the number of infectors, $r$ is the quantum generation rate, $\xi$ is the breathing rate, $Q$ is the volume
flow rate of the space, and $t_0$ is the exposure time. Notice that the Wells-Riley equation was originally applied to evaluate the risk of infection for one room. When it is applied to assess the risk of cross-infection in a multistory building with several rooms, the quantum generation rate for the receptor rooms can be determined based on the re-entry ratio [30,49]. Therefore, the Wells-Riley equation is rewritten as,

$$p_R = 1 - \exp\left(-\frac{nr_\delta t_0}{\Delta R}\right)$$

(15)
The quantum generation rate $r$ in Equation (15) cannot be directly obtained, which is generally estimated from a specific outbreak case of pandemic virus. The breathing rate $\xi$ and the exposure time $t_0$ can be specified based on the detailed information of infectors. In our study, the parameters $n$, $r$, $\xi$ and $t_0$ are specified according to the work by Gao et al. [30]. In their study [30], the infection risk in a high-rise building with single-sided ventilation driven by the combination of wind and buoyancy forces was assessed. To illustrate the differences of the infection risk caused by different forces, the parameters for our present study are $n = 1,$
Fig. 11. Relationship of re-entry ratio versus ACH for different floors.

Fig. 12. Relationship of infection risk versus ACH for different floors.
$r = 13$ quanta/h, $\xi = 0.6\text{ m}^3$/h, $t_0 = 8\text{ h}$. It is assumed that an infecter stands in the center of the first floor room, and the virus transmission is between the source floor and the second floor and between the source floor and the third floor.

Fig. 12 presents the relationship of infection risk versus ACH for different floors. As shown in Fig. 12(a), the infection risks for different window configurations are almost identical in the first floor room due to the amount of virus released by the infecter. However, the infection risks for window styles on the second and third floors are different from each other. Obviously, the infection risks for TILT, VSW and VPW cases are relatively higher when the ACH is small in the second floor room. With increasing ACH, the differences between window styles gradually decrease, as illustrated in Fig. 12(b). On the third floor, the infection risk for each window style further decreases the re-entry ratio of the exhausted air, as shown in Fig. 12(c).

Fig. 12(d) presents the infection risk in the case of airborne transmission driven by a combination of buoyancy and wind forces determined by Gao et al. [30]. As shown in Fig. 12(d), the infection risks in the floor room where the infecter is located (i.e., source floor) and the receptor room (i.e., upper floor) present similar orders of magnitudes to our study. On the source floor, the infection risk decreases with increasing ACH although ambient wind is considered in Gao et al., which is the same as our findings on the first floor (i.e., source floor). The largest risk of infection is 6.6% on the upper floor when the wind is 2 m/s, which corresponds to the highest re-entry ratio of the exhausted air but does not correspond to the smallest ACH. Therefore, the wind in practical conditions may either reinforce or suppress the pollutant cross-transmission.

To represent realistic performances of window configurations on cross-transmission, the incident wind must be carefully considered in future research.

4. Conclusions

A computational study investigated gaseous pollutant transmission through variable window styles between vertical floors in a multistory building with buoyancy-driven, single-sided natural ventilation. Detailed characteristics of airflow and pollutant distributions inside and outside the building were obtained using CFD. It was shown that it was reasonable to combine the RANS model and a scalar transport equation to solve passive pollutant transmission. The CFD predictions were compared with experiments by Jiang and Chen [41] and Grabe et al. [42] to substantiate the computational models employed.

Six window styles were examined to determine their performance with reducing pollutant cross-transmission to rooms above the source room. The ACH generally increased with increasing open area for each window style. However, there was a decrease in average pollutant concentration with the increasing window open area. The pollutant concentration reduced one order of magnitude between the source floor and the upper floors for each window style. Furthermore, the pollutant concentration on different floors was not only affected by the ventilation rate but also by the window configuration. Among the six window types, the AW style showed the best performance for restricting pollutant cross-transmission, although it was not able to provide larger ventilation rates. The VSW and HPW styles performed adequately and the VPW, TILT and TURN types performed the worst.

It was further shown that the re-entry ratio of the exhausted air re-entering the upper floors generally decreased with increasing floor for each window type. The risk of infection was shown to decrease when evaluated using the Wells-Riley model. Coupled with the previous conclusions, the infection risk can also be controlled by ventilation rate and window configuration. Therefore, window configuration and the ventilation rate should be considered together to reduce the risk of infection in practice.

Acknowledgements

The present research in the paper was co-supported financially by National Key Research Program in the Thirteen Five-year Plan Period of China through Grant No. 2016YFC0700500 and China Scholarship Council through Grant No. 201506060017. The Advanced Research Computing at Virginia Tech provided the computational resources and technical support that have contributed to the results reported within this paper (www.arc.vt.edu).

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