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Numerical investigation of gaseous pollutant cross-transmission for single-sided natural ventilation driven by buoyancy and wind

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**ABSTRACT**

Single-sided natural ventilation was numerically investigated to determine the impact of buoyancy and wind on the cross-transmission of pollution by considering six window types commonly found in multistory buildings. The goal of this study was to predict the gaseous pollutant transmission using computational fluid dynamics based on the Reynolds-averaged Navier-Stokes equations and baseline k-ω turbulence equations. The results indicated that ventilation rates generally increased with increasing wind speeds if the effects of buoyancy and wind were not suppressed; however, the re-entry ratio representing the proportion of expelled air re-entering other floors and the corresponding risk of infection decreased. If the source of the virus was on a central floor, the risk of infection was the highest on the floors closest to the source. Different window types were also considered for determining their effectiveness in controlling cross-transmission and infection risk, depending on the source location and driving force (e.g., buoyancy and wind).

1. Introduction

People spend 85%–90% of their time indoors, motivating the need to control indoor pollutants, and prevent or reduce indoor health risks [1, 2]. Natural ventilation is generally considered to be an effective solution for reducing indoor pollutants but must be carefully examined to determine its effectiveness. For example, natural ventilation may cause pollutant transmission between multistory households [3], which can be adversely affected if they are adjacent to households with high levels of indoor pollutants [4]. Moreover, the airborne transmission may contribute to the spread of infectious diseases, as demonstrated during the worldwide outbreak of severe acute respiratory syndrome (SARS) in 2003 [5–7]. The SARS virus was detected in rooms where the occupants did not carry the virus, suggesting that natural ventilation was responsible for the cross-transmission [8]. Clearly, additional efforts should be dedicated to investigate the mechanisms of pollutant cross-transmission through natural ventilation. In that regard, single-sided natural ventilation through windows that are flush with a building facade significantly increases the potential for pollutant transmission between multistory households and motivates our study [9].

The driving forces of single-sided natural ventilation are buoyancy or wind, or a combination of the two. These forces considerably impact the pollutant transmission between households in multistory buildings [9, 10]. Pollutant transmission with either buoyancy- or wind-driven airflow has been extensively studied. The methods primarily included full-scale experiments, small-scale experiments, multi-zone simulations, and computational fluid dynamics (CFD) simulations. Lim et al. [11, 12] used full-scale experiments and multi-zone simulations to investigate pollutant cross-transmission in a hospital. Pollutants expelled by patients on the lower floors re-entered upper floors via buoyancy-driven airflow; hence, inhibiting cross-transmission was proposed as a preventative measure. Mu et al. [13, 14] utilized wind tunnel tests and CFD simulations to evaluate the impacts of the wind direction and source location on pollutant cross-transmission via wind-driven ventilation in a multistory building. The results indicated that the cross-infection risks in leeward conditions were not always lower than those in windward conditions. Other similar studies based on experiments and simulations have examined airflow paths and the corresponding pollutant cross-transmission, as impacted by balconies [15–17], mechanical exhaust systems [18], and the characterization of a global Reynolds number for indoor and outdoor airflow [19].

Pollutant cross-transmission driven by a single force is not realistic because buoyancy and wind typically act together to transport pollutants between households in buildings. Wu et al. [20] applied full-scale...
experiments to compare the contributions of buoyancy and wind forces during pollutant transmission between households on the same floor in a residential building. The experiments revealed that the wind force was dominant and produced more noticeable effects on the cross-transmission. The spread of pollutants from the released location to other spaces was shown to be enhanced by the ambient wind. Mao et al. [21] utilized multi-zone simulations to study the spread of pollutants via a combination of buoyancy and wind on the same and different floors. The indoor-outdoor temperature difference, ambient wind, building tightness, and source location collectively affected the pollutant cross-transmission in high-rise buildings. The pollutant concentration was reduced by 3–4 orders of magnitude on the floors above the pollutant source. Gao et al. [22] used CFD simulations to assess if wind exacerbated or suppressed the upward pollutant transmission. The results indicated that low-speed winds induced pollutants to enter upper floors, whereas high-speed winds formed an air curtain near the building facade and restricted pollutant transmission between floors. Furthermore, Mu et al. [23] used CFD to simulate the effects of solar radiation on the facade of a high-rise building and determined the impact of the facade’s direction (sun-side or shade-side) on the re-entry of pollutants into the upper floors.

The driving forces, as well as window and door configurations, that altered the ventilation rates can impact pollutant cross-transmission. It has been shown that some openings serve as a barrier (e.g., a partially opened tilt window) and effectively restrict pollutant transmission between floors, even under active ventilation conditions [4]. Gao and Lee [24] applied full-scale experiments to identify the ventilation performance of three window types and found that the performances varied based on the window types and locations. Heiselberg et al. [25] and Grabe et al. [26,27] used small-scale experiments to further study the characteristics of jets and stratified airflows through typical windows.

Table 1

| Window types | VSW | TILT | AW | HPW | TURN | VPW |
|--------------|-----|------|----|-----|------|-----|
| Open area A (m²) | 0.8733 | 0.8733 | 0.8733 | 0.8733 | 0.8733 | 0.8733 |
| Open gap δ (m)  | 0.355 | 0.401 | 0.401 | 0.223 | 0.324 | 0.209 |

Table 2

| Building | External domain |
|----------|-----------------|
| Location | Type/Value      | Location | Type/Value |
| Ceiling  | No-slip/Adiabatic | Top      | Free-slip/20 °C, 1 atm |
| Floor    | No-slip/28 °C | Ground   | No-slip/Adiabatic |
| Walls    | No-slip/28 °C | Sides    | Symmetric (left and right sides) |
| Front    | No-slip/Adiabatic | Front   | Velocity inlet/ambient (y/10)\(^{0.14}\) |
| Back     | Ambient/20 °C, 1 atm |

Fig. 1. Building model and computational domain for the study.

Fig. 2. Schematic of each window type (refer to Table 1 for dimensions).
and compared the ventilation rates and airflow resistances. Wang et al. [28] utilized CFD simulations to characterize wind-driven ventilation through three window types and developed semi-empirical models to predict ventilation rates. Furthermore, Wang et al. [29,30] numerically investigated single-sided ventilation using six window types, based on buoyancy alone and a combination of buoyancy and wind. The building thermal conditions and window ventilation depended on the window type, even when the window opening areas were identical. Recently, Larsen et al. [31] developed a new formula for predicting the airflow rate for single-sided natural ventilation, which was more accurate than the existing equations. However, the new model underestimated airflow rates compared to the CFD predictions.

The review of the previous studies indicates that pollutant cross-transmission in single-sided natural ventilation driven by either buoyancy or wind alone is not a realistic scenario, but combinations of these forces need to be considered. Furthermore, the impacts of window configurations on ventilation rates have received considerable attention, whereas studies on pollutant cross-transmission and window configurations remain somewhat limited. Extending our previous study [4], the work herein investigates gaseous pollutant cross-transmission due to buoyancy and wind for single-sided natural ventilation. The impacts of ambient wind, window configuration, and source location on pollutant cross-transmission are discussed, and new insights into cross-transmission are provided.

Fig. 3. CFD validation of air velocity and temperature in buoyancy-driven natural convection with experiments by Betts and Bokhari [44].
2. Methodologies

In this section, the geometrical model for single-sided natural ventilation through various windows in a multistory building is described, followed by a brief introduction of the governing equations, numerical solutions, and model validation studies.

2.1. Geometrical model

The geometrical model representing the multistory building for the study of pollutant cross-transmission is shown in Fig. 1. Three floors were used to represent the multistory building, and the rooms on each floor had the same dimensions of 2.5 m (L) × 3.5 m (W) × 3.2 m (H), similar to that proposed by Grabe et al. [26,27]. Six types of windows were considered: vertical slide window (VSW), tilt window (TILT), awning window (AW), horizontal pivot window (HPW), turn window (TURN), and vertical pivot window (VPW). Fig. 2 illustrates the window types: each window is 1.23 m (w) × 1.48 m (h). The open area A and gap δ of each window type, which correspond to a typical window opening, are summarized in Table 1. The open gaps were not identical to ensure the same open area for each window.

The size of the computational domain was 25L × 9W × 12H, and the resulting blockage ratio of the domain was 2.8% (and within the recommended limit of less than 3.0%), ensuring fully developed airflow [32–34]. The combined force that drives the airflow through the building was induced by the indoor-outdoor temperature difference and ambient wind. When the outdoor temperature was below 23 °C, the mean thermal sensation could be controlled within 0.5 °C [35]. Therefore, to ensure meaningful results, an outdoor temperature of 20 °C was specified. In accordance with guidelines from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, if the outdoor temperature is 20 °C, the maximum acceptable indoor temperature is 27.5 °C [35]. Hence, an indoor temperature of 28 °C was specified, and the 8 °C temperature difference between the interior and exterior of the building was consistent with our previous study [4].

A power law velocity profile was employed to represent the wind in the atmospheric boundary layer. The mathematical form of the power law equation is $U_{\text{wind}} \approx U_{\text{net}} \alpha (y/\delta)^{\beta}$, where $U_{\text{net}} = 1–5$ m/s, $\delta = 10$ m, $\alpha = 1.0$, and $\beta = 0.14$, to represent a breeze over terrain with some trees or low-rise buildings [36]. Fig. 1 shows one scenario when the pollutant source (marked by *) was located in the center of the first floor room. For this study, the pollutant source was alternately located on the first, second, or third floor, and was denoted as Source 1, Source 2, or Source 3, respectively. A tracer gas representing the gaseous pollutant was released at a constant rate of 20 μg/s. More details regarding the settings are provided in our previous studies [4,29,30].

2.2. Numerical model

The Reynolds-averaged Navier-Stokes (RANS) equations and the baseline k-ω turbulence model were employed to predict the incompressible turbulent airflows in the indoor and outdoor environments [37,38]. The RANS equations govern the transport of averaged flow quantities, with an appropriate turbulence model for representing a
range of turbulence scales. Compared with large eddy simulation and detached eddy simulation models, the RANS-based modeling approach significantly reduces the required computational power and resources [34,37]. Several studies have successfully employed RANS models to predict indoor and outdoor airflows in windward and leeward conditions [23,39]. The baseline k-ω turbulence model, which is a two-equation eddy-viscosity model, was also found to yield satisfactory accuracy and stability when modeling an indoor airflow [40]. Moreover, studies have indicated that the baseline k-ω model performs better for solving flow over a back-step, which is a similar configuration to flow around a building, as compared with other two-equation eddy-viscosity models [38]. The use of the RANS and baseline k-ω models to predict the turbulent airflow will be validated in the study.

The Boussinesq approximation was used to model the buoyancy effect caused by the variations in air density [37,41]. A scalar transport equation based on the Eulerian method was used to solve the gaseous pollutant transmission along with airflow [37,42]. The governing equations were solved using ANSYS Fluent (Version 18.0) and were discretized using second-order upwind schemes. A pressure staggering option scheme and semi implicit pressure linked equation algorithm were used to solve the dependent variables. The convergence criteria were set to 10^{-5} for all the variables, and several representative variables were monitored to ensure that convergence was reached. The computational boundary conditions are summarized in Table 2.

The appropriate grid resolution was determined using the procedure for discretization uncertainty proposed by Celik et al. [43]. The building interior mesh study used uniform cells with lengths of 2.5 cm (fine), 5.0 cm (medium), and 10 cm (coarse). Exterior to the building, the mesh was refined near surfaces where the average cell lengths were 15.0 cm (fine), 17.5 cm (medium), and 20.0 cm (coarse). The discretization error for the medium-to-fine mesh was 4.25% using the grid convergence index [43], demonstrating that the solutions were not grid-dependent. The final mesh used the medium resolution for the building interior and the coarse mesh for the building exterior, for a total of 740–760 million cells for the different window cases. The computations ran on dual-node 2.6-GHz Intel Xeon processors with 64 GB of RAM. Each processor contained eight processing cores and a single simulation required approximately 120 h to achieve convergence. Further details regarding the governing equations, numerical solutions and grid resolution have been discussed in detail by the authors [4,29,30].

Fig. 5. CFD validation of air velocity in wind-driven ventilation with experiments by Jiang et al. [46].

Fig. 6. Airflow pattern around a multistory building for the VSW case at the wind speed of 5 m/s.
2.3. Model validation

The numerical models were validated using three different experiments for buoyancy- and wind-driven airflow to guarantee the accuracy of the simulations. The work by Betts and Bokhari [44] was used to validate the thermal airflow profiles during buoyancy-driven natural convection. The experiment by Perino and Heiselberg [45] was utilized to validate the tracer gas transmission via buoyancy-driven ventilation. The measurements from Jiang et al. [46] were applied to validate the isothermal airflow profiles in the wind-driven ventilation. The three published experiments provided data for air velocity, temperature, ventilation rates and passive scalars, which were applied to comprehensively examine the validity and robustness of the CFD models.

In the experiment by Betts and Bokhari [44], natural convection of air in a rectangular cavity was measured at three vertical locations, as shown in Fig. 3(a). The internal turbulent airflow was driven by a temperature difference created by cold (left surface) and hot (right surface) walls, corresponding to a Rayleigh number of $1.43 \times 10^6$. The air velocity and temperature profiles in the cavity were measured by laser Doppler anemometry and K-type thermocouples [44], and Fig. 3(b)–(g) compare the profiles with our CFD simulations at each vertical location. Between the cavity walls, the velocity profiles demonstrated that the air descends near the cold wall and rises near the hot wall,
corresponding to the changes in temperature and thus density. In general, the CFD predictions for the air velocity and temperature were in excellent agreement with the experimental data.

In the experiment by Perino and Heiselberg [45], the facility consisted of a small test chamber situated within an environmental chamber, as shown in Fig. 4(a). The temperature difference between the test chamber and the environmental chamber was kept as 5 °C, whereby the indoor (chamber) environment was warmer. Due to the temperature difference, air in the test chamber moved through the open window and exhausted via two small openings in the ceiling of the environmental chamber. The fiber shield was used to prevent the warm air from the test chamber mixing with the supply air. Carbon dioxide (CO\textsubscript{2}) was chosen as the tracer gas, which was uniformly distributed in the test chamber.

Perino and Heiselberg [45] also performed a CFD analysis employing the RNG k-ε turbulence model, and compared the prediction for airflow rate in terms of air change rate per hour (ACH) with their experiment. As shown in Fig. 4(b)–(c), the ACH and CO\textsubscript{2} concentration decreased as time progressed. Perino and Heiselberg [45] reported that their CFD simulation under-predicted the experiment for ACH; however, our CFD predictions are in better agreement with their experiments. Furthermore, our CFD predictions for CO\textsubscript{2} concentrations were in good agreement with the experiments [45]. Therefore, the results provided further evidence that the CFD models were credible to solve the tracer gas transmission via buoyancy-driven airflow.

In the experiment by Jiang et al. [46], a cubic building with a door was placed in a wind tunnel to replicate ambient conditions, as shown in

Fig. 8. Relationship of average concentration versus ambient wind.
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Fig. 5(a). Velocities were measured along the center-plane of the wind tunnel at 10 downstream positions, and data were collected at 18 vertical positions for each downstream position. The velocities at three downstream positions, denoted as P1 (windward), P2 (center of the building), and P3 (leeward) in Fig. 5(a), were used to validate our CFD model. Fig. 5(b)–(d) compare the air velocity profiles for the windward, center, and leeward locations relative to the building, respectively, with an unmistakable agreement between our CFD predictions and the experimental data of Jiang et al. [46]. Therefore, the validation studies comparing the CFD data to the experimental data have shown that the CFD models can predict gaseous pollutant cross-transmission along with single-sided natural ventilation, as driven by the combined forces of buoyancy and wind.

3. Results and discussion

Six types of windows (Fig. 2) were assessed for pollutant cross-transmission through single-sided natural ventilation in a multistory building (Fig. 1). The effects of the ambient wind and pollutant source location on cross-transmission and the assessment of infection risks are discussed. The Archimedes number Ar, which represents the ratio of the buoyancy force to the inertial force of the ambient wind, is used to identify the dominant driving force of the natural ventilation. The wind speed is estimated to be approximately 1.6 m/s when the buoyancy force is comparable to the wind force. When the wind speed is higher than 1.6 m/s, the wind becomes dominant. Otherwise, buoyancy is the dominant force. Notably, the dominant force driving airflow through windows into buildings also varied with window configurations and spatial positions. Therefore, identifying the dominant force using the Ar criteria can only provide a preliminary estimation.

3.1. Effects of ambient wind on ventilation

The three dimensional flow around a bluff body is paramount to our understanding of the flow mechanisms for wind-driven scenarios in the vicinity of buildings [47,48]. Fig. 6 shows the airflow pattern for the VSW case at a wind speed of 5 m/s in the windward condition. As shown in Fig. 6, the airflow can be divided into a downward circulation region (A), a stagnation region (B), an upward separation region (C), and a recirculation region (D) consisting of a large vortex [49,50]. The flow separation and vortex development demonstrate the complex nature of the flow around a building. As the dominant driving forces change, the airflow patterns become more complex. Moreover, with windows located in different regions relative to the airflow, the ventilation can vary significantly from one configuration to the next. Hence, the transmission of pollutants can fluctuate significantly between different floors.

The air change rate per hour is used to quantify the ventilation rate, which is defined as the ratio of the volume flow rate through a room to the volume of the room in a 1-h period. The volume flow rate was calculated by integrating the velocity perpendicular to the window opening based on the steady airflow field provided by the RANS-based model [18,51,52]. The air velocity near the opening should be carefully examined to eliminate false contributions by short-circuiting flows or turbulence-induced ventilation. Notably, the method for determining the ACH used herein is reasonably valid for steady airflow conditions. The impacts of time-dependent dynamics caused by the fluctuating ambient wind on heat and mass transfer were not considered. In addition, it has been reported by Mu et al. [23] that the ACH calculations were slightly higher than the tracer gas decay method, while the results approximated those predicted by empirical models [23]. Nevertheless, the calculation of ACH based on the steady flow field from the RANS-based model was still widely used, in view of the desirable computing efficiency and detailed information that can be provided [18,23,52]. Fig. 7 presents the relationship of the ACH and wind speed for windward (left column) and leeward (right column) conditions for each floor. In the windward conditions, the wind could either assist or oppose the buoyancy force to ventilate the building, depending on the wind speed. The buoyancy force was dominant when the wind speed was low, whereas the wind force became dominant as the wind speed increased. When the dominant force switched from buoyancy to wind, the ACH first decreased and then increased with increasing wind speed. After that, the wind dominated the building ventilation, and the ACH generally increased with increasing wind speed in the windward conditions (and was more substantial than that in the leeward conditions). ACH was the largest for the first floor, moderate on the second floor, and increased slightly on the third floor. This was due to the airflow patterns in front of the building, and the higher ACH on the third floor was also

Fig. 9. Contours of concentration for different window configurations at the wind speed of 1 m/s.
caused by the flow separation above the building. Fig. 7 also shows a comparison of the window types, and indicates that the airflows driven by the combined force for different window types were not equal, even though the areas of the openings for each window type were identical. The HPW, VPW and TILT types performed noticeably better than the other three window types (Fig. 7(a), (c), and (e)). The HPW, VPW, and TILT types create openings that effectively direct ambient wind into a building. In contrast, the other three window types impede the wind from entering the building, whereby the window panes block the airflow path. In leeward conditions, changes in the ACH with wind speed and building floor were less prominent than in the windward conditions. By comparing the ventilation rates for each window, the TILT type was found to provide better ventilation performance across all flow conditions, whereas the other window types were similar to each other (Fig. 7(b), (d), and (f)). Overall, greater ventilation was achieved as more air entered the buildings. Notably, the ventilation performance of the HPW type varied significantly with the floor level.

3.2. Effects of ambient wind on cross-transmission

Fig. 8 presents the relationship between the average concentration and wind speed in both windward and leeward conditions; the pollutant source was located in the center of the first floor room. The ordinates in Fig. 8 (a, b), (c, d), and (e, f) are different, as the pollutant concentration...
concentrations were significantly different for each floor. In the windward conditions, the average concentration reached approximately ~100 ppb on the first floor (where the pollutant source was located), and less than ~1 ppb on the second and third floors. The average concentrations fluctuated with increasing wind speeds because the buoyancy and wind forces counteracted one another. The wind suppressed the airflow, and the buoyancy induced the airflow; once the forces matched intensity, minimal air was allowed through the windows, and the pollutants remained indoors. The pollutant concentration fluctuation was more evident on the first floor. Further discussion on the counteracting phenomenon of the buoyancy force and wind force was provided in our previous work [30].

Among the six window types, the AW and TILT types exhibited the best and worst abilities in restricting the pollutant from entering upper floors, as shown in Fig. 8(c) and (e). The average concentrations in the leeward conditions were higher than those in the windward conditions. The concentrations reached approximately ~10 ppb and ~1 ppb on the second and third floors, respectively. A monotonic decrease in the average concentrations appeared when the wind speed increased. In conditions with low wind speed, the AW and VSW types demonstrated the best and worst performances, respectively, in preventing pollutants from entering the upper floors. With increasing wind speed, the HPW and TURN types gradually performed better, whereas the TILT and VPW types were not as effective, as shown in Fig. 8(d) and (f).

Fig. 9 presents the contours of the pollutant concentration at the central x-plane of the building with the various window types at a wind speed of 1 m/s. The AW type effectively restricted the pollutant within the room where the source was located, as shown in Fig. 9(e) and (f). In contrast, the TILT type had the adverse effect of directing the pollutant into the upper floor windows, as these window panes do not redirect the flow, as shown in Fig. 9(c) and (d). The VSW and TURN types generated similar paths for pollutant transmission between floors, although the window configurations were very different from each other, as shown in Fig. 9(a), (b), (g), and (h). The airflow paths for the HPW and VPW types were almost identical to those of the TILT and TURN types, respectively; hence, the HPW and VPW cases are not shown in Fig. 9. Regarding the pollutant concentration for each window type, a pollutant cloud was visible near each window, which exacerbates the infection risks to adjacent buildings owing to cross-transmission.

3.3. Effects of source location on cross-transmission

Fig. 10 presents the relationship of the average concentration and source location in both windward and leeward conditions for each window type at 1 m/s. The location of the pollutant source in a multi-story building is another critical factor affecting cross-transmission. When the source was situated in the first floor room, the pollutant transmission to the upper floors was more significant for each window configuration in leeward conditions. When the source was in the second floor room, more pollutant was transported to the lower floor in windward conditions. In contrast, the pollutant transmission to the upper floor became more substantial in leeward conditions for all window types except the AW. When the source was located in the third floor room, the pollutant concentration on the first floor was minimal, as the first floor was far from the source. Overall, the VSW and AW types were the most effective in reducing pollutant transmission. The airflow driven by the buoyancy force transported the pollutant to the upper floors,
whereas the wind-driven airflow created a bidirectional transmission because of the different flow patterns forming near the facade. Consequently, the pollutant transmission to the upper and lower floors caused by the coupled effects of buoyancy and wind depended on the location of the source.

3.4. Infection risk by cross-transmission

The previous sections demonstrated the importance of pollutant transmission and the need to understand the risk of infection. The re-entry ratio was used as an additional indicator of the infection risk due to cross-transmission. The re-entry ratio $\eta$ is the fraction of expelled air from the source floor to other floors [3],

$$\eta_R = \frac{C_{ave,S}Q_R}{C_{ave,SR}Q_{SR}}$$

where $C_{ave}$ is the average pollutant concentration, $Q$ is the volume flow rate, $R$ is the floor number (1, 2, 3, etc.), and SR is the source floor.

Fig. 11 shows re-entry ratios $\eta_2$ and $\eta_3$ versus wind speed when the source was located on the first floor. Generally, the re-entry ratio decreased with increasing wind speed and floor level. A clear trend was not apparent in the re-entry ratio when the wind speeds were less than 3 m/s in the windward conditions, and the buoyancy and wind forces were comparable. With wind speeds greater than 3 m/s, the TILT and VPW
types exhibited higher re-entry ratios, as shown in Fig. 11(a) and (c). In the leeward conditions, the buoyancy was insignificant with increasing wind speeds. The HPW and VSW types had larger re-entry ratios at low wind speeds, but all window types were progressively more comparable with increasing wind speeds. However, the HPW type performed the worst among the six window types on the third floor, as shown in Fig. 11(d). Overall, the maximum re-entry ratio reached approximately 5% and 11% in the windward and leeward conditions, respectively. Therefore, the infection risk due to cross-transmission should be carefully considered when selecting windows for multistory buildings.

The infection risk of a pandemic virus through airborne transmission can be predicted by the Wells-Riley equation [53,54] using the re-entry ratio. The Wells-Riley equation for evaluating the infection risk from cross-transmission in adjacent rooms in a multistory building can be expressed as [53-56],

\[
P_R = \exp \left( \frac{-nm_{r}RT_{0}}{Q_{r}} \right)
\]

where \( n \) is the number of infectors, \( r \) is the quantum generation rate, \( \xi \) is the breathing rate, and \( t_{0} \) is the exposure time. Further details on the parameters and their values are discussed in the references [4,22,57]. Fig. 12 shows the infection risk versus wind speed for each floor when the virus is released by an infector on the first floor. In the windward conditions, the infection risk decreased with increases in wind speed and floor level, except with the VSW and TURN types at 2 m/s; this effect was caused by the suppression of buoyancy and wind. The risk of infection when using the VSW and TURN types on the first floor was greater than 50%. With increasing wind speeds, the AW and TILT windows had the highest infection risk, as shown in Fig. 12(a), (c), and (e). In the leeward conditions, the infection risk was smaller on the virus-released floor, but was larger on the non-released floors. Among the six window types, the VSW type created the highest infection risk because of cross-transmission, as shown in Fig. 12(d) and (f). Additionally, the highest infection risk owing to cross-transmission was less than 3% in the windward and leeward conditions for the floors above the source of the virus. If the flow conditions, such as the driving force, window type, and source location, are changed, the infection risk from cross-transmission during the outbreak of a pandemic virus may become

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**Fig. 13.** Comparison of infection risk maps for different virus release locations.
extremely severe.

The Archimedes number (Ar) was used to further analyze the infection risk in cross-transmission by identifying if the dominant force was buoyancy or wind. The Ar is the ratio of the buoyancy force to the inertia force of ambient wind [30],

\[
Ar = \frac{gH}{T_{ave} U_{inert}}
\]

where \(g\) is the gravitational acceleration, \(H\) is the building height, \(\Delta T\) is the indoor-outdoor temperature difference, and \(T_{ave}\) is the average temperature between the indoor and outdoor environment. If \(Ar\) is greater than one, the buoyancy force induced by the indoor-outdoor temperature difference is dominant; if it is approximately one, the buoyancy and wind forces are comparable; if it is less than one, the wind force dominates the airflow during ventilation.

Fig. 13 presents infection risk maps when the virus is released on different floors as a function of the wind speed in windward or leeward conditions. The selected wind speeds are related to \(Ar\); hence, three cases are shown: \(Ar\) 2.5 (buoyancy-dominant), \(Ar\) 1.0 (buoyancy and wind), and \(Ar\) 0.1 (wind-dominant). When the infector released the virus on the first floor, the infection risk in the leeward conditions was higher when the buoyancy force was dominant, as shown in Fig. 13(a) and (b). With increasing wind speeds, the infection risk in the windward conditions was higher with comparable buoyancy and wind, as shown in Fig. 13(c) and (d). With higher wind speeds, there were no obvious differences in the infection risks for the windward and leeward conditions. Moreover, the infection risk was significantly reduced once the wind became dominant, as shown in Fig. 13(e) and (f). If the infector released the virus on the second floor, the infection risks on the first floor in the windward conditions and on the third floor in the leeward conditions were higher, as shown in Fig. 13(a)–(d). Once the wind exceeded the buoyancy, the infection risks on the first and third floors in the leeward conditions were higher, as shown in Fig. 13(e) and (f). When the infector released the virus on the third floor, the variances in infection risks versus wind directions were opposite to those in the first floor scenario, as shown in Fig. 13(a)–(d). If the wind speed was large enough, the infection risk became higher in the leeward conditions, as shown in Fig. 13(e) and (f). Furthermore, the infection risk when the virus was released on the second or third floor was reduced by 1–2 orders of magnitude compared to the infection risk on the virus-released floor. Therefore, an infector releasing a virus on the central floor of a building may pose a more severe threat, owing to the cross-transmission by upper and lower airflows between floors. Furthermore, the performances of the various windows in controlling the infection risks were inconsistent. Overall, the VSW type led to the highest infection risk when the virus was released on lower floors, whereas the AW type led to the highest infection risk when the virus was released on the upper floors. Moreover, the infection risks with the various window types on floors further from the virus release location were reduced when the ambient wind was sufficiently strong. Therefore, it was essential to combine the driving force and source location to evaluate the performances of the various windows in reducing the infection risk.

4. Conclusions

This study numerically investigated gaseous pollutant cross-transmission for single-sided natural ventilation driven by the combined force of buoyancy and wind, considering six typical window types. The impacts of the ambient wind and source location on the pollutant transmission between floors in a multistory building were evaluated based on CFD predictions. Moreover, this study assessed the infection risk from cross-transmission during an outbreak of a pandemic virus. The main conclusions and findings are drawn as follows.

The ACH increased with increasing wind speed when the buoyancy and wind were not suppressed. In the windward conditions, the HPW, VPW, and TILT window types provided better ventilation. In the leeward conditions, the TILT type showed better ventilation behavior, whereas the other window types were similar to each other. When the pollutant source was situated on the first floor, the average concentration caused by cross-transmission fluctuated with increasing wind speeds in the windward conditions. The AW and TILT types showed the best and worst abilities in restricting the pollutants from entering the upper floors, respectively. In the leeward conditions, the average concentration decreased when the wind speed increased. During low wind speed conditions, the AW and VSW types had the best and worst performance in preventing pollutant cross-transmission, respectively. The HPW and TURN types performed better with increasing wind speed, and the TILT and VPW types were worse.

The re-entry ratio decreased with increasing wind speeds, and was lower in the windward conditions, as the buoyancy and wind counter-acted each other. The re-entry of air may increase the risk of infection during an outbreak of a pandemic virus. The infection risks varied depending on whether the cross-transmission was dominated by buoyancy or wind. Moreover, the virus release location had a significant influence on the infection risk. Overall, the infection risk on the floor closest to the virus location was the highest. The performances of the various windows in controlling the infection risk were not consistent. When the flow conditions were changed, the abilities of the various windows to restrict the virus infection varied. Therefore, the driving force and source location should be considered together when evaluating the performances of various window types in reducing infection risk.

The findings revealed that the application of different window types on different floors in the same building may be a viable solution for controlling cross-transmission. These findings are helpful for guiding engineers and architects in selecting window types and operation strategies to maintain better ventilation and lower infection risks. Further studies are required on building geometries (width, height, orientation, etc.), surrounding building arrays, and multiple source locations. A large eddy simulation or detached eddy simulation could be used to explore the pollutant cross-transmission via transient airflow driven by the combined force of buoyancy and wind in future works.

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References

[1] C. Chen, B. Zhao, Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor, Atmos. Environ. 45 (2011) 275–288.
[2] World Health Organization, Health, sustainable development, Natural ventilation. https://www.who.int/sustainable-development/housing/strategies/natural-ventilation/en/, 2019.
[3] J.L. Niu, T.C.W. Tung, On-site quantification of re-entry ratio of ventilation exhausts in multi-family residential buildings and implications, Indoor Air 18 (2018) 12–26.
[4] J.H. Wang, T.F. Zhang, S.G. Wang, F. Battaglia, Gaseous pollutant transmission through windows between vertical floors in a multistory building with natural ventilation, Energy Build. 153 (2017) 325–340.
[5] I.T.S. Yu, Y.G. Li, T.W. Wong, W. Tam, A.T. Chan, J.H.W. Lee, D.Y.C. Leung, T. Ho, Evidence of airborne transmission of the severe acute respiratory syndrome virus, N. Engl. J. Med. 350 (2004) 1731–1739.
[6] Y.G. Li, X. Huang, I.T.S. Yu, T.W. Wong, H. Qian, Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong, Indoor Air 15 (2004) 83–95.
[7] Y. Li, S. Duan, I.T.S. Yu, T.W. Wong, Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens, Indoor Air 15 (2004) 96-111.
