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Airborne infection risk of inter-unit dispersion through semi-shaded openings: a case study of a multi-storey building with external louvers

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Abstract: Building design for natural ventilation and indoor air quality have become increasingly important during the past decades. Investigating airflow routes of airborne transmission and evaluating the potential infection risk in the multi-storey building is helpful to the reduction of airborne transmission. Therefore, this study applies computational fluid dynamics simulations to investigate the inter-unit dispersion pattern of gaseous pollutant between different units through semi-shaded openings. The airflow exchange and pollutant dispersion in a multi-storey building is driven by wind-induced natural ventilation. External shading louvers, which are widely used in building facades to reduce heat gain from solar radiation, are chosen to establish the semi-shaded environment. Experimental validation is performed to make sure the accuracy of numerical settings in airflow investigation of semi-shaded openings. The airflow characteristics around semi-shaded openings is analyzed in the numerical simulations. The re-entry ratio of tracer gas and the airborne infection risk of COVID-19 is investigated in the cases with different louvers’ locations and source units. The results show that the airflow is commonly slower in the semi-shaded space between louvers and openings. But the ventilation rate is not always consistent with the airflow speed because of the diversion effect from louver slats. The inter-unit infectious risk in the worst unit rises from 7.82% to 26.17% for windward
shading, while it rises from 7.89% to 22.52% for leeward shading. These results are helpful to the further understanding of inter-unit transmission of infectious respiratory aerosols through external openings with complex structures.

**Keywords**: Semi-shaded opening, Shading louvers, Natural ventilation, Gaseous pollutant, Infection risk

**Nomenclature**

- \( A \) Surface area, m\(^2\)
- \( ACH \) Air change rate per hour, h\(^{-1}\)
- \( C \) Concentration, ppm
- \( C_0 \) Initial concentration, ppm
- \( C_\mu \) Experimental constant for atmosphere boundary description, 0.09
- \( F_s \) Safety factor for grid-convergence index
- \( GCI \) Grid-convergence index
- \( h_0 \) Building height, m
- \( I \) Turbulence intensity
- \( k \) Turbulent kinetic energy, m\(^2\)/s\(^2\)
- \( n \) Number of infected persons
- \( p \) Formal order of accuracy for grid-convergence index
- \( P \) Infection risk
- \( Q \) Ventilation rate, m\(^3\)/h
- \( q \) Quanta generation rate, h\(^{-1}\)
- \( r \) linear refinement factor
- \( Re \) Reynolds number
- \( R_{re} \) Re-entry ratio
\( S_\varphi \)  Universal source term  
\( t_e \)  exposure time, h  
\( \bar{\overline{u}} \)  Mean velocity, m/s  
\( U \)  Airflow velocity, m/s  
\( U_0 \)  Airflow velocity for experimental fans, m/s  
\( U_1 \)  Airflow velocity from a relatively coarser grid, m/s  
\( U_2 \)  Airflow velocity from a relatively finer grid, m/s  
\( X, Y, Z \)  Coordinates, m  
\( y^+ \)  Dimensionless wall distance  

Greek symbols  
\( a \)  Power-law index for wind velocity profile  
\( \delta \)  pulmonary ventilation rate, m\(^3\)/h  
\( \varepsilon \)  Turbulent viscous dissipation rate, m\(^2\)/s\(^3\)  
\( \varphi \)  different scalars in general governing equation  
\( \Gamma_\varphi \)  Universal transport coefficient  

Subscripts  
\( H \)  characteristic height of building  
\( i \)  the source unit  
\( j \)  the target unit  
\( \text{ref} \)  reference  
\( v \)  ventilation  
\( W \)  characteristic height of window
1. Introduction

Airborne transmission is considered to be responsible for the spread of many respiratory infectious diseases such as tuberculosis, measles, influenza, smallpox and SARS[1]-[4]. Cross-infection of airborne transmission arises from the viral aerosols, which is generated in the respiratory tract and then spread by breathing, coughing, talking and sneezing [5]. During the pandemic of coronavirus disease 2019 (COVID-19), people are advised to stay indoors for longer time, such as remote work and self-isolation, in order to avoid cross-infection from short social distance and high density of occupants [6][7]. Natural ventilation is an effective method to reduce indoor gaseous pollutants, especially for resource-limited isolation buildings without negative-pressure ventilation settings [8]. However, for multi-storey buildings, airflow from indoor environment with viruses can spread over long distances and lead to larger outbreaks of infectious diseases [9]. In previous studies of airborne transmission of infectious diseases, viruses of Severe Acute Respiratory Syndromes (SARS) have been detected in units without infected occupant, which indicates the potential for cross-transmission under the influence of natural ventilation [10]. Therefore, it is necessary to evaluate cross-transmission of aerosol pollutants released from different units and cross-infection of indoor occupants in multi-storey buildings with natural ventilation.

Gaseous pollutants within a building unit can diffuse through windows and doors on the facade and then be carried back to other areas within the building via outdoor airflow. The dispersion characteristics and re-entry mechanisms of pollutants among units have been studied for different types of buildings and windows. In multi-storey buildings, wind-induced ventilation can significantly enhance gaseous dispersion within units and diffusion from the polluted unit to other units through external windows [11][13]. Previous studies have shown that the self-shading structural characteristics of building envelope have a significant impact on airflow characteristics near the walls and can change the natural ventilation effect of building units. Some accessory elements for envelope such as balconies and eaves, have blocking and diversion effects to change airflow routes around buildings, which is not negligible for evaluation of pollutant dispersion among building units[12]. For building facade with external shading devices, such as louvers [14], the semi-enclosed structure creates a narrow airflow
layer that can exchange exhaust air between different units in the same façade. Therefore, it is necessary to assess the wind-induced natural ventilation through semi-shaded external openings and to investigate the dispersion routes and re-entry effect of aerosol pollutants in semi-shaded environment.

The investigation of wind environment of shaded buildings was conducted in previous research by using experimental, numerical and analytical methods. Some studies evaluated ventilation capacity of buildings with shading devices. Argiriou et al. [15] used regression technique to introduce the correction coefficient in order to calculate airflow rates for different shading devices. Hien & Istiadji [16] investigated airflow velocity distribution of single rooms with different settings of overhangs. Research on horizontal and vertical shading boards shows that the type, the inclined angle and the number of shading devices can significantly influence indoor airflow pattern and ventilation rate of buildings [17]-[22]. Some studies focus on wind characteristics around buildings with louvers. Jiang et al. [23] experimentally measured airflow fields and numerically evaluated distributions of wind pressure coefficient on the sealed surfaces of a cubic building with semi-shading louvers. The shuttle louvers were also investigated by Zheng et al. [24]. The wind pressure changes through external louvers were measured by Lee et al. [25] around a cross-ventilation room to quantify the pressure loss rate for different rotation angles. It was found that the geometric dimensions of louvers, such as rotation angle and louver width, can affect airflow fields around shaded buildings as well as wind-induced characteristics on building surfaces. Kosutova et al. [26] performed wind-tunnel experiments and CFD simulations to investigate the cross-ventilation capacity of a isolated building equipped by two opposite louvered windows. The impact of window location on age of air and air exchange efficiency was discussed. Jiang et al. [27] investigated the ventilation rate and age of air in a multi-storey building and performed regression analysis to predict ventilation rate in different units for cross ventilation. However, the measured characteristics in the above studies only describe the airflow field and replacement capacity of ventilation. Although ventilation is often considered to be effective in diluting the infectious respiratory aerosols, these results cannot reflect the re-entry effect of virus aerosols during transmission and are not sufficient to describe the infection risk from virus aerosol transmission in multi-storey buildings with semi-shaded openings.

Cross-infection cases of aerosol transmission in public spaces have been reported in different kinds of indoor environment (e.g. apartments, offices, restaurants, school, and hospitals) and transportation process (e.g. airplanes, trains, buses, and cruises) [28]. Recent research of transmission
cases confirmed the aerosol transmission of SARS-CoV-2 and highlighted the biological stability of viruses in aerosols for days[29]-[31]. In this situation, accumulation effect of aerosol clouds is of concern for ventilated multi-storey buildings with potentially infective sources, such as the asymptomatic self-isolation patients, who have long periods to stay indoors. For these places, keeping social distances is not sufficient to the prevention of airborne pathogen infections because of the longer exposure time for occupants in other units. The virus-loaded aerosol from a distant occupant can accumulate to the minimum infectious dose in a unit during a long exposure time. To operate a better ventilation strategy, the assessment of inter-unit airborne transmission by computational fluid dynamics (CFD) method is recommended to predict the potential infection risks of residential occupants [32],[33].

Tracer gas measurements and CFD simulations were applied to simulate the dispersion of aerosol pollutants through airflow routes and have good performance to analyse the infection risk in COVID-19 outbreak[34],[35]. For multi-storey buildings with balconies in wind-induced natural ventilation, re-entry effect of exhaust airflow was evaluated and the reentry ratios are around 10% for obvious interunit dispersion from open windows on building facades [12]. However, many studies just focus on transport of gaseous pollutants and do not investigate specific infectious diseases. According to relevant medical studies, different viruses have different particle numbers in exhaled airflow [36]. The previous results cannot be directly applied to evaluate the infection risk of COVID-19 from airflow exchange through semi-shaded openings. Therefore, targeted prediction of COVID-19 cross-transmission based on experimental data of infection cases becomes critically important for ventilation strategies in multi-storey buildings with semi-shaded openings.

This study applies the CFD method to investigate the dispersion pattern of gaseous pollutant through semi-shaded openings in a multi-storey building with wind-induced natural ventilation. External shading louvers are installed near the building envelope to investigate the impact of limited near-wall space on airflow routes and inter-unit infection risk of COVID-19 by tracer gas technology. Experimental validation is performed to ensure the accuracy of computational settings in airflow velocity fields at semi-shaded openings. The effects of louvers’ location and source units on the pollutant dispersion are discussed. The results of this study will extend the understanding of building design to avoid the outbreak of respiratory infectious diseases in naturally ventilated buildings with semi-shaded openings.
2. CFD Simulation

2.1 Governing equation

The CFD approach has been widely applied to predict airflow fields and pollutant dispersion in built environment [12], [37]-[41]. To evaluate the influence of shading louvers on airflow characteristics for coupled indoor and outdoor environment, the steady Reynolds-averaged Navier-Stokes equations (RANS), which have a good balance between accuracy and computational consumption, were used to solve the airflow fields. For incompressible flow, the general form of time-averaged governing equations is given by Eq. (1) as follows:

\[
\frac{\partial}{\partial t}(\phi) + \nabla \cdot (\rho \mathbf{u}) = \nabla \cdot (\Gamma \nabla \phi) + S_{\phi}
\]  

(1)

where \( \phi \) represents different scalars including three velocity ingredients \( u_x, u_y \) and \( u_z \), turbulent kinetic energy \( k \), dissipation rate \( \varepsilon \), mean velocity \( \overline{\mathbf{u}} \), effective diffusion coefficient \( \Gamma \), and source term \( S_{\phi} \).

The governing equations in numerical simulations are discretized into algebraic equations by using finite volume method (FVM).

2.2 Turbulence Model

The \( k-\varepsilon \) turbulence models are widely used to investigate urban environment and indoor environment[42]. The Reynolds-averaged and time-averaged properties of airflow have sufficient accuracy to perform the simulation around lover-shaded buildings, despite some turbulent fluctuations are ignored in \( k-\varepsilon \) turbulence models[26],[27]. Based on the standard \( k-\varepsilon \) (SKE) turbulence model[43], some modified \( k-\varepsilon \) turbulence models, such as realizable \( k-\varepsilon \) (RKE) turbulence model [44] and renormalization group \( k-\varepsilon \) (RNG) turbulence model [45], can provide higher accuracy for some situations because of their better reproduction of swirling flows. Previous numerical research of wind environment around building show that the realizable \( k-\varepsilon \) turbulence model has good agreement with experimental data, especially at various angles of attack on buildings with facade components [38], [46], [47]. In our previous numerical and experimental investigation of a sealed building with louvers, the numerical results from the realizable \( k-\varepsilon \) turbulence model has a good agreement with experimental data of airflow velocity around the building [23],[48]. Therefore, the realizable \( k-\varepsilon \) turbulence model was applied to solve airflow characteristics and pattern of pollutant dispersion. An additional sensitivity
analysis of turbulence model, including SKE, RNG and RKE, is also performed for the detailed velocity fields at openings of the semi-shaded building in Section 2.7.1.

2.3 Geometric Model

In order to investigate the inter-unit dispersion around a multi-storey building with/without external louvers under wind-induced natural ventilation, a 1:15 reduced scale of a five-storey building was adopted. The geometric dimensions for the building, shuttle louvers and their geometric relationships are shown in Fig.1. Each floor has two units, and each unit has only one window on the external windward/leeward façade to generate single-sided ventilation. There is no any airflow connection (door, window, etc.) on internal surfaces between different units. The prototype geometry of shuttle louvers in the work of Tao et al. [49] is used in this present paper. For each shaded case, there are forty-eight slats of louvers near the shaded facade. The non-shaded building, windward or leeward shaded buildings are shown in Fig.2. The unit W1-W5 and L1-L5 represent the windward and leeward units from the first floor to the fifth floor. The wind direction of the approaching airflow is normal to the façade with openings. The reference case without louvers was applied to evaluate the distinctions from cases with windward and leeward single-sided louvers.

![Fig.1 Dimensions of the multi-storey building and shading louvers (dimensions in mm).](image-url)
Fig.2 Cases for non-shaded, windward louvers and leeward louvers.

2.4 Computational domain and boundary condition

The computational domain for the airflow fields of indoor and outdoor environment is based on the practical guidelines for numerical approach to be large enough to simulate airflow characteristics, as demonstrated in Fig.3. Two standards were applied to establish the dimensions of the computational domain, where the blockage ratio is below 3%[50],[51].

Fig.3. Dimensions of the computational domain for CFD simulation.

The boundary conditions of the computational domain are described in Table 1. The inlet of computational domain was defined as velocity inlet for the approaching airflow which follows a power-law profile. The airflow velocity $U$ and turbulent intensity $I$ were defined by the environmental parameters of terrain category. The reference velocity $U_{ref}$ of approaching airflow was 5.0 m/s. The reference building height $h_0$ is 1m for the case study. The power-law coefficient $\alpha$ describes the ground surface roughness, which was taken as 0.27 to correspond with our previous wind-tunnel experiments [23] and represents urban and suburban terrain with several buildings according to AIJ
Recommendations for Loads on Buildings [52] and ASHRAE handbook[53]. The kinetic energy $k$ and dissipation rate $\varepsilon$ are the parameters for turbulence model. The constant value $C_\mu$ is set as 0.09 [51]. The Reynolds number $Re_H$ for the characteristic height of the building is around $3.2 \times 10^5$, while $Re_W$ for the characteristic height of the opening on façade is around $3.2 \times 10^4$. The two $Re$ results achieve the critical values of the $Re$-independent requirement for coupled indoor and outdoor environment in wind-induced ventilation investigated in previous research from Dai et al. [54], whose recommended values are $7.9 \times 10^4$ for $Re_H$ and $3.0 \times 10^4$ for $Re_W$ to reproduce the full-scale flow.

**Table 1.** Boundary condition.

| Location          | Equation and type                                           |
|-------------------|-------------------------------------------------------------|
| Inlet             | $U(z) = U_\infty \left( \frac{z}{h_0} \right)^\alpha$     |
|                   | $I(z) = 0.1 \left( \frac{z}{h_0} \right)^{-0.85}$        |
|                   | $k(z) = [U(z)I(z)]^2$                                      |
|                   | $\varepsilon(z) = C_\varepsilon \alpha k(z) \frac{U(z)}{h_0} \left( \frac{z}{h_0} \right)^{-1}$ |
| Outlet            | $\frac{\partial (u_x,u_y,u_z,k,\varepsilon)}{\partial x} = 0$ |
| Ceiling           | $u_z = 0$                                                   |
|                   | $\frac{\partial (u_x,u_y,u_z,k,\varepsilon)}{\partial x} = 0$ |
|                   | $\frac{\partial (u_x,u_y,u_z,k,\varepsilon)}{\partial y} = 0$ |
| Lateral surfaces  | $u_z = 0$                                                   |
|                   | $\frac{\partial (u_x,u_y,u_z,k,\varepsilon)}{\partial x} = 0$ |
|                   | $\frac{\partial (u_x,u_y,u_z,k,\varepsilon)}{\partial z} = 0$ |
| Building surfaces, louver’s surfaces and the ground | Non-slip for wall shear stress, enhanced wall treatment |
The boundary conditions were defined as no-slip wall for the louvers, ground and building surfaces. For all wall boundaries, enhanced wall treatment was used to simulate the near-wall airflow. The top and lateral boundaries were defined as symmetry, where the normal vectors and normal gradients of all variables are defined as zero. The flow diffusion fluxes are set to zero at the outlet boundary.

2.5 Grid Resolution and grid independence analysis

The heights of the first near-wall grids on the ground, building surfaces and shading louvers are about 0.0003m, which is applicable for the enhanced wall treatment with $y^+ < 5$ and $y^+ \approx 1$ in near-wall boundary layers [55]. Fig.4 shows the grid resolution in the global computational domain and around the multi-storey building. The number of structured hexahedral cells is around $4.5 \times 10^6$ for each case.

![Grid resolution for numerical investigation.](image)

In the grid-independent analysis, a coarse grid and a fine grid resolution is performed based on the basic grid of the windward louvers with the linear refinement factor $r$ of about 1.3. As shown in Fig.5(a)-(c), the coarse, basic and fine grids have $2.0 \times 10^6$, $4.5 \times 10^6$ and $10.6 \times 10^6$ cells, respectively. Fig.5(d) and (e) present average dimensionless velocity distribution $U/U_{ref}$ at openings in different units obtained from the simulations with three grid resolutions. The grid-convergence index ($GCI$) [56],[57] given by Eq.(2) is applied to estimate the deviation between different grid resolutions:

$$GCI = \frac{r^p(U_1-U_2)/U_{ref}}{1-r^p} \times 100\%$$

where $U_1$ and $U_2$ represent the velocity from a relatively coarser and a relatively finer grid.
respectively. the safety factor $F_s$ is set as 1.25, and the formal order of accuracy $p$ is taken as 2 for the second-order discretization schemes in the simulations. The $GCI$ values at the openings of the ten units are all below 5%, which fulfills the requirement from Vinchurkar and Longest [58]. The $U/U_{ref}$ distribution at openings from the coarse grid has $GCI$ of 2.3% based on the fine grid, while the $U/U_{ref}$ distribution at openings from the basic has $GCI$ of 2.1% based on the fine grid. According to these results, the basic grid is considered to achieve grid independence and is therefore applied to perform the numerical study.

![Grid Resolutions](image)

**Fig.5.** Three grid resolutions for grid-sensitivity study and comparison of the average dimensionless velocity $U/U_{ref}$ at the openings in different units for $U_{ref}=5.0$ m/s.

### 2.6 Solver Settings

The numerical cases were performed by using the finite volume method for steady state in the commercial program ANSYS Fluent 19.2. The semi-implicit pressure linked equation (SIMPLE) algorithm was used for the pressure-velocity coupling. The second-order methods were applied to discretise the pressure, the convective and diffusive terms. More details about the solver settings are summarized in Table 2. Convergences were reached when the scaled residuals for $x$, $y$, $z$ momentum, energy and $CO_2$ concentration were below $10^{-5}$, and the scaled residuals for continuity, $k$ and $\varepsilon$ were
below $10^{-4}$. The gaseous pollutant was released and the concentration fields were generated after the airflow fields were stable for more than 1000 iterations. The monitors were set at specific points around building and louvers to verify convergences for more than 10,000 iterations.

| Item                        | Scheme                                                                 |
|-----------------------------|------------------------------------------------------------------------|
| Solver                      | Three-dimensional, pressure-based, segregated, implicit, double precision |
| Velocity Formulation        | Absolute                                                               |
| Time                        | Steady                                                                 |
| Pressure-velocity coupling  | SIMPLE                                                                 |

Spatial discretization:

| Gradient                  | Least squares cell based                                           |
| Pressure                  | Second order                                                      |
| Momentum, turbulent kinetic energy, turbulent dissipation rate, energy, CO$_2$ concentration | Second order upwind                                               |

Convergence criteria:

| Energy, $x, y, z$ momentum, CO$_2$ concentration | $10^{-5}$                        |
| Continuity, turbulent kinetic energy, turbulent dissipation rate | $10^{-4}$                        |

2.7 Model validation

The CFD methods have been validated in our previous research in wind-tunnel experiment for airflow pattern around a sealed building with shading louvers [23]. In this paper, since the inter-unit transmission is caused by aerosols dispersion through external openings, the experimental measurement and numerical validation is conducted for velocity fields at windows to predict airflow exchange of a shaded building. In addition, the validation of the numerical model to predict tracer gas
CO₂ concentration of exhaust flow from a ventilated building is also performed by an experimental study from Cui et al. [59].

### 2.7.1 Experiment measurement and CFD validation: airflow velocity at openings

The experiment validation was conducted in a cubic building with the dimensions of 2.0m×2.0m×2.0m, as shown in Fig.6(a). There were two openings with the dimensions of 1.38m×1.15m located at the windward and leeward facades. The external array of shading louvers was installed 0.6m in front of the windward façade. In Fig.6(b), the sizes of each slat of louvers were 2.0m×0.3m×0.05m and the rotation angle of louvers was set as 30°. The experiment set-up are set in an enclosed workshop (3.3m height) to avoid unsteady airflow from outside. The wind-induced airflow towards the studied building is generated by four multiple fans, which refers to the previous research from Lee et al. [25]. The empty region behind the leeward façade was more than 2.0m away from the cubic building to reduce blocking effect of indoor ventilation. In addition, there were some storage lockers and obstacles in the downstream section. An outlet was set at the downstream section to reduce obvious backflow around the experimental section. The velocity distributions were measured on the windward and leeward openings. The locations of measurement points of normal velocity are shown in Fig.6(c). To support the further numerical investigation where the velocity distribution at openings is important for airflow exchange between indoor and outdoor environment, the dense measurement points were set at the windows to verify the airflow fields through openings in our experimental set-up and CFD validation. Each opening had 35 measurement points. The point 1-35 located on the windward opening and point 36-70 located on the leeward opening. The wind generator parameters including airflow velocity and turbulence intensity were measured by anemometer with the range of 0-45m/s, the response time of 1s and the accuracy of ±3%. 
In the numerical simulation of the experiment, the computational domain was consistent with the whole workshop. The grid resolution with hexahedral mesh is shown in Fig. 7. The blockage ratio exceeded 10% in the experimental site and computational domain. Therefore, the studied building, wind generators, shading louvers and downstream obstacles were set as those in the experimental workshop to reduce the potential deviations in CFD validation. The shapes of obstacles were simplified as cuboids or prisms to reflect the ground roughness and the high blockage ratio. The iron frame of louver slats and the measurement equipment were ignored. The total cell number was around $4.0 \times 10^6$. The cell sizes in different regions are summarised in Table 3. The near-wall grids were densified by the mesh adaptation technology to ensure the average $y+$ value is close to 1.0 and the maximum $y+$ smaller than 5.0 for the enhanced wall treatments. For the wind generator inlet, the airflow velocity $U_0$ is 6.7 m/s and turbulence intensity is 21%. The approaching airflow provided a Reynolds number of
$9 \times 10^5$ to reach Reynolds-number independence. The pressure outlet had the static pressure of 0 Pa. Other boundaries were non-slip surfaces for wall shear stress. The solver settings and convergence criteria were the same as those in Section 2.6.

**Fig. 7.** Grid resolution for experiment validation.

**Table 3.** Main characteristics of the cell sizes.

| Location                     | Cell size (m)               |
|------------------------------|----------------------------|
| Building and louvers         | Average 0.03, maximum 0.06 |
| Upstream test section        | Average 0.04, maximum 0.07 |
| Downstream obstacles section | Average 0.06, maximum 0.08 |
| First near-wall layer        | About 0.0003                |

The validation of numerical methods are performed and three different steady RANS turbulence models, including SKE, RNG and RKE, are evaluated in sensitive analysis for predicting airflow fields at openings. Fig. 8 shows the comparison between the experimental and numerical data of the normal dimensionless velocity $U_x/U_0$ at the windward and leeward openings predicted by three turbulence models. The three simulation results along measurement points show the similar tendencies as that of experimental results. The absolute deviations of dimensionless velocity at each measurement point are calculated by Eq.(3):

$$\text{Absolute deviation} = \left| \frac{(U_{\text{CFD}} - U_{\text{EXP}})}{U_0} \right|$$  \hspace{1cm} (3)
where \( U_{\text{CFD}} \) and \( U_{\text{EXP}} \) represent the velocity from the numerical and experimental results, respectively. The average absolute deviations for SKE, RNG and RKE are 0.035, 0.042, and 0.036, respectively. For the windward opening, the maximum absolute deviations for SKE, RNG and RKE are 0.076 at point 19, 0.102 at point 7, and 0.083 at point 15, respectively. For the leeward opening, the maximum absolute deviations for SKE, RNG and RKE are 0.110 at point 69, 0.130 at point 68, and 0.089 at point 69, respectively. The deviation results show that the maximum discrepancy is more likely to locate near the window edges rather than the window center, which is similar to the previous research for indoor velocity distribution of a cubic building with embedded louvers from Kosutova et al. [26]. The main reason for deviations may be the non-rectified airflow generated by the multiple fans which lead to the unpredicted fluctuations of velocity distribution on the inlet. Nevertheless, the numerical methods with realizable \( k-\varepsilon \) turbulence model can reproduce the variation trend of velocity at openings in this study and the airflow fields around a shaded building in our previous research [23], [48], the realizable \( k-\varepsilon \) turbulence model are applied in the following study.

**Fig.8.** Comparison of dimensionless velocity \( U_i/U_0 \) between experimental data and numerical data from three RANS turbulence models for \( U_0=6.7 \text{m/s} \).

### 2.7.2 CFD validation: tracer gas concentration

In the experimental investigation performed by Cui et al. [59], the dimensions of test chamber was
3m×2m×3m for the tracer gas decay process to evaluate ventilation efficiency. The computational domain, dimensions and grid resolution in the CFD validation of tracer gas concentration are shown in Fig.9(a). The ventilated space was surrounded by wall with an inlet and an outlet at two parallel surfaces. At the beginning of tracer gas decay process, the CO₂ was mixed to obtain a uniform concentration distribution. Then, the decay method was taken when the CO₂ concentration reaches $C_0=3000$ppm to avoid the impact of transition period. The background CO₂ concentration of 430ppm was for the inlet airflow. The surrounding surfaces were defined as non-slip wall boundary and the outlet was set as outflow boundary. The dimensionless concentration $C/C_0$ was compared for the exhaust flow at the central point near the outlet as shown in Fig.9(a). Two cases with different airflow change rate per hour (ACH) were selected in the validation, where the higher $ACH$ is 40.6 h$^{-1}$ with the inlet velocity of 2.26m/s and the lower $ACH$ is 7.8h$^{-1}$ with the inlet velocity of 0.43m/s. The unsteady RANS method with the realizable $k$-$\epsilon$ turbulence model and enhanced wall treatment was applied in CFD validation. The second-order implicit scheme was applied for temporal discretization. Other solver settings were consistent with those in Section 2.6. The time step was taken at the range of 0.2-1.0s during the decay process according to the relevant research of contaminated air exiting from Liu et al. [60].
Fig. 9. Schematic view of tracer gas validation and comparison of dimensionless CO\textsubscript{2} concentration $C/C_0$ between experimental and numerical data for $C_0=3000$ppm.

The numerical results of dimensionless CO\textsubscript{2} concentration $C/C_0$ at the measurement point during the decay period are compared with the experimental results in Fig.9(b) and (c). The average absolute deviations of $C/C_0$ for the cases with $ACH$ values of 40.6 h\textsuperscript{-1} and 7.8h\textsuperscript{-1} are 0.008 and 0.015, respectively. The maximum absolute deviations of $C/C_0$ for the cases with $ACH$ values of 40.6 h\textsuperscript{-1} and 7.8h\textsuperscript{-1} are 0.033 and 0.089, respectively. In general, although there are some deviations between the simulation data and the experimental data, the numerical results are considered to be acceptable for predicting tracer gas concentration.

3. Results and discussion

In this section, the numerical investigation of airflow patterns, reentry effects and airborne...
transmission is performed in the five-storey building with/without shading louvers under single-sided natural ventilation. The impact of the location of louvers on airflow characteristics and pollutant dispersion is evaluated and then the infection risk of SARS-CoV-2 is discussed for different source units.

### 3.1 Airflow characteristics

The contours of airflow velocity and streamlines on the vertical midsurface are shown in Fig.10. Comparing the windward shaded condition with the non-shaded condition in Fig. 10(a) and (b), it is found that the airflow fields near the windward windows are changed greatly. Because of the diversion effects of the windward louvers on the airflow fields, some obvious vortexes are found at the windows on the first to fourth floors of the windward units, and the indoor vortexes also move to deeper regions in the units. The reattachment zone above the roof is extended backward due to the presence of windward louvers. Unlike the windward units, there is no vortex at the windows of the leeward units, and only the indoor vortex zones in the leeward units are modified slightly, which means that the windward single-sided louvers have less impact on the near-wall airflow fields around the leeward facade. In the simulation with leeward shading louvers in Fig.10(c), the airflow fields in the windward unit are basically similar to those in Fig.10(a), but the centers of vortexes in the leeward units move to the deeper position in each unit. These distinctions indicate that the existence of shading louvers can affect air exchange between indoor and outdoor environment and then change the dispersion routes of gaseous pollutants among different units. Fig.11(a) and (b) show the outdoor velocity distributions in the diversion zones between the windows and shading louvers (if present). Compared the two shaded conditions with the non-shaded condition, the air velocity in most of the airflow regions decreases, and the variation ranges of air velocity also decrease. This phenomenon can change the dilution effect of gaseous pollutants in the source unit and then influence the inter-unit transmission of respiratory infectious diseases.
Fig. 10. Dimensionless velocity contour and streamlines in the coupled indoor and outdoor environment for $U_{\text{ref}}=5.0\text{m/s}$. 
The natural ventilation capacities of different units in wind environment can be evaluated by air change rate per hour $ACH (h^{-1})$ in Eq. (4):

$$ACH = \frac{Q_v}{Vol} = 3600 \times \frac{0.5 \int [U_x] dA}{Vol}$$

where the ventilation rate ($Q_v$, m$^3$/h) of a unit is calculated by the integral method based on normal velocity component ($U_x$, m/s) at the opening [61]. In the prototype, the dimensions of each opening are $1.5m(Y) \times 2.4m(Z)$ with the area $A=3.6m^2$, while the dimensions of each unit are $4.5m(X) \times 4.5m(Y) \times 3.0m(Z)$ with the unit volume $Vol=60.75m^3$. 

Fig.11. Velocity distribution near the façade and air change rate of different units in the non-shaded, windward shaded and leeward shaded conditions with $U_{ref}=5.0m/s$. 

(a) Velocity along the windward line (b) Velocity along the leeward line 

(c) Air change rate per hour $ACH$ of prototype units
The results of $ACH$ of different units under the non-shaded and shaded conditions are shown in Fig.11(c). For the windward shaded condition, the ventilation capacities of the windward unit W1-W5 are much higher compared with the non-shaded condition, and the maximum growth rate is over seven times in the unit W4. These results demonstrate that the air exchange between indoor and outdoor environment at windows can significantly increase because of the vortexes introduced by the diversion effect of windward louvers, according to the windward outdoor airflow pattern near the façade in Fig.10(b). Note that although the velocity in the diversion zone under the windward shaded condition is mostly lower than other two cases in Fig.11(a), the momentum of near-wall airflow is transferred to the direction with lower incident angles along the rotation angle of louvers. As a result of the significant diversion effect, the incident airflow becomes closer to the vertical direction at windows than those in Fig.10(a) and (c), resulting the increasing normal velocity component $|U_x|$ and ventilation capacity calculated by Eq. (4). These results show that the transferred wind direction plays a more important role in the change of $ACH$ than the weakened wind speed for the windward shaded condition. For the leeward unit L1-L5, the ventilation capacity decreases in all units under the windward shaded condition. These results indicate that the larger recirculation zone in Fig.10(b) leads to the slighter air exchange at the leeward openings, although the airflow velocity is higher in the center region of recirculation zone. For the leeward shaded condition, the $ACH$ of windward units have small differences compared with those under the non-shaded condition, because the downwind louvers have less impact on the upwind airflow patterns. The lower $ACH$ of leeward units in Fig.11(c) is consistent with the lower air velocity in the diversion zone in Fig.10(c), and only the $ACH$ of L1 is slightly higher compared with that under the non-shaded condition. These results indicate that the $ACH$ of units in different locations depends on both incident angle and airflow velocity. The lower airflow velocity can lead to higher $ACH$ with the strong diversion effect on airflow direction from louvers. And if the diversion angle of louvers is close to the original direction of airflow without louvers, the $ACH$ of units tend to become lower because of the blocking effect on airflow velocity.

3.2 Gaseous pollutant concentration

In multi-storey building, gaseous pollutants can release from a unit and re-enter other units through external openings on facades by natural ventilation. For each case of the numerical study, the source term of tracer gas was located at the center of pedestrian level in a specific unit. The pedestrian level is set as 1.6m (full-scale), and the mass rate of tracer gas CO$_2$ is 8mg/s to simulate the expired gas
from human beings [37].

Fig. 12 shows the pollutant concentration distribution for the cases with the pollutant source term located in different windward units under the non-shaded and windward shaded conditions. The windward louvers significantly increase the pollutant concentration in the unit where the source item is located, indicating that the gaseous pollutant in the source unit is more difficult to be diluted by natural ventilation. There is a counter-intuitive result that the increases of indoor concentration for the source units in the windward shaded condition are not consistent with the much higher ACH values compared with the non-shaded condition. Although ACH indicates the indoor and outdoor air exchange efficiency, it cannot characterize clearly the dilution of gaseous pollutant especially for an opening with inverse flow cased by vortexes as illustrated in Fig.10(b). The outflow carrying gaseous pollutant discharged from the unit is more likely to flow back into the same unit because of the presence of the vortex at the only opening. Then, the gaseous pollutant can accumulate significantly inside the source unit. Therefore, a higher ACH does not always make the gaseous pollutant dilute faster in the windward shaded condition. On the other hands, the concentration in front of louvers decreases obviously, and the concentration gradient is higher between the louvers and the windward facade. The windward louvers have a blocking effect on the development of vortex zone, stagnation zone and separation zone in the near-wall region in front of the façade. For this reason, it is difficult for the gaseous pollutant released from the source unit to directly penetrate the diversion zone surrounded by the row of shading louvers. This blocking effect can weaken the inter-unit transmission of gaseous pollutants from external windows between windward units. These results are consistent with the airflow field characteristics described in Section 3.1. The concentration distinction of gaseous pollutant between the non-shaded and windward shaded conditions in leeward units is obviously affected by the location of the pollutant source. For the source term located at the windward floors, the pollutant concentration increases by an order of magnitude for some leeward units near the location of pollutant source. When the source term located in the windward unit W1, the pollutant concentration in the leeward unit L1 rises from around $7 \times 10^{-6}$ to $1 \times 10^{-5}$ mol/L. When the source term located in the windward unit W5, the pollutant concentration in the leeward unit L3 rises from around $2 \times 10^{-7}$ to $1 \times 10^{-6}$ mol/L. This phenomenon is due to the diversion effect of the louvers, which modified the airflow pattern of the reattachment zone near the roof and the leeward recirculation zone near the facade, leading to the enhanced accumulation of gaseous pollutants in some leeward units.
Fig. 12. Concentration distribution of tracer gas CO₂ in the multi-storey building with and without windward louvers.
3.3 Re-entry ratio

For the gaseous pollutants released from the multi-storey building, re-entry ratio \( R_k \) is used to measure the non-dimension dispersion potential of pollutants from the source unit to other ones. The calculation method is given by Eq. (5) as follows:

\[
R_k = \frac{C_j \cdot ACH_j}{C_i \cdot ACH_i}
\]

where \( C_j \) and \( C_i \) are the average pollutant concentrations in the target unit and the source unit, respectively. \( ACH_j \) and \( ACH_i \) are air change rates per hour of the target unit and the source unit, respectively. The results of \( R_k \) are shown in Fig. 13. Generally speaking, the units of the same facade nearby the source unit have the maximum \( R_k \), and there is an order of magnitude difference between the unit with the maximum \( R_k \) and other units.

![Fig. 13. Re-entry ratio \( R_k \) in different units for the cases with different tracer gas locations and shaded conditions (red mark * indicates the source unit).](image-url)
3.3.1 Source unit on the windward façade

Fig. 3(a), (c) and (e) show the distributions of re-entry ratio \( R_k \) for all building units and different source units under non-shaded, windward shaded and leeward shaded conditions. It is found that when tracer gas is released from the unit W1, the \( R_k \) of other units on windward facade are less than 0.01%, and the \( R_k \) of units on leeward facade are less than 1%. This is because the stagnation zone on the windward facade has a resistance effect on the upward diffusion of gaseous pollutants. The downward airflow at the corner of the windward facade and the ground can lead tracer gas to the leeward recirculation zone, which makes the higher \( R_k \) in leeward units and the negligible \( R_k \) in windward units. Compared with the cases without single-sided shading louvers, cases with windward or leeward louvers can reduce the \( R_k \) of most units on leeward facade, and the \( R_k \) of lower units is higher than that of higher units. Leeward louvers can increase the \( R_k \) of the unit L1 to the maximum value of 0.63%.

When the tracer gas is released from W2, the \( R_k \) of the unit W1 is the highest under the non-shaded and shaded conditions, and the \( R_k \) of higher units in windward units is negligible. The \( R_k \) of the unit W1 is between 5% and 10% under the non-shaded and leeward shaded conditions. The \( R_k \) of the unit W1 is the maximum value under the leeward shaded condition. The windward louvers reduced the \( R_k \) of the unit W1 from 7.48% to 0.77%. This result show that the windward louvers have a blocking effect on the vortex below the stagnation zone to reduce the vertical diffusion and inter-unit transmission of gaseous pollutants between windward units. The \( R_k \) of most units on leeward facade is less than 1% and decreases under two shaded conditions, but the \( R_k \) of the unit L1 room under the leeward shaded condition increases to 1.26%.

When the tracer gas is released from W3, similar to that from W2, the gaseous pollutant tends to diffuse downward in the vertical direction near the windward facade, but the \( R_k \) of windward units are relatively lower. The \( R_k \) of the unit W2 is reduced from 1.79% to 0.56%. This is because the unit W3 is close to the stagnation zone, which makes it more difficult for the gaseous pollutant released from the source unit to be diluted by natural ventilation. Compared with other shaded conditions, the \( R_k \) of the units above the source unit in the windward shaded condition can be ignored. The changes of \( R_k \) of units on leeward facade under two shaded conditions are also similar to those when tracer gas is released from W2, but the total \( R_k \) is lower. In the leeward shaded condition, the maximum \( R_k \) of units on leeward facade room is 0.31%.
When the tracer gas is released from W4, the $R_k$ of the unit W3 and W5 adjacent to the source unit are the highest, which are more than 1% in the non-shaded and leeward shaded conditions. But the $R_k$ of the unit W5 can be ignored in the windward shaded conditions. This is because the external window of the unit W4 is located at the stagnation zone where wind pressure is the highest on the facade, which leads to a stronger diffusion effect of the approaching airflow. Therefore, when there is no shading louver near the windward facade, the gaseous pollutants can easily return to the unit above. The existence of windward shading louvers can reduce the wind pressure in the stagnation zone, which disturb the diffusion of near-wall airflow and has a strong resistance to the inter-unit transmission of gaseous pollutants from the unit W4 to the higher the unit W5. The changes of $R_k$ of units on the leeward facade are similar to those when tracer gas is released from the unit W2 and W3, and the $R_k$ of units are all lower than that of the unit W3. The distinction is that the $R_k$ of higher units is slightly higher than that of lower units, which indicates that gaseous pollutant diffused at the stagnation zone are more likely to accumulate in higher units on the leeward facade.

When the tracer gas is released from W5, the maximum $R_k$ under the non-shaded and leeward conditions are in the unit W4, and the $R_k$ of most units can be ignored.

### 3.3.2 Source unit on the leeward facade

In Fig.13(b), (d) and (f), when tracer gas is released from the units on the leeward facade, it is difficult for tracer gas to diffuse to the windward units after entering the recirculation airflow near the leeward facade. Therefore, the $R_k$ of windward units can be ignored under the non-shaded and leeward shaded conditions. The pollutant dispersion from leeward units is affected by upward recirculation airflow, so the $R_k$ of the units above the source unit are generally higher than those of the units below. For non-shaded and windward shaded conditions, the maximum $R_k$ occurs in the unit L5 when the source unit is the unit L4, which are 7.70% and 10.73%, respectively. The maximum $R_k$ under leeward shaded condition is 4.78%, which occurs in the unit L4 when the source unit is L3. Overall, with the presence of windward shading louvers, the $R_k$ of the lower units below the leeward source unit increase, while the $R_k$ of the higher units decrease. But when the source unit is L4, the $R_k$ of the unit L5 increases. The $R_k$ of most units decrease under the leeward shaded condition, but for the pollution source located in L2 and L3, the $R_k$ of adjacent higher units increase.
3.4 Infection risk

To quantitative infection possibility of respiratory diseases through airborne pollutants, Wells [62] used the quantum of infection to define the number of infectious airborne particles, which are considered to have one or more particles of airborne pollutants and are distributed randomly in the spaces of air. Riley et al. [63] used the number of quanta to define the intake dose of airborne pathogens and to evaluate the infection risk by using this implicit method to consider the pathogen infectivity, the characteristics of infectious spaces, etc. The Wells-Riley model is extensively applied to investigate the airborne infection risk for the ventilated units [64]. This method assumes a well-mixed state of indoor air and a steady state of concentration distribution of infectious gaseous pollutants effected by the ventilation condition. The equation is given by Eq. (6):

\[ P = 1 - \exp \left( -\frac{nq \delta t}{Q_e} \right) \]  

where \( P \) is the infection risk of an infectious disease. \( n \) is the number of infected persons and is taken as 1. \( q \) is the quanta generation rate. \( \delta \) is the pulmonary ventilation rate. \( t_e \) is the exposure time for susceptible person. In this study, computational parameters for infection risk are chosen according to relevant research for indoor exposure simulation [13],[37],[65],[66]. The production number of infectious quanta per hour \( q \) cannot be directly measured but calculated epidemiologically from some outbreak cases for the specific disease. To investigate the infection risk of COVID-19 in indoor environment, the value of \( q \) is calculated based on a reported event of cluster infection in a ventilated restaurant. According to the investigation research from Li et al. [34], the relevant parameters of the airborne SARS-CoV-2 transmission had been measured, resulting the quanta generation rate is 79.3h\(^{-1}\) in this epidemic case. For the respiratory aerosols related to airborne transmission, the transport patterns are widely investigated in CFD simulations by two methods: (1) the multi-phase method for aerosol particles [67],[68] and (2) the tracer gas method for gaseous aerosols [37],[69]. In the previous investigation, the aerosol particles in exhaled breath flow are mostly below 5 μm [70]. For the SARS-CoV-2 aerosols, the submicron region of the diameter mainly ranges from 0.25 to 1.0 μm [71]. This range of particle diameters is small enough to treat airborne aerosols as gaseous pollutants in the transport process for the tracer gas method in natural ventilation[69],[72]. It is assumed that the pulmonary ventilation rate \( \delta \) of each indoor person is set as 0.54m\(^3\)/h. This value is at the range of 0.25-0.78m\(^3\)/h for the different age groups over 21 years old at the activity levels of sleep/nap,
sedentary/passive and light intensity [66]. The exposure time \( t_e \) is set as 8h to represent the typical scenarios with infectious possibility for natural ventilation, including indoor work period, self-isolation in a hotel or at home. Note that this exposure time is obviously shorter than the laboratory test period of 16h for the SARS-CoV-2 virus retained infectivity and integrity in the respirable aerosols [73].

For the units with the re-entry phenomenon of gaseous pollutants from other units, the Wells-Riley model is applied to predict the airborne transmission of infectious diseases by using re-entry ratio and air change rate[62],[63],[65], as shown in Eq. (7):

\[
P = 1 - \exp \left( - \frac{nqR_0 \delta t_r}{ACH} \right)
\]

Fig.14 shows the infection risk \( P \) of all building units with different source units under non-shaded, windward shaded and leeward shaded conditions. In general, infection risks \( P \) are much higher for all source units, especially for the leeward source units with lower ventilation rates. The windward source units in the cases with windward louvers have the lowest \( P \) (all below 40%) because of the higher ventilation rates contributed to the introduced vortexes at windward windows. The leeward source units have higher \( P \) (all over 80%) for both shaded conditions compared with the non-shaded conditions. The windward louvers make the \( P \) in most units decrease for the cases with windward source units, while the \( P \) in most units increase when infectious pollutant released from leeward units. The impacts of leeward louvers on the \( P \) in most units are opposite of the windward shaded condition.
For the units without source terms, the infection risk $P$ are related to the re-entry ratio $R_k$ and air change rate $ACH$, resulting the similar magnitude distributions of $P$ and $R_k$. However, a higher $R_k$ does not always lead to a higher $P$ due to the differences of $ACH$. This phenomenon is more common under the leeward shaded conditions. It can be a magnitude distinction of $P$ between two units with similar $R_k$ but one of them has extremely low $ACH$, which occurs in the unit L4 and L5 for the case with the source unit L3 under the windward shaded condition. The greatest impact of shading louvers on the risk of inter-unit infection is usually at the upper unit of leeward source unit. For the windward louvers, the highest growth of $P$ is in the unit L5, of which the $P$ rises from 7.82% to 26.17% in the case with the source unit L4. For the leeward louvers, the highest growth of $P$ is in the unit L3, of which the $P$ rises from 7.89% to 22.52% in the case with the source unit L2. These results indicate that for the in the multi-storey building with shading louvers, the cross-infection risks of COVID-19 due to re-entry

| Location | W1 | W2 | W3 | W4 | W5 |
|----------|----|----|----|----|----|
| W1       | 0.01 | 0.11 | 2.31 | 0.17 | 0.00 |
| W2       | 0.03 | 0.18 | 1.21 | 0.00 | 0.00 |
| W3       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W4       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W5       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Location | L1 | L2 | L3 | L4 | L5 |
|----------|----|----|----|----|----|
| L1       | 2.10 | 0.85 | 0.09 | 0.00 | 0.00 |
| L2       | 1.65 | 1.15 | 0.13 | 0.00 | 0.00 |
| L3       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L4       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L5       | 1.00 | 0.85 | 0.13 | 0.00 | 0.00 |

| Location | W1 | W2 | W3 | W4 | W5 |
|----------|----|----|----|----|----|
| W1       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W2       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W3       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W4       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W5       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Location | L1 | L2 | L3 | L4 | L5 |
|----------|----|----|----|----|----|
| L1       | 3.00 | 0.85 | 0.09 | 0.00 | 0.00 |
| L2       | 1.65 | 1.15 | 0.13 | 0.00 | 0.00 |
| L3       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L4       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L5       | 1.00 | 0.85 | 0.13 | 0.00 | 0.00 |

| Location | W1 | W2 | W3 | W4 | W5 |
|----------|----|----|----|----|----|
| W1       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W2       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W3       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W4       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W5       | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Location | L1 | L2 | L3 | L4 | L5 |
|----------|----|----|----|----|----|
| L1       | 3.00 | 0.85 | 0.09 | 0.00 | 0.00 |
| L2       | 1.65 | 1.15 | 0.13 | 0.00 | 0.00 |
| L3       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L4       | 1.56 | 5.26 | 11.71 | 0.00 | 0.00 |
| L5       | 1.00 | 0.85 | 0.13 | 0.00 | 0.00 |

---

Fig.14. Infection risk $P$ in different units for the cases with different tracer gas locations and shaded conditions (red mark * indicates the source unit).
airflow from other units can be greater than the risks in the situations of travelling by public transport such as bus and airplane in other studies [71],[74],[75].

4. Conclusion

A numerical study based on CFD is performed to investigate the effect of semi-shaded openings on the gaseous pollutant dispersion between units in a multi-storey building with external shading louvers. The computational methods to obtain airflow fields are validated by the comparison of experimental and numerical measurement. The airflow characteristics, ventilation capacity, dispersion routes and inter-unit infection risk of COVID-19 were discussed. The main conclusions are as follows:

(1) The presence of shading louvers disturbs the near-wall airflow fields around external windows, which changes the air exchange between indoor and outdoor environment at the facade openings of different units. The distinction of airflow patterns can influence the pollutant dispersion between different units. The ventilation ability can be higher when there are vortexes introduced at windows, although the air velocity is lower. For the windward shaded condition, the maximum growth rate of ACH is over seven times. However, the higher ACH does not always make the gaseous pollutants dilute faster because of the reverse flow at openings as a result of the vortices.

(2) The gaseous pollutant dispersion effected by shading louvers is related to the source and louvers’ location. When the pollution source is located at the windward units, the presence of windward louvers can weaken the dilution effect of natural ventilation on gaseous pollutants in the source units and reduce the re-entry ratio $R_k$ of other units except some leeward units. The effect of leeward louvers on the $R_k$ of windward units can be neglected, but the $R_k$ of leeward lower units increase slightly. When the pollution source is located at the leeward units, the $R_k$ of the windward units can be ignored, and the $R_k$ of the units above the source unit are generally higher than those of the units below. For non-shaded, windward and leeward shaded conditions, the maximum $R_k$ are 7.70%, 10.73% and 4.78%, respectively.

(3) For the infection risk $P$ of COVID-19, the presence of shading louvers can increase the $P$ for the units with and without the infectious person, although the windward louvers can significantly reduce the $P$ in the windward units with windward source units. The inter-unit infectious risk in the worst unit rises from 7.82% to 26.17% for the windward shaded condition, while it rises from 7.89% to 22.52% for leeward shaded condition. In some leeward units for shaded conditions, the infection risk of
re-entry airflow can be near the values of cross-infection occurs in public transportation such as bus and airplane from the reported cases. Therefore, it is necessary to improve ventilation capacity of the building with shading louvers to reduce the inter-unit transmission of gaseous pollutants and avoid airborne infection.

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Highlights
- Infection risk is studied for inter-unit dispersion through semi-shaded openings.
- CFD methods are validated in the experiment of a cubic building with louvers.
- Air characteristics and re-entry ratio are investigated in a multi-storey building.
- Louvers and source locations are analysed for the inter-unit infection of COVID-19.
- The highest growth of inter-unit infectious risk rises from 7.82% to 26.17%.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: