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CFD modeling of airborne pathogen transmission of COVID-19 in confined spaces under different ventilation strategies

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ABSTRACT

Airborne transmission is an important route of spread of viral diseases (e.g., COVID-19) inside the confined spaces. In this respect, computational fluid dynamics (CFD) emerged as a reliable and fast tool to understand the complex flow patterns in such spaces. Most of the recent studies, nonetheless, focused on the spatial distribution of airborne pathogens to identify the infection probability without considering the exposure time.

This research proposes a framework to evaluate the infection probability related to both spatial and temporal parameters. A validated Eulerian-Lagrangian CFD model of exhaled droplets is first developed and then evaluated with an office case study impacted by different ventilation strategies (i.e., cross- (CV), single- (SV), mechanical- (MV) and no-ventilation (NV)). CFD results were analyzed in a bespoke code to calculate the tempo-spatial distribution of accumulated airborne pathogens. Furthermore, two indices of local and general infection risks were used to evaluate the infection probability of the ventilation scenarios.

The results suggest that SV has the highest infection probability while SV and NO result in higher dispersions of airborne pathogens inside the room. Eventually, the time history of indices reveals that the efficiency of CV and MV can be poor in certain regions of the room.

1. Introduction

Droplets exhaled by different respiratory events are responsible for spread of COVID-19 airborne pathogens from infected to exposed occupants. In particular, airborne transmission of these pathogens is believed to be one of the major routes of the disease propagation (Morawska & Cao, 2020). On the other hand, flow field inside confined spaces are mainly formed based on the applied ventilation strategy, which can promote further the airborne transmission of respiratory airborne pathogen droplets (Noorimotlagh, Jaafarzadeh, Martinez & Mirzaee, 2021). During pandemic of COVID-19, the necessity in development of better ventilation systems for indoor environments has been highlighted by many ventilation associations such as ASHRAE (In-Room Air Cleaner Guidance for Reducing Covid-19, 2021) and SHASE and AIJ (Tranabe & Takekaki, 2020).

In general, ventilation systems are divided into natural and mechanical systems. The former relies on passive airflow through openings while the later uses fans and ducts to bring the fresh air inside the target space. In this regard, ASHRAE, REHVA and WHO have published documented guidelines with the aim of improving indoor areas ventilation system and air quality (“ASHRAE 62.1, 2019; ANSI/ASHRAE, 2013.”). Besides that, extensive research works have been conducted to investigate the impact of ventilation on propagation of pollution at indoor areas. Melikof (Melikof, 2016) and Thatiparti (Thatiparti, Gha & Mead, 2017) stated that building-up viral contamination in a confined space can be avoided by proper placement of inlet and exhaust ducts to assure that sufficient level of dilution is achieved. In many similar studies, the target was to replace the polluted air with the clean air. However, this requirement is not always met because of barriers existing inside rooms. On the other hand, in most of spaces like shops, offices, schools, public transport, etc., the ventilation rate is not sufficient for the economical purposes. So, According to Kulkarni et al. (Kulkarni et al., 2016) and Sornboot et al. (Sornboot et al., 2019) with low ventilation rates in indoor environments, the infection probability will rise among the occupants in enclosed spaces. In order to investigate the impact of ventilation systems on propagation of pollutants in restricted spaces.
both experimental and numerical techniques have been developed (Lindsay et al., 2013; Version & Universit, 2018). The outbreak of respiratory infections in the past decade has attracted far more attentions to apply CFD to study transmission routes of airborne pathogens in different environments under different ventilation strategies.

Gao et al. applied a transient Eulerian CFD model to simulate different human respiration processes and to evaluate their potential impacts on an adjacent person in a room with displacement ventilation system. They found that a normal respiration process is associated with a low risk of infection while in case of sneeze or cough, the risk would elevate to a large extent, depending on occupants’ relative orientation. They used thermal manikin with real geometry to precisely resolve the flow field in the micro-environment around the subjects. Exhaled flows were modeled by tracer gas (Gao & Niu, 2006). Seepana et al. (Seepana and Lai, 2012) numerically and experimentally analyzed the interpersonal exposure of sneezing under well-mixed and displacement ventilation strategies in a climatic chamber. They placed two manikins at different positions inside the chamber while taking the generated thermal plume into account. Results indicated higher infection risks for the cases in which manikins were placed near the wall compared with those being placed at the center. So, as to model the airborne pathogens they applied drift-flux model, which describes the transient concentration of droplets in terms of kg/m^3 or number/m^3 using a transport equation for each droplet diameter size. Their model neglected evaporation and coagulation of exhaled droplets while only 0.1-micron airborne pathogens were simulated. Kang et al. (Kang et al., 2015) applied a transient CFD approach to compare the dispersion of droplets in cough between two simplified manikins placed face-to-face in different distances in a room with mixing and displacement ventilation methods. Results showed that the displacement ventilation strategies were more efficient in discharging the droplets in cough and in reducing the infection rates. They used Eulerian approach to simulate the airflow and Lagrangian model to calculate time-dependent position of the airborne pathogens inside the room. They only considered 10-micron droplets in their computations and ignored the impact of evaporation, collision and coalescence of droplets. In a similar research work, Zhang et al. (Zhang et al., 2017) studied the impact of supply and return ducts positions in a conference room on the transportation of droplets generated by coughing. They considered the class of 5-micron diameters droplets and suggested that the room bottom-supply, and top-return arrangement can better control the distribution of airborne pathogen and provide a healthier condition for occupants. Yang et al. (Yang et al., 2018) applied a transient CFD model to simulate the local airflow and contaminant transport induced by a cough-jet in a typical airliner cabin environment with three seated passengers. They applied Lagrangian model for modeling of the unsteady behavior of droplets and used a size distribution for the exhaled droplets in the range of 5 to 25 μm. The evaporation of discrete phase was neglected. Furthermore, Ren et al. applied a steady Eulerian CFD model to find proper dimension for physical barrier in order to restrict the propagation of airborne pathogens inside an open office room during cough. The office room was ventilated using supply and return ducts on the ceiling while different scenarios were defined for the position of infected subjects and barrier heights. They proposed that physical barriers with the height of 60 cm provide an effective prevention against pathogens’ transmission. Exhaled pathogen droplets were considered as a continuum phase and species-transport equation was solved to describe droplet propagation inside the room. In general, it can be concluded that the application of CFD in simulation of pathogen transmission in restricted spaces reveals that research works in this area are mostly limited on modeling of certain aspects of airborne pathogens modeling since full representation of the physics underlying propagation of exhaled droplets such as evaporation, condensation, coagulation, etc., can result in a complex model.

Most of the numerical studies on the spread of infection such as COVID19 employ air quality exposure indices, which generally incorporates concentration sources at a room’s inlet and exhaust to assess contaminated regions within an enclosed environment. For example, Liu et al. studied the transmission of short-range exhalation droplets between two occupants. They used susceptible exposure index to estimate the viral load intake, which is exhaled by an infected occupant (Liu, Li, Nielsen, Wei & Jensen, 2017). Ai et al. also used exposure index to investigate the impact of the pulmonary ventilation rate and breathing cycle period on the infection risk (Ai, Hashimoto & Melikov, 2019). Nonetheless, aside from the exposure to the airborne pathogens, the number of viruses transmitted with the droplets remains as a key factor in the disease transmission. In this aspect, Karimzadeh et al. stated that the minimum infectious dose of COVID-19 in humans is higher than 100 particles (H. Karimzadeh, Bhopal & Tien, 2020). Basu introduced a strategy, by synergizing computational tracking and virologic data, to quantify the infectious dose (Basu, 2020). Buonanno et al. suggested a novel quantitative approach to estimate the risk of airborne transmission of COVID-19 infection. For this purpose, they divided the whole process into evaluation of the emission rate, exposure to a dosage concentration, received dosage and infection probability calculations (Buonanno, Morawska & Stabile, 2020). Despite of the mentioned efforts, a crucial gap in these studies is that estimation of infection risk needs accumulated dosage of viral loads, which cannot be directly extracted from the outputs of CFD simulations. In other words, physical social distance is not the only determining factor in the prevention of airborne pathogen infections, but the exposure time is mutually crucial. For instance, if an exposed occupant receives only a small viral load per unit time from a distant infected occupant in a long enough time, this can gradually reach the minimum infective dosage. On the other hand, keeping the safe social distance in some places is not practical due to a high concentration of people or lack of enough spaces to ensure keeping the proper distance between all occupants. Office rooms, in general, are characterized by both long exposure times and confined spaces that make it difficult to set a safe distance between all the workers. Hence, evaluating the temporal infection risk can be a beneficial assessment in selection of suitable ventilation strategies and even working hours management.

Thus, this paper aims to proposes a framework to develop risk models that accounts the accumulation of exhaled airborne pathogens under different ventilation scenarios within confined spaces. Thus, the proposed framework predicts the tempo-spatial infection risk based on the outputs of a CFD model, taking into the consideration of the pivotal factors in the pathogen droplet transmission such as evaporation and droplets’ size distribution. The framework is then applied to an office room under different ventilation strategies to assess their performance in restriction of pathogen droplets propagation inside the room. For this purpose, a CFD model of a room under a natural ventilation strategy was first validated against an experimental wind tunnel test data. Then, three human manikins were added to the simulation domain to consider the effect of their thermal plume on the room background flow. After that, the droplet release of speaking mode from manikins was modeled inside the room in a one-hour timespan. Droplets’ distribution and size were adapted from the related clinical literature using a time dependent Lagrangian approach. Finally, a separate bespoke code was developed to exploit accumulated distribution of droplets extracted from CFD output results to calculate a 3D distribution of airborne droplets as well as the temporal probability of infection inside the modeled office room.

Section 2 is the methodology section, which introduces the governing equations, applied models and infection probability model. Section 3 presents the selected case studies i.e., cross-ventilation (CV), single-ventilation (SC), mechanical-ventilation (MV) and no-ventilation (NV). Then, numerical setup for both continuous and discrete phases are discussed in Section 3. Validation of the introduced numerical setup is reported in Section 4. Furthermore, the simulation results, including airflow distribution and resultant particle concentrations, iso-surfaces of infection probability, global and local risks as well as time-dependent infection risk for the cases are presented in Section 4.
2. Methodology

The applied methodology to assess the performance of ventilation system from viewpoint of infection risk has two main steps. First, a transient CFD simulation is implemented to track the pathway of the exhaled droplets during a speaking mode. The outputs of the CFD results are then transferred to a bespoke code to estimate the accumulated concentration of droplets during the simulation run-time and to calculate the infection probability based on available clinical data of a minimum threshold of airborne pathogens’ transmission against COVID-19.

2.1. Eulerian-Lagrangian CFD model

Details of Eulerian-Lagrangian CFD model used to simulate airborne pathogens’ release is presented in this section.

2.1.1. Eulerian CFD model

Steady incompressible Eulerian model includes governing equations for continuity, momentum, and energy conservation equations as the following:

\[
\frac{\partial U_i}{\partial x_i} = S_m
\]

(1)

where \(U\) represents the velocity vector and \(S_m\) is the source term, which models the added mass from discrete phase of droplets to the surrounding air.

\[
\rho U_i \frac{\partial U_i}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \rho \left( \mu \left[ \frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_j} \right] - \rho \sigma n_i n_j \right) + S_{bf}
\]

(2)

In which \(P\) is the pressure, \(\mu\) and \(\nabla n\) represent viscosity and Reynolds stresses, respectively and \(S_{bf}\) is the sum of all body forces exerted. Also, the energy equation can be expressed as follows:

\[
\rho \frac{\partial (hU_i)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \kappa \left( \frac{\partial T}{\partial x_i} \right) + S_t
\]

(3)

where \(T\) and \(h\) are temperature and sensible enthalpy, \(\kappa\) is the thermal conductivity and \(S_t\) represents the source term (ANSYS Academic Research, 2018).

2.1.2. Lagrangian model

Lagrangian model is applied to model the trajectory and distribution of the discrete respiratory droplets exhaled from a bio-source’s mouth:

\[
\frac{dm_i}{dt} = m_i \left[ U - U_P \right] \left( 1 + \frac{g(\rho_s - \rho)}{\rho_s} \right) + F
\]

(4)

where \(m_i\) is the particle (or droplet) mass, \(U\) is the continuum phase velocity vector, \(U_P\) is the particle velocity vector, \(\rho\) is the continuum phase density, \(\rho_s\) is the droplet density, \(g\) is the gravity constant, \(F\) is the additional exerted force and \(\tau\) is the particle relaxation time, which can be calculated as:

\[
\tau = \frac{18m}{\rho \rho_s D_p} \frac{C_D Re}{24}
\]

(5)

where \(D_p\) is the particle diameter and \(C_D\) is the drag coefficient. Re is the relative Reynolds number that is calculated as:

\[
Re = \left| \frac{\rho_s D_p |U - U_P|}{\mu} \right|
\]

(6)

According to Vejerano et al., the exhaled droplets comprise water and non-evaporating salt and protein Vejerano and Marr (2018). Once a droplet is discharged to the environment, its water content evaporates. So, mass transfer occurs between the phases, which can be influenced by temperature difference between continuum and discrete phases, resulting on droplet’s size change. Thus, mass transfer and heat transfer equations are presented as follows (ANSYS Academic Research, 2018):

\[
\frac{dm_i}{dt} = m_i
\]

(7)

where \(m_i\) denotes the mass of the particle, and \(m_p\) represents the rate of mass transfer to the particle.

The righthand-side of the above equation is necessarily non-zero when evaporation takes place. Suitable modeling of \(m_p\) has a crucial impact on the accuracy of the results. For cases associated with high rates of evaporation, where the convective impact of evaporating material from the droplet plays an important role, the following formula proposed by Miller et al. can be used:

\[
\frac{dm_i}{dt} = k_i A_P \rho h (1 + B_m)
\]

(8)

where \(k_i\) is the mass transfer coefficient, \(A_P\) is the droplet surface area, \(\rho\) is the gas density and \(B_m\) is Spalding mass transfer coefficient, which can be obtained as:

Fig. 1. Infection risk assessment framework.
2.2. Framework for infection risk evaluation

The proposed framework to evaluate the airborne infection risk of virus includes five steps as illustrated in Fig. 1. First, the instantaneous distribution of exhalation droplets is calculated in step-1 using a CFD solver and required inputs as per step-0. In the step-2, the accumulated concentration of droplets is calculated all over the room. The viral load carried by exhaled droplets of respiratory systems is determined in step-3, which results in resolving the tempo-spatial distribution of infective viruses in a target space. In step-4, the dose received by an exposed occupant is estimated. Finally, a dose-response model is applied to find the infection probability for exposed occupants who have already received certain quanta of virus during a specific time interval. As stated earlier, the CFD simulation of the model comprises the step-0 and step-1 of the risk assessment, respectively. Other steps from second to fifth one according to Fig. 1 will be further discussed in the following sections with more details.

2.2.1. Emission rate of viral loads

As mentioned in Fig. 1, estimation of the emitted viral load is the step-3 in the infection risk calculation. Therefore, a forward emission approach proposed by Buonanno et al. (Buonanno et al., 2020) is adapted to estimate the quanta emission \( \text{ER}_q \) per hour as follows:

\[
\text{ER}_q = C_v C_i IR V_d \tag{11}
\]

where \( C_v \) is the sputum viral load (RNA copies mL\(^{-1}\)), \( C_i \) is the infectious quantum divided by infectious dose (quanta per RNA copies\(^{-1}\)), \( IR \) is the inhalation rate (m\(^3\) h\(^{-1}\)) and \( V_d \) is the volume concentration of exhaled droplets by an infected occupant (mL m\(^{-3}\)). \( C_v, C_i \) and \( IR \) values are selected according to the previous studies (Buonanno et al., 2020). Some works have suggested that \( V_d \) strongly depends on the respiratory activity (Yang et al., 2018; Zhang et al., 2017). It should be noted that \( \text{ER}_q \) in the form presented in Eq. (11) is not directly applicable to emission and distribution of airborne pathogens inside the room as it is calculated using a 3D CFD model while Eq. (11) assumes a uniform emission of viral load all over the room. Therefore, this equation will be further adjusted to be employed in the 3D CFD model. For this purpose, it is suffice to calculate the accumulated particles inside each cell within the target timespan. This concentration comes from CFD solution and depending on the background flow of the room can be irregularly distributed inside the room. According to Eq. (11), the dimension of the term \( C_v C_i \) is quanta mL\(^{-1}\), which represents the viral load carried by a droplet with the volume of one mL. Therefore, time-dependent accumulated concentrations of the viral load at each cell will be calculated according to the following equation:

\[
n(t, \text{ER}_q) = C_v C_i \sum_{j=0}^{3} \sum_{i=1}^{m} (m_i V_{cell}) \tag{12}
\]

where \( n \) (quanta m\(^{-3}\)) is the time-dependent quanta concentration of the viral load, \( V_{cell} \) (m\(^3\)) is the volume of each cell. \( \text{ER}_q \) is obtained from Eq. (11) \( p \) and \( m \) are size class number of droplets within each size class respectively.

To facilitate the calculation of the accumulated concentration of the viral load throughout the field (step-2 according to Fig. 1), the selected domain is uniformly meshed called as the secondary mesh. Then, the spatial concentration of droplets is calculated at each cell during the time span of a simulation. A schematic representation of the secondary mesh and accumulated droplets is shown in Fig. 2. Hence, the output results of Eulerian-Lagrangian CFD simulations will be conducted by development of a bespoke code, which generates a secondary uniform
and coarse mesh inside the room. Since trajectory of each particle parcel is reported at each time-step in the output results file, the accumulated droplets can be found at each element of the secondary mesh. After that, based on the volume of the concentrated droplets, accumulated viral load is exploited. The calculated viral loads is then used to evaluate the infection risk distribution inside the room after one hour of simulation.

2.2.2. Evaluation of received dosage by exposed occupants

To calculate the droplets’ dosage taken by exposed occupants at each computational cell, in relation with step-4 of Fig. 1, the accumulated quanta concentration is calculated from Eq. (12). Other required data include inhalation rate of subjects as well as the exposed time. Hence, integrating the quanta concentration over time according to the following equation represents the received dosage:

\[ D_q = \int_0^T n(t, ER) \, dt \]  

(13)

where \( D_q \) is the received dosage by exposed occupants, \( T \) is the simulation time and IR is the inhalation rate (m\(^3\)h\(^{-1}\)) of the exposed occupant, which strongly depend on the respiratory event while the estimated values are adapted here from Adams (1993).

2.2.3. Infection probability calculation (step-5)

The step-5 of the framework, as presented in Fig. 1, is the calculation of the infection probability. Amongst available dose-response models in the literature, a simplified model of Poisson summation equations is chosen to evaluate the infection probability of the exposed subjects expressed as:

\[ P_i = 1 - e^{-\theta_i} \]  

(14)

where \( P_i \) is the probability of the infection stated in percentile (Buonanno et al., 2020).

3. Case study description

3.1. Description of ventilation strategies

The cases study room is a small office with dimensions of 4m \( \times \) 4m \( \times \) 3.2m (L \( \times \) W \( \times \) H). Different ventilation strategies as explained in the following sections were applied to this room while three occupants were assumed to work in this office for one hour. So, each occupant occupies nearly a 60-square foot area in accordance with the available guidelines (Territories, 2012). Arrangement of the occupants was selected in a way that they stay in a maximum distance from each other while seated. At each simulation case, there is only one infected occupant. Therefore, the influence of different ventilation strategies as well as the position of the infected occupant on the dispersion of airborne pathogens and on distribution of the infection probability is investigated. As shown in Fig. 3,
circular plumes were used to mimic the seated occupants while thermal plumes were generated by assigning a constant heat flux on their skins. The height of the cylinders was 1 meter. The overall size of the room and windows were the same for all cases. Exhaled activity of the infected occupant was assigned as a normal speaking mode. This activity was assumed to be continuous for a time span of one hour. Droplets were released into the room with a size distribution as presented in Table 1 with an initial velocity of 4 m/s (Chao et al., 2009). Mouth was modeled as a source point and the impact of nose was not modeled. Speaking was considered as a steady activity to further simplify the modeling. The propagation of airborne pathogens and therefore the risk of infection under different ventilation strategies were defined as the investigated scenarios.

a) Cross-ventilation (CV)

In Case CV, the office room was assumed to have two opposite openings with dimensions of 1m × 0.64m (W × H) as presented in Fig. 3. Outdoor airflow was set such that the maximum air velocity inside the office room remains below 0.25 m/s to be able to compare this case with the other strategies.

a) Single-sided ventilation (SV)

Case SV was identical to Case CV except that only one of the opposite windows was open as shown in Fig. 3. So, the flow pattern in this case is quite different from that of the CV strategy.

a) No-ventilation (NV)

NV ventilation strategy ventilation was characterized by isolated airflow of the room from outside flow field as depicted in Fig. 3. However, a realistic approach requires that a small air leakage to occur between the indoor and outdoor spaces. In this case, the flow field inside the room was significantly affected by the thermal plume of the occupants.

a) Mechanical ventilation (MV)

In Case MV, instead of windows, there were inlet and outlet ducts through which the room air flow was circulated. In this case, the inlet duct, instead of window, was placed on the top of the wall and two outlet ducts were placed on the bottom of the opposite wall. The dimensions of inlet and outlet ducts sizes of Case MV were 1m × 0.15m(e × c) and 0.5m × 0.15m(f × c), respectively. Specifications of the mentioned ventilation strategies is described in Table 2. The calculated air exchange rate (ACH) in the table is a measure of the air volume added to or removed from a space in one hour divided by the volume of the space (ANSI/ASHRAE, 2013). This index is employed as it is an import one in the ventilation design of spaces. For each case of Table 2, the volumetric airflow of the room and maximum air velocity inside the room were determined through postprocessing of the simulation results.

### Table 2

| Ventilation Type       | Max. Air Velocity inside the Room (m/s) | ACH |
|-----------------------|----------------------------------------|-----|
| Cross Ventilation (CV)| 0.25                                    | 8   |
| Single-sided Ventilation (SV) | <0.25                               | 1.1 |
| No-opening (NO)       | <<0.25                                  | 0.1 |
| Mechanical Ventilation (NV) | 0.25                                | 3 (ASHRAE Standards) |

#### 3.2. Numerical setup for flow field and discrete phase

The flow field was simulated using steady Reynolds averaged Navier-Stokes (SRANS) approach in Ansys Fluent 19.0. Turbulence was modeled by realizlable (RLZ) k – ε (Shih, Liou, Shabbir, Yang & Zhu, 1995) and enhanced wall-function was adopted to solid walls of the office as well as the ground in the outdoor spaces. Second-order upwind scheme was used to discretize the transport equations and SIMPLE algorithm was applied to model the pressure-velocity coupling.

Exhaled droplets were simulated using Discrete Phase Model (DPM). In the DPM computations, interactions between droplets and the surrounding air (continuous phase) were considered and droplet equations source terms were updated after every single iteration of the solution of the continuous phase. Droplet time-step was set as 0.01 second and the overall simulated time was 1 hour. Convergence level of 10⁻⁵ was applied to control the accuracy of the particle tracking. Implicit and trapezoidal schemes were selected as the particle tracking strategies. According to the literature, respiratory droplets will evaporate rapidly after being exhaled until they turn into non-evaporative nuclei, which are responsible for airborne propagation of airborne pathogens (Tang, Li, Eames, Chan & Ridgway, 2006). Hence, here droplets were modeled as a multi-component type, nearly up to 95 percent of which consists of water and were allowed to be evaporated (Vejerano & Marr, 2018). For Cases SV and CV, the airflow distribution outside the building was also included to obtain more accurate air distribution inside the building while for Cases MV and NV cases, only the airflow distribution inside the building was considered. So, for modeling of Cases SV and CV, a rectangular flow domain as shown in Fig. 4 was generated according to AIJ guidelines. According to this guideline, the top and lateral boundaries should be placed at least 5H from the building surfaces. While the distance between the inlet boundary and building was confined by the maximum allowed space by the wind tunnel, the outlet boundary was suggested to be at least 15H far from the building’s wall (Tominaga et al., 2008). Overall dimension of the domain was 84m × 52m × 19.2m (L × W × H). Ansys Workbench 19.0 mesh tool was used to generate a hexahedral cutcell type computational grid as illustrated in Fig. 4.

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Fig. 4. Geometry and mesh distribution of the office room and its surrounding outdoor environment.
A mesh sensitivity study was conducted for three different grid settings for the CV case, as coarse, medium, and fine meshes with element numbers of 564,320, 814,715, and 1112,584, respectively. The vertical profiles of $U/U_H$ at three different streamwise locations ($x/H = 0, 0.39$) are plotted in Fig. 5 for all mesh settings. In general, the deviations between three meshes were not so high, however, medium, and fine meshes showed very close values all over the three vertical lines.

The settings for the medium mesh was used for the CV and SV cases. The same mesh configuration was applied to the MV and NV cases.

The boundary conditions to the target environment were obtained with a power-law profile with an exponent of $\beta = 0.27$ and a boundary layer height of $z_{el} = 550$ m for a reference height of $z_{ref} = 10$ m using the recommendations by AIJ guideline (Tominaga et al., 2008):

### Table 3

| Boundary Type                      | Boundary condition                                                                 | Boundary Value                                      | Fluid density $\rho$ $\text{kg/m}^3$ | Dynamic Viscosity $\mu$ $\text{Pa.s}$ |
|------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------|---------------------------------------|----------------------------------------|
| **Domain Inlet**                   | Inlet Velocity, TKE, kinetic energy and Dissipation rate                           | Eq. (15) to (17)                                     | Air / Water 1.184 / 997               | 1.86E-5 / 8.9                           |
| (CV and SV only)                   | Inlet Temperature                                                                  | 25 °C                                               |                                       |                                        |
|                                   | Inlet Relative Humidity                                                            | 50%                                                 |                                       |                                        |
| Infected Occupant Inlet            | Droplets Velocity                                                                  | 4 m/s (Chao et al., 2009)                           | Water / solid nuclei                  | 6.95E-4 / NA                           |
|                                   | Droplet Temperature                                                                | 37 °C                                               |                                       |                                        |
|                                   | Droplet Size distribution                                                          | Table 2                                             |                                       |                                        |
| Manikin surfaces                   | Heat Flux                                                                          | $64.5 \text{ W/m}^2$ (Villafruela, Olmedo, Ruiz de Adana, M´endez & Nielsen, 2013) | NA                                    | NA                                     |
| Room and Ground walls              | Heat Flux                                                                          | Adiabatic                                           | NA                                    | NA                                     |
|                                     | No slip wall                                                                       | NA                                                  | NA                                    | NA                                     |
| Room Inlet (MV only)               | Static Pressure                                                                    | 1 bar                                               | NA                                    | NA                                     |
|                                     | Heat Flux                                                                          | Adiabatic                                           | NA                                    | NA                                     |
| Room Inlet (NV only)               | Inlet mass flow                                                                    | 0.05 kg/s                                           | Air / Water 1.184 / 997               | 1.86E-5 / 8.9                           |
|                                     | Inlet Temperature                                                                  | 25 °C                                               |                                       |                                        |
|                                     | Inlet Relative Humidity                                                            | 50%                                                 |                                       |                                        |
|                                     | Inlet Turbulence Intensity                                                         | 5%                                                  |                                       |                                        |
| Room Outlet (MV and NV only)       | Static Pressure                                                                    | 1 bar                                               | NA                                    | NA                                     |
|                                     | Heat Flux                                                                          | Adiabatic                                           | NA                                    | NA                                     |

A mesh sensitivity study was conducted for three different grid settings for the CV case, as coarse, medium, and fine meshes with element numbers of 564,320, 814,715, and 1112,584, respectively. The vertical profiles of $U/U_H$ at three different streamwise locations ($x/H = -0.39, 0, 0.39$) are plotted in Fig. 5 for all mesh settings. In general, the deviations between three meshes were not so high, however, medium, and fine meshes showed very close values all over the three vertical lines.
\[
\frac{U(z)}{U_{ref}} = \left( \frac{z}{z_{ref}} \right)^{\beta}
\]  \hspace{1cm} (15)

\[
\varepsilon(z) = \sqrt{0.09 k(z)} \frac{U_{ref}}{z_{ref}} \left( \frac{z}{z_{ref}} \right)^{\beta-1}
\]  \hspace{1cm} (16)

\[
k(z) = \left( 0.1 \left( \frac{z}{z_0} \right)^{1-\beta} \right)^2 U(z)^2
\]  \hspace{1cm} (17)

where \( U(z) \) is the streamwise velocity at the height of \( z \) and \( U_{ref} = 0.5 \) m/s is the reference velocity at the reference height \( z_{ref} = 10 \) m.

Distribution of different exhaled droplet sizes was extracted from the literature (Chao et al., 2009) as presented in Table 1. Boundary conditions required to solve the described case studies is also shown in Table 3. It should be noted that the hydraulic diameter for Cases MV and NV is set as 1.08 m. Furthermore, since the continuum is solved on a steady state basis, the defined humidity at the inlet propagates through and reaches to a time-independent condition all over the domain, including the office room. For this purpose, the inlet humid air is modeled as a mixture of water and air species.

4. Results and discussion

4.1. Validation of airflow predictions

A validation study is conducted for CV and SV cases to evaluate the reliability of CFD simulations for airflow predictions inside the building. To this end, results of the CFD simulations are compared to the results of a wind tunnel experiment that was conducted in the atmospheric boundary layer wind tunnel at Niigata Institute of Technology (Akabayashi, Mochida, Tominaga, Yoshida & Sakaguchi, 1996; Kubota, Miura, Tominaga & Mochida, 2008). The building model is a generic cuboid building \( 0.2m \times 0.2m \times 0.16m (L \times W \times H) \) with two openings \( 0.092m \times 0.036m (W \times H) \) at the center of two opposite walls for the CV case, and one opening on the windward façade for the SV case. This building model is used in the previous extensive cross-ventilation studies by authors (Tominaga & Blocken, 2016, 2015; M. Shirzadi, Tominaga, & Mirzae, 2019, 2020; Mohammadreza Shirzadi, 2020).

The indoor velocity field over a vertical plane was measured using a two-dimensional (2D) particle image velocimetry (PIV) system (SEIKA Digital Image Corporation). Mist oil droplets with nominal diameter of \( 3-4 \mu m \) were released upstream of the building model using a droplet generator (CTS-1000). The building model was made by transparent acrylic plates with 3-mm thickness, which makes it possible to capture reflection images from the vertical plane inside the building. A Double pulse YAG laser (Photonics Industries DM20–527 PIV) with a high-speed camera (FASTCAM MiniAX 50) were installed above and in front of the building, respectively. The image resolution per pixel was about 0.2 mm/pixel while the camera frame rate was set to 1000 Hz. All PIV analyses were conducted using Koncerto II software provided by Seika Digital Image, which is based on Fast Fourier transform (FFT)-cross correlation with the multi-grid interrogation method (Scarano & Riethmuller, 1999). The Gaussian distribution function was used for sub-pixel interpolation of the velocity field. The reference velocity was \( U_H = 3.56 m/s \) at the building roof height \( (H = 0.16 m) \). The wind tunnel profiles for \( U, k, \) and \( \varepsilon \) can be found in Shirzadi, Tominaga and Mirzae, (2019).

Vertical profiles of the time-averaged stream-wise velocity over three vertical lines at \( \frac{H}{L} = -0.47, 0, 0.47 \) are shown in Fig. 6 for CFD and wind tunnel measurement. According to Fig. 6, the calculated velocity...
Profiles are plotted against experimental data with discrete black circles depicted in blue lines. An error bar of 10% is also considered for each measured point, reflecting the measurement uncertainties. The comparison between the CFD and experimental profiles shows good agreements for the CV and SV cases. The highest deviation is seen in the SV case near the window where the inlet air exerts shear stresses on the strong circulating flow inside the room where the turbulent kinetic energy is intensified. In the case of CV, however, this deviation has a lower value since the room inside airflow pattern is dominated by the cross flow between the opposite windows. Results of the validation study show the reliability of the CFD predictions for the calculation of the airflow pattern inside the building for CV and SV cases, which have more complex flow pattern than NV and MV because of the strong coupling between airflows inside and outside of the building.

4.2. Airflow distribution

Office flow pattern has a substantial impact on both dilution and
dispersion of airborne pathogens and therefore studying the flow field may give an insight of droplets streamlines. Considering the size of the released droplets and their rapid evaporation, which drastically reduces their sizes, the impact of droplets on the larger scales of the flow field inside the room is quite low. So that the generated flow field inside the office room can be considered independent from the position of the infected occupant. The flow field inside the room, instead, is strongly influenced by the ventilation strategy and thermal plume of the occupants. In other words, at each ventilation strategy, the airflow patterns are identical no matter which occupant is the infected one.

The velocity contours of the described ventilation strategies are depicted over the horizontal and vertical mid-planes as illustrated in Fig. 7 and Fig. 8. An overall comparison of the contours implies that the velocities of NV and SV strategies in the mid parts of the room are at their lowest range while an upward motion of the air near the walls can be found to be considerable due to the thermal plume of the occupants. In general, MV and CV ventilation types show higher velocities in the center of the room. Inward flows of the recent cases can suppress the upward motion of the flow caused by the thermal plume. Comparing the results of Fig. 7 and Fig. 8 also implies that further stretch of the thermal plume throughout the office room strongly relies on the selected ventilation strategy and also the position of the occupants, which in turn can influence the infection propagation in particular around the occupants. According to Fig. 7, the thermal plume of manikins in Case NV are nearly identical in the absence of the supply and return ducts. While in Cases MV, CV and SV, the upward flow caused by the thermal plume is suppressed by the inlet flow to the room. Case CV also reveals that the outlet window can extract the upward flow induced by the thermal plume. Fig. 8 implies that, in Case SV, non-zero velocity regions are limited to the vicinity of the occupants while in Case CV a strong flow exists in most parts of the room, which affects the propagation of droplets inside the room as well as the thermal plume patterns. These contours suggest

![Infection probability (%)](image)

**Fig. 9.** Infection probability (in percent) of CV and SV strategies with different position of the infected occupant.
that in the ventilated rooms, there is a strong interaction between the thermal plume and room airflow, which affects the airborne pathogen transmission. Therefore, position of the occupants should be considered as an important parameter in different ventilation method assessments.

One key point is to consider that the infection of an exposed occupant is not only a function of the concentration of airborne pathogens, but it significantly depends on the duration of the exposure. This means that the infection happens if an exposed occupant receives a certain dosage of the viral load. Thus, this needs accumulative calculation of airborne pathogen droplets reaching to the exposed occupant.

4.3. Particle concentration

The non-zero background airflow inside a room simultaneously disperse and dilute the airborne pathogens. So, if the droplets are not modeled, it is nearly impossible to quantify the infection risk and to determine either dispersion or dilution of the droplets is the dominant phenomenon. Hence, each ventilation strategy is simulated three times with identical boundary conditions considering that the position of the infected occupant to be changed in different scenarios. For instance, CV1 refers to the cross-ventilation scenario in which the occupant number 1 (according to Fig. 3 (a)) is infected and two other occupants are exposed.

3D scatter diagram of the infection probability in Case CV, in accordance with the introduced methodology at Section 2.2, is presented in Fig. 9. As it can be seen, scattered diagrams are colored by the infection probability as per Eq. (15). As shown in Fig. 7, inlet and outlet windows are on the left and right sides of the room, respectively. So, it is not unexpected that in Case CV3 droplets and the resultant infection risk are directed toward the outdoor spaces and are not dispersed inside the office. Dispersion of the airborne pathogen droplets inside the room in Cases CV1 and CV2, however, is higher in comparison with CV3. As shown in CV2, it is evident that the thermal plume of the infected occupant forms a relatively high-risk region on its upper region. The higher infection risk near the ceiling is also caused by this upward motion. Impact of the infected occupant’s thermal plume on the propagation of the airborne pathogens in Case CV1 is quite limited while the upper section of the room has a lower risk of infection compared with Case CV2. The reason is that the inlet airflow from the left side window, where the infected occupant-1 is positioned, prevents upward movement of the thermal plume at this point. The common issue in all the cases of Fig. 9 is that the highest risk of infection can be observed at 1.5 m to 2 m distance from the infected occupant.

3D Scatter plot of the infection probability of SV case is also depicted in Fig. 9. In this figure, SV2 and SV3 show a similar infection risk distribution, which is mainly caused by the upward motion of the thermal plumes. The central zone of the room, however, encounters a low airflow movement. So, in SV1 and in the absence of an effective airflow, a great deal of the pathogens falls and then a high-risk part of this room will be in the lower half of the room. In other words, airborne transformation mechanism is nearly weak in Case SV1.

3D distribution of the infection probability for MV scenario is presented in Fig. 10. In general, this strategy results in a strong dispersion of the airborne pathogen droplets all over the room. In fact, the ventilation type combined with the thermal plume leads in a strong flow field inside the room, which is responsible for a strong propagation of the airborne pathogen droplets. For example, while the thermal plume of the cases
Fig. 11. Infection probability of NV strategy with different position of the infected occupant.

Fig. 12. Iso-surface infection probability of 10% (IP_1 is infected).
MV2 and MV3 moves upwards and reaches the ceiling, that of the case MV1 is cut off under the influence of the inlet flow. Therefore, the propagation of airborne pathogen droplets in MV1 will be quite different from that of the cases of MV2 and MV3.

Case NV infection risk inside the room after 1 hour is shown in Fig. 11. Since no ventilation exists in the room, case of NV3 is identical to NV1 due to a geometric symmetry. As expected, lack of ventilation in the presence of the thermal plume disperses the droplets continuously in an upward direction. It can be concluded that NV and MV results in a higher dispersion of the airborne pathogens in the office room. Moreover, the health risks of CV and SV strategies are generally dependent on the relative position of the infected occupant and location of the windows.

4.4. Iso-surface for the different ventilation strategies

3D scatter data of the infection probability presented in Section 4.3 can also be represented in an isosurface form. Iso-surface reported here are geometric locus of points in the room having the same infection probability. So, if properly set, isosurfaces can be regarded as a border that separates high risk infection zones from the lower ones. In this section, isosurfaces of different ventilation strategies, assuming that occupant-1 (see Fig. 3) as the infected person (IP), are presented in Fig. 12. This demonstration method provides a useful tool to investigate details of the infection risks in indoor spaces. Here, the onset value for the isosurface is selected as 10 percent. This means that the regions wrapped by such surfaces have the infection risks of equal or above 10 percent while the infection probability outside of this surface becomes below 10 percent after one hour.

According to Fig. 12, CV1 and MV1 show almost a similar distribution of the infection risk. Both cases yield dam-shaped isosurfaces caused by the inlet flow, which surpasses the thermal plume. It also implies that in the cases of CV1 and MV1, the exposed occupants are not under serious infection risk after an hour. However, in SV1 and NV1, the same infected occupant can cause a greater risk to other occupants because of a substantially different airflow patterns from what is observed in the cases of CV and MV. Although the inlet flow in SV1 confines the thermal plume and consequently the upward motion of the airborne pathogen droplets in the office, the lower part of the room is dominated by falling of the droplets. In NV1, the thermal plume in the absence of the inlet flow toward the room is the driving force to expand the risky zone with infection probability of above 10 percent toward the roof. The infected occupant in both cases of SV1 and NV1 can be a threat to other occupants as the risk can further increase if the simulation timespan is extended.

4.5. Tempo-Spatial global and local infection risks

3D scatter diagrams of the previous section give a qualitative overview of the infection probability of different ventilation strategies. Although these graphs are informative, a quantitative comparison of different ventilation strategies should be further provided. For this purpose, the global and local infection risk indices are firstly defined as \( P_{nG} \) and \( P_{nL} \), respectively. \( n (-1, 2 \ or \ 3) \) refers to the infected occupant number. The global index \( P_{nG} \) is an averaged value of the probability over the volume of 2 m from the ground level. Above this height, airborne pathogen droplets will not be a threat to an averaged standing human. The local infection risk by definition is the averaged value of the infection probability inside a sphere around the head of the infected occupant with the diameter of 1 m. This value is selected because of 2 m safe distance proposed by WHO as a 1 m sphere around each individual can result in a 2 m distance amongst them. These indices give an overall estimation of the infection risk inside the room at a height that is likely to encompass occupants either in seated or standing positions. Therefore, in this section, the variation of the global and local risk indices for the occupants as a function of time is first presented and then the infection probabilities after one-hour exposure time are discussed.

Assuming that IP_1 is infected, the growth of the infection risk in terms of the global and local indices within the simulation timespan are depicted in Fig. 13 and Fig. 14, respectively, for different ventilation strategies. According to Fig. 13, the highest infection risk can be found in the SV strategy. The NV strategy is the next case while CV and MV show the lowest risk level. One noticeable fact that can be drawn from this diagram is that NV, MV and CV present nearly identical trends in the increase of the global index at first 2,400 s of the simulation. As the exposure time increases, however, NV strategy gradually deviates from the other two. This means that the accumulation of the airborne pathogens depends on the ventilation type and consequently on the flow field.
inside the room as it can significantly change through the time.

The variation of the local index around the infected person (IP_1) during the simulation time of one hour is also depicted in Fig. 14. Although the calculated infection risks of different ventilation strategies are close to each other, the probability of infection in the cases of CV and SV are at the highest level around the IP_1. MV is at the middle level while the lowest risk is caused by the NV case. Comparison of Fig. 13 and Fig. 14 shows that although CV is associated with the lowest level of the general index, it imposes the highest risk around the infected occupant. This comparison also implies that while the general index of NV increases rapidly with the time, its local infection risk around IP_1 remains below the other ventilation strategies. Hence, the results suggest that the proposed framework can help to assess the performance of different ventilation types within a target simulation run-time considering the impact of occupants.

The local index parameter is also illustrated in Fig. 15 for the exposed persons (EP) i.e., EP_2 and EP_3. Both diagrams of Fig. 15a and b illustrate that Cases SV and NV result in the highest infection risks for the susceptible occupants. The only different behavior that can be seen is that Case MV imposes a higher infection risk on EP_2 while the infection risk of EP_3 is higher when CV is applied. This implies that the performance of ventilation system in restriction of airborne pathogen droplets’ propagation at the near field (the infected case) is different from the far field regions (EP_2, EP_3). So, a proper evaluation of a ventilation system requires that the local index is applied to all occupants in the room. It also indicates that the position of occupants has a considerable influence on the level of the infection risk.

Global indices calculated for each ventilation type after the exposure time of one hour are presented in Table 4. According to this table, if IP_1 is the infected one, the case SV is associated with the highest level of risk. Although most of the droplets fall and are not strongly dispersed inside the room, they are concentrated in the target integration zone of the global index’s parameter. This results in the related averaged risk factor to become the highest among other methods. Case NV possesses the second-highest value of the global indices. Unlike case of SV, in NV, the room flow field is only impacted by the thermal plume. So, there is always an upward motion, bringing out a fraction of airborne pathogen droplets from the lower part of the zone. Cases of MV and CV, as observed in Fig. 7 and Fig. 8, form similar flow fields inside the room and thus demonstrate similar global risk indices. Although low values of indices reported in Table 4 may not show a serious infection risk after one hour, this gives a measure to compare the performance of different ventilation strategies in propagation of airborne pathogen droplets inside the room. Hence, the risk can be developed in a longer period of simulation and exposure time of the occupants.

As seen in the Table 4, the global risk indices only consider the condition of the room as a whole and does not provide any information about the infection risk of other occupants inside the office. So, the local

| Table 4 |
|---|
| Global indices for different ventilation methods (IP_1 is infected). |
|     | NV | MV | SV | CV |
| $P^G_1$ (%) | 5.73 | 4.00 | 8.83 | 4.72 |

Table 5
Local indices for different ventilation methods (IP_1 is infected).

| Infection Probability | NV | MV | SV | CV |
|---|---|---|---|---|
| $P^L_1$ (%) | 20.2 | 23.5 | 25.37 | 25.8 |
| $P^L_2$ (%) | 10.6 | 6.34 | 15.9 | 4.7 |
| $P^L_3$ (%) | 8.5 | 3.18 | 20.87 | 4.6 |

Fig. 15. Time-dependent variation of the local infection index during one hour for (a) EP_2 and (b) EP_3 (IP_1 is infected).
risk indices are applied to offer a better vision about the infection mechanism among the other exposed occupants in different scenarios. According to schematic image of Table 5, IP_1, EP_2 and EP_3 represent the occupants of the room, each of which can be considered as the infected occupant and others as the exposed ones. Here, it is assumed that IP_1 is the infected person and EP_2 and EP_3 are the exposed occupants.

According to Table 5, the infection risk around the IP_1 is nearly similar in all four scenarios. Although in NV, the local infection risk is lower than that of other cases; this implies that the micro-environment around the infected occupant is not strongly influenced by the ventilation strategy. For the exposed occupants (here, EP_2 and EP_3) in the office room, however, this is not necessarily true. According to the local infection risk of EP_2 and EP_3, it is evident that the infection probability of the exposed occupants is strongly affected by the selected ventilation strategy. For instance, while the SV and CV types provide a same infection risk value for the infected occupant, the probability of infection for EP_2 and EP_3 in the case of SV is 15.9% and 2.9%, respectively, which is considerably higher than 4.7% and 4.6% as calculated in the case of CV. Based on the results of Table 5, it can also be concluded that in the office room, the infection probability does not necessarily drops as the distance from the infected occupant increases. Although this is a valid point for the cases of NV, MV and CV, in SV, the infection risk of EP_3 is higher than EP_2 while the distance of EP_3 from the infected occupant is higher. This shows that a social safe distance in an office room is deeply affected by the selected ventilation strategy and not merely the distance from the infection source. Similar calculations can be conducted for ventilation cases in which a second or a third occupant is infected. This is a critical issue in designing suitable ventilation strategies for office rooms and gives a practical means to assess the existing ventilation cases.

5 Conclusion

To assess the transmission of airborne pathogen droplets inside confined spaces like office rooms, a framework is presented in this paper. According to the proposed framework, a case study of airflow inside an office room is simulated using CFD technique. Exhaled droplets during the speaking activity are modeled using the available data in literature about droplets’ size and distribution. Captured data of the instantaneous position of droplets’ trajectories is then directed to a computational bespoke code to calculate the accumulated viral loads all over the office room. The room is occupied by three occupants while different ventilation strategies (i.e., CV, SV, NV and MV) as well as the position of the infected occupant is investigated to evaluate the performance of the bespoke code at different situations. Following remarks can be concluded from the simulation results:

- 3D scatter plots of the infection probability and its associated 2D slice contours can be regarded as a useful mean to assess the dispersion of pathogen droplets inside a room under influence of different factors such as selected ventilation type, relative position of infected and exposed occupants inside the room and the exposure time. For example, the infection risk in the case of MV1 is more uniformly dispersed inside the room compared with SV1. Nevertheless, this does not necessarily mean that SV1 has a better performance in general.
- Definition of the local and global indices can offer a quantitative comparison between different strategies. The former evaluates the general condition of a room from viewpoint of the infection risk while the later can be used to determine the infection risk around infected and exposed occupants. The underlying reason is that different ventilation strategies generate diverse background flow fields inside a room, so that the transport of pathogen droplets can be significantly affected.
- Time history of the local and global indices is particularly beneficial in assessing the trend of the accumulated viral loads inside a room under different conditions. For instance, while the global index’s accumulation behavior of the cases of NV, MV and CV shows similar behavior in the first 2,400 s of the simulations, in the case of NV, the global index’s accumulation slope starts to deviate from the other two cases afterwards. So, the behavior of the ventilation systems from the viewpoint of the infection risk does not necessarily change linearly with time.

The proposed framework can be applied to assess the designed ventilation system, managing work hours and also find optimum layout of occupants in confined spaces like office rooms. One important feature of the present research work is that it adds output data of CFD to the infection risk models through the calculation of accumulated droplets inside the room and also application of clinical data on COVID-19 infective dosages. By inserting a wide range of exhaled droplet sizes (from 3 to 750 μm) and inclusion of evaporation and defining droplets as a multicomponent material, a fraction of which is not evaporated, a more realistic airborne behavior of airborne pathogen droplets can be obtained inside the room.

One of the restrictions of the present research work is that simple cylinders mimic the occupant, which can have an impact on the flow field and infection risk in micro-environment around them. One-hour timespan of the simulations also imposes a limitation. Although one hour is not a considerable time-span compared to daily work hours, it should be pointed out that the main aspect and novelty of this work is that it proposes a framework that can be applied to investigate the infection probability of different ventilation strategies in different confined spaces. Realistic time spans will be subject of future works of the authors to demonstrate practical capabilities of the introduced framework. Thus, further assessments are needed with longer work hours. Another point to mention is that the room geometry is simple, and furniture is not considered in this research work, which can have an impact on the flow pattern inside the room. It is well understood that every piece of furniture or barriers inside the room can alter the flow patterns and consequently the propagation of aerosols in a room. So, our future work will focus on finding practical solutions and guidelines to minimize the risk of airborne pathogen transmissions in more realistic confined spaces for more diverse applications.

Declaration of Competing Interest

None.

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