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Contaminant removal and contaminant dispersion of air distribution for overall and local airborne infection risk controls

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HIGHLIGHTS

• Contaminant removal is proposed as the mechanism for overall airborne infection risk control.
• Contaminant dispersion is proposed as the mechanism for local airborne infection risk control.
• Overall airborne infection risk is closely related to contaminant removal index.
• Local airborne infection risk is closely related to contaminant dispersion index.

ABSTRACT

Proper air distribution is crucial for airborne infection risk control of infectious respiratory diseases like COVID-19. Existing studies evaluate and compare the performances of different air distributions for airborne infection risk control, but the mechanisms of air distribution for airborne infection risk control remain unclear. This study investigates the mechanisms of air distribution for both overall and local airborne infection risk controls. The experimentally validated CFD models simulate the contaminant concentration fields in a hospital ward based on which the airborne infection risks of COVID-19 are evaluated with the dilution-based expansion of the Wells-Riley model. Different air distributions, i.e., stratum ventilation, displacement ventilation, and mixing ventilation, with various supply air flow rates are tested. The results show that the variations of the overall and local airborne infection risks under different air distributions and different supply airflow rates are complicated and non-linear. The contaminant removal and the contaminant dispersion are proposed as the mechanisms for the overall and local airborne infection risk controls, respectively, regardless of airflow distributions and supply airflow rates. A large contaminant removal ability benefits the overall airborne infection risk control, with the coefficient of determination of 0.96 between the contaminant removal index and the reciprocal of the overall airborne infection risk. A large contaminant dispersion ability benefits the local airborne infection risk control, with the coefficient of determination of 0.99 between the contaminant dispersion index and the local airborne infection risk.
1. Introduction

During the pandemic of COVID-19, nosocomial infections occur all over the world. The attack rate for healthcare workers in some hospitals is as high as 8.1%, with a considerable portion (e.g., 49%) of asymptomatic infections, which may cause further cross infections (Abbas et al., 2021). There is growing evidence supporting the airborne transmission of COVID-19 (Correia et al., 2020). The SARS-CoV-2 RNA has been found in the samples from ventilation openings, central ducts, and HEPA filters in a hospital (Nissen et al., 2020). The SARS-CoV-2 RNA aerosols have also been detected in hospital wards (Liu et al., 2020a). The above facts make ventilation become one of the most crucial engineering measures in preventing the infection of COVID-19 (REHVA, 2021; Wang et al., 2021).

Air distribution controls the airborne infection risk by diluting the contaminant in the room with clean supply air and extracting the contaminant from the room with the exhausted air (Fan et al., 2022). Air distribution of ventilation significantly affects the transmission of airborne pathogens (Guo et al., 2021). Berlanga et al. (Berlanga et al., 2018) compared the peak value and mean value of inhaled contaminant concentration of the healthcare worker under four different configurations of mixing ventilation and displacement ventilation and highlighted the good performance of displacement ventilation for hospital rooms. The intake fraction (as the exposure index calculated from the aerosol contaminant concentration) of displacement ventilation was maintained at 0.2, while that of mixing ventilation could exceed 0.6 (Berlanga et al., 2018). Liu et al. (Liu et al., 2020b) found that under unilateral downward ventilation, the removal efficiency of aerosol contaminant concentration in the breathing zone was 50% higher than that under bilateral downward ventilation. Cho (Cho, 2019) proposed a new ventilation strategy of “low-level extraction” for isolation rooms which employed two exhaust air grilles on the wall behind the bed at the low floor level and effectively reduced the aerosol contaminant concentration in the breathing zone by up to 66.4%. Zhang et al. (Zhang et al., 2021a) found that compared with the ceiling air supply or the upper side-wall air supply, adaptive wall-based attachment ventilation reduced the aerosol contaminant concentration by 15%–47%. Lu et al. (Lu et al., 2020) found that the exposure risk (indicated by the exhaled contaminant concentration) in the hospital ward was lowest under stratum ventilation compared with that under mixing ventilation, downward ventilation, and displacement ventilation. Lu and Lin (Lu and Lin, 2022) further compared the coughed droplet dispersion patterns under different air distributions and found that compared with mixing ventilation and displacement ventilation, stratum ventilation had better control over the 50 μm diameter droplet by increasing the deposition of the 50 μm diameter droplet. Dao and Kim (Dao and Kim, 2022) compared the behaviors of cough droplets by COVID-19 patients under different configurations of air distributions. Kong et al. (Kong et al., 2021) compared 16 different air distributions in hospital wards and found that the air distribution with upper diffusers on the side-wall for supplying air and lower diffusers on the same sidewall for exhausting air achieved the maximal reduction in the accumulated exposure level (indicated by the accumulated contaminant concentration) of 70.8%.

Existing studies focus on comparing airborne infection risk control performances of different air distributions, but few studies directly look into the effect of air distributions on the airborne infection risk control remains unclear (Su et al., 2022).

The contribution of this study is to reveal the mechanisms of air distribution for controlling both overall and local airborne infection risks, which provides a better understanding of how air distribution controls airborne infection risk and helps to guide the design and operation of air distribution for better airborne infection risk control. The contaminant removal and the contaminant dispersion are proposed as the mechanisms which explain the overall airborne infection risk control performance and local airborne infection risk control performance respectively under different air distributions (i.e., stratum ventilation, displacement ventilation, and mixing ventilation) with various supply airflow rates. The remaining part of this paper is organized as follows. In Section 2, the computational fluid dynamics models (CFD) are established, and experiments are conducted to validate the CFD models of different air distributions. In Section 3, based on the validated CFD models, airborne infection risk control performances of different air distributions with various supply airflow rates are computed using the dilution-based expansion of the Wells-Riley model. In Section 4, the mechanisms of air distributions for airborne infection risk control are discussed.

2. Methodology

2.1. Studied hospital ward

As shown in Fig. 1, the hospital ward is 5.5 m in length, 3.0 m in width, and 2.4 m in height. There are two beds, two nightstands, three ceiling lamps, one ordinary patient (left) (i.e., the susceptible), and one asymptomatic infector (right) in the hospital ward. The height of the bed is 0.5 m. The patients are in supine position (lying with face facing up). Stratum ventilation, displacement ventilation, and mixing ventilation are studied. Stratum ventilation (supply momentum dominated) and displacement ventilation (thermal buoyance dominated) are two representatives of advanced air distributions, and mixing ventilation is a conventional air distribution (Yang et al., 2019). For stratum ventilation, the supply air grilles (S1–S4) are arranged at the wall near the bed and are 1.5 m above the floor level to supply the conditioned air directly into the breathing zone of healthcare workers (Lu & Lin, 2022), and the exhaust air grilles (E1–E4) are at the wall near the bed and 0.3 m above the floor level. For displacement ventilation, the supply air diffusers (S8–S13) are at the wall opposite to the beds and 0.3 m above the floor level, and the exhaust air grilles (S5–S7) are at the ceiling (Cheng and Lin, 2015). For mixing ventilation, the four-way supply air diffusers with the discharge angle of 20° (S5–S7) are at the ceiling, and the exhaust air grilles are the same as those of stratum ventilation. All the supply/exhaust terminals are of the same size (0.2 m × 0.2 m). Seven sampling points (P1–P7) are determined. The sampling points P1–P3 are distributed at the height of 1.5 m above the floor level around the corridor. The sampling points P4–P6 are at the height of 1.5 m above the floor level around the susceptible. The sampling points P1–P6 are the typical positions where healthcare workers could be. The sampling point P7 is close to the nose of the susceptible. Since the real-time monitoring of airborne pathogen concentration is unrealistic (Lu et al., 2021), CO₂ exhaled by the infector is
used as a biomarker for airborne infection risk evaluation (Zhang et al., 2021b). CO₂ as a biomarker has been validated to be effective for the study of airborne infection of respiratory diseases (Rudnick and Milton, 2003). The clothing insulation of patients is 1.38 clo and the metabolic rate is 0.8 met (reclining) (Lu et al., 2020). The supply air temperature and supply airflow rate are set to maintain the predicted mean vote in the occupied zone within ±0.5 for thermal comfort (Brohus, 1997; Cheng et al., 2022). The detailed boundary conditions are listed in Table 1.

### 2.2. Numerical model

The Reynolds-averaged-Navier-Stokes (RANS) turbulence model is applied to solve the airflow field. The RNG k-ε model is applied as the turbulence model because it performs well in room ventilation (Lu et al., 2020).

#### Table 1

| Boundary surfaces       | Boundary conditions                                      |
|------------------------|----------------------------------------------------------|
| Air supply             | Velocity inlet                                           |
|                        | Stratum ventilation: 6 ACH, 0.41 m/s/22.0 °C; 9 ACH, 0.62 m/s/22.5 °C; 12 ACH, 0.83 m/s/23.0 °C |
| Air exhaust            | Pressure outlet                                           |
| Wall/ceiling/floor/bed | Boundary wall, adiabatic                                   |
| Ceiling lamp           | Wall boundary with constant heat flux, 150 W/m²           |
| Patients               | Wall boundary with constant heat flux, 45 W/m², (76 W, equivalents to the metabolic rate of a sedentary occupant) |
| Mouth                  | CO₂: 40000 ppm, Velocity inlet: 0.49 m³/h, 34.0 °C       |

* Four-way diffuser with the discharge angle of 20° is used for mixing ventilation.

It is simplified as a square, and the square is divided into four parts with four supply air directions.

* Velocity magnitude perpendicular to the surface of air supply. The velocity magnitude parallel to the surface is the velocity magnitude perpendicular to the surface times \(\tan^{-1} 20°\).

The governing equations for mass, energy, and momentum are described in Eq. (1). Table 2 shows the explanations of the variables in Eq. (1).

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \vec{U} \phi) = \nabla \cdot (\Gamma_\phi \nabla \phi) + \overline{S}_\phi \tag{1}
\]

where \(\rho\) is the fluid density, kg m\(^{-3}\); \(\phi\) represents the variables; \(t\) is the time, s; \(\vec{U}\) is the velocity vector, m s\(^{-1}\); \(\Gamma_\phi\) represents the effective diffusion coefficient for each variable; \(\overline{S}_\phi\) is the source term.

The species transport model is used to solve the dispersion of the exhaled contaminant (Eq. (2)).

\[
\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho \vec{U} Y_i) = -\nabla \cdot \overline{J_i} + R_i + S_i \tag{2}
\]

where \(Y_i\) is the local mass fraction of the exhaled contaminant; \(\overline{J_i}\) is the diffusion flux of the exhaled contaminant, kg m\(^{-2}\) s\(^{-1}\); \(R_i\) is the net rate of production, which is 0; \(S_i\) is the contaminant generation rate of the source, kg m\(^{-3}\) s\(^{-1}\).

#### Table 2

| Values of variables, effective diffusion coefficient, and source term. |
|-----------------------------------------------------------------------|
| Equation | \(\phi\) | \(T_{\phi}\) | \(\overline{S}_\phi\) |
|-------------------|--------|-------------|----------------------|
| Mass              | 1      | 0           | 0                    |
| Momentum          | \(u_t\) | \(\mu + \mu_t\) | \(-\frac{\rho}{\rho} + S_a\) |
| Energy            | \(T\)  | \(\frac{R}{\mu} + \frac{\mu}{2}\) | \(S_T\) |
| Kinetic energy    | \(k\)  | \(a(\mu + \rho)\) | \(C_a G_k + G_a - \rho\epsilon\) |
| Turbulent dissipation rate | \(\epsilon\) | \(a(\mu + \rho)\) | \(C_a G_k (G_k + G_a) - C_2 \rho \frac{\epsilon^3}{\nu} - R_{\epsilon}\) |

Where \(u_t\) is the component of velocity vector on the i direction, m s\(^{-1}\); \(T\) is the temperature, K; \(k\) is the kinetic energy per unit mass, J kg\(^{-1}\); \(\epsilon\) is the turbulent dissipation rate per unit mass, W kg\(^{-1}\); \(\mu\) and \(\mu_t\) are the laminar viscosity and turbulent viscosity respectively; \(\alpha, \beta, c_{1a}, c_{2a}\), and \(\gamma\) are the laminar number and turbulent Prandtl number respectively; \(a (a = 1.39)\) is the inverse turbulent Prandtl number; \(\rho \) is the static pressure, Pa; \(S_a\) is the external and gravitational body force on the i direction, N m\(^{-3}\); \(S_T\) is the volumetric heat source, kg K m\(^{-3}\) s\(^{-1}\); \(G_k\) and \(G_a\) represent the generation of turbulence kinetic energy due to the mean velocity gradient and buoyancy respectively, W m\(^{-3}\); \(R_{\epsilon}\) is the source term from renormalization, W m\(^{-3}\) s\(^{-1}\); \(C_{1a} = 1.42, C_{2a} = 1.68, \) and \(C_{3a} = \tanh \left( \frac{\rho \epsilon}{\nu} \right)\).
The numerical model is solved by the FLUENT software. The standard wall function is applied for the near-wall treatment. The discrete ordinates radiation model is applied to simulate the radiative heat transfer among indoor surfaces. The Boussinesq approximation is applied for the buoyancy of the airflow. The SIMPLE algorithm is used to couple the pressure and velocity. The second order scheme is used for pressure interpolation. The second order upwind scheme is used for convection terms. Firstly, the steady state of the airflow field is obtained as a reasonable initial condition. Then, the transient evolutions of the air velocity, air temperature, and CO₂ concentration are simulated.

2.3. Independence tests of grid and time step

The structured grids for the hospital ward with different spatial resolutions are generated. The maximum grid size ranges from 25 mm to 100 mm, and the grid numbers range from 52,275 to 2,743,986. The air velocity, air temperature, and exhaled contaminant concentration using different grids are obtained and compared. The grid with the maximal grid size of 50 mm is good enough regarding the simulation accuracy. With the further refinement of the grid, the increase in the simulation accuracy is limited. Considering both the simulation accuracy and computation load, the grid with the maximum size of 50 mm is adopted and the corresponding grid number is 407454. Compared with the finest grid with the maximum size of 25 mm, the relative differences for the air velocity, air temperature, and exhaled contaminant concentration are less than 6.1%, 0.18%, and 4.9% respectively. The transient simulations with time steps of 0.1 s, 0.2 s, 0.5 s, 1 s, and 2 s are further tested. The time step of 0.5 s is adopted considering both the simulation accuracy and computation load. Compared with the time step of 0.1 s, the relative differences for the air velocity, air temperature, and exhaled contaminant concentration are less than 1.8%, 1.1%, and 2.0% respectively.

2.4. Experiments

The experiments are conducted in an environmental chamber equipped as a hospital ward (Fig. 2a). The layout of the environmental chamber and

Fig. 2. (a) Photo of environmental chamber (b) Schematic of environmental chambers served by stratum ventilation (SV), displacement ventilation (DV), and mixing ventilation (MV) (Unit: mm).
the schematics of different air distributions are shown in Fig. 2. The environment chamber is 9.0 m in length, 5.1 m in width, and 2.4 m in height. There are three beds and four manikins. The height of the bed is 0.75 m. The manikin consists of the head, torso, and legs, and the specific dimensions adopt from (Brohus, 1997). The manikin is 1.7 m in height with the surface area of 1.62 m². The heat output of the manikin in the experiment is 76 W (Srebric et al., 2008) to simulate the occupant. The environmental chamber is at the inner zone of the building without any exterior walls, therefore the walls can be considered adiabatic. For SV, four supply air grilles on the wall are 1.3 m above the floor, and four exhaust air grilles are 0.3 m above the floor. For MV, six four-way supply air diffusers are at the ceiling, and four exhaust air grilles are 0.3 m above the floor. For DV, 11 supply air diffusers are 0.3 m above the floor, and three exhaust grilles are at the ceiling. The supply airflow rates for SV, MV, and DV are 11.60 ACH, 9.15 ACH and 11.55 ACH, respectively. The supply air temperatures for SV, MV, and DV are 21.5 °C, 19.0 °C, and 22.3 °C, respectively. The indoor temperatures at steady state for SV, MV, and DV are 26.0 °C, 24.4 °C, and 25.3 °C, respectively. The air velocity and air temperature are measured at the sampling line S1 (within the heights of 0.7 m–1.7 m above the floor level). The SF6 tracer gas is released from the mouth of the infector lying in the middle of the ward at the flow rate of 2 ml/s at the environment temperature. The existing studies (Yi et al., 2009; Bolashikov et al., 2012; Rim and Novoselac, 2009) have demonstrated that the tracer gas released at the environment temperature can provide sufficiently reliable results for indoor air quality study. The sampling point S2 for SF6 concentration is 1.5 m above the floor level (i.e., the breathing level of the healthcare worker).

The air velocity, air temperature, and tracer gas concentration are measured. The anemometers (SWEMA 03) are used for measuring the air velocity and air temperature. The uncertainty is ±0.03 m/s for the air velocity and ±0.2 °C for the air temperature. A multipoint doser and sampler (INNOVA 1403) is used for dosing and sampling the tracer gas of SF6 (Zhang and Lin, 2021). The sampling rate is 30 s. The sampled SF6 concentration is measured by the photoacoustic gas monitor (INNOVA 1412i) with a measurement accuracy of ±0.06 ppm.

Compared with the studied hospital ward described in Section 2.1, the ward in the environmental chamber is of a larger area and with one more bed and two more manikins. Although the dimensions of the hospital ward in Fig. 2 are different from those of the hospital ward in Fig. 1, the two hospital wards share similar inner configurations and layouts of air distributions. Thus, the experiments can be used for the validation of the CFD model (Lu et al., 2020). To validate the CFD model, the grid generation strategy and temporal resolution described in Section 2.3 are used.

3. Results

3.1. Experimental validation of CFD model

Figs. 3 shows that the variations of the simulated air velocity, simulated air temperature, and simulated contaminant concentration are similar to those from the measurements respectively. Compared with the measured air velocity, the mean absolute errors of the simulated air velocity are 0.08 m/s, 0.03 m/s, and 0.01 m/s under stratum ventilation, displacement ventilation, and mixing ventilation respectively. Compared with the measured air temperature, the mean absolute errors of the simulated air temperature are 0.49 °C, 0.52 °C, and 0.46 °C under stratum ventilation, displacement ventilation, and mixing ventilation respectively. Compared with the measured contaminant concentration, the mean absolute errors of the simulated contaminant concentration are 0.76 ppm, 0.60 ppm, and 0.62 ppm under stratum ventilation, displacement ventilation, and mixing ventilation respectively. The reasonable errors of the simulated air velocity, air temperature, and contaminant concentration indicate that the CFD models of stratum ventilation, displacement ventilation, and mixing ventilation are acceptable (Lu et al., 2020).

3.2. Airflow pattern

The airflow fields under stratum ventilation, displacement ventilation, and mixing ventilation with the supply airflow rates of 6ACH–12 ACH are shown in Fig. 4a. For stratum ventilation, the supply air jet drops with the spread of the airflow and the air velocity decays with the spread of the airflow. Recirculation zones are formed outside of the supply air jet. Overall, a sandwich airflow field is formed, with the air velocity higher in the breathing zone of the healthcare worker (about 1.5 m above the floor) and lower in the upper and lower zones (Zhang et al., 2022). For displacement ventilation, the air is supplied from the lower part of the room with a low air velocity. The air velocity decays with the spread of the airflow. The air velocity above the patient increases slightly because of the heat exchange with the patient. The typical air distribution of mixing ventilation is also formed. The supply airflow from the diffuser attaches to the ceiling and wall because of the Coanda effect (Yang et al., 2019) which causes the backflow in the occupied zone.

Increasing the supply airflow rate generally increases the air velocity (Fig. 4a), but could decrease the local air velocity. For example, at the sampling point P4, the air velocity increases with the increasing supply airflow rate under displacement ventilation, decreases with the increasing supply airflow rate under mixing ventilation, and firstly increases and then decreases with the increasing supply airflow rate under stratum ventilation (Fig. 4b). Under stratum ventilation, the air velocity reaches up to 0.58 m/s. The air velocity is particularly high at sampling points P2 and P5 since these two sampling points are within the supply air jets and close to the supply air grilles. Under displacement and mixing ventilation, the air velocity is below 0.25 m/s, and generally lower than 0.15 m/s.

3.3. Airborne infection risk

As introduced in Section 1, the dilution-based expansion of the Wells-Riley model is used to calculate the airborne infection risk. The original Wells-Riley model (Sze To and Chao, 2010) is shown in Eq. (3), the term \( \frac{I_{q}}{I_{T}} \) represents the quantity inhaled by the susceptibles, which is based on the assumption that the infectious particles are uniformly distributed in a room. According to the Wells-Riley equation, the intake dose of the infectious particles at one quantum results in the average infection risk of 63.2%. In reality, the air distribution in a room is nonuniform and leads to nonuniform distribution of infectious particles, hence the original Wells-Riley model has limitations in predicting the infection risk in spatial resolution.

For the dilution-based expansion of the Wells-Riley model (Zhang and Lin, 2021), the dilution ratio is introduced to calculate the inhaled quanta. The dilution ratio can be calculated from the distribution of CO2 concentration exhaled by the infector, which is the ratio of the contaminant concentration exhaled by the infector to that inhaled by the susceptible (Eq. (4)) (Zhang et al., 2021b). The inhaled quanta of the susceptible can be inferred by the dilution ratio and the exhaled quanta of the infector as Eq. (5), where the term \( \int_{0}^{T} \frac{p_{s}(t)}{p_{i}(t)} \ dt \) shows the inhaled quanta during the exposure time. The airborne infection risk is calculated according to the Poisson distribution (Eq. (5)). In this study, the CO2 concentration distribution from CFD (Fig. 5a) is used to calculate the dilution ratio \( D(t) \) at each sampling point. Then, the inhaled quanta \( \int_{0}^{T} \frac{p_{s}(t)}{p_{i}(t)} \ dt \) during the exposure time is calculated. The quantum generation rate \( q \) of 48 quanta/h of COVID-19 is adopted for the airborne infection risk evaluation (Dai and Zhao, 2020). According to reference (Buonanno et al., 2020), because of the different activity levels of the patients and healthcare workers, their breathing rates are set to 0.49 m³/h and 0.54 m³/h, respectively.

\[
P_{i} = 1 - \exp\left( -\frac{I_{q}I_{T}}{Q} \right) \tag{3}
\]

\[
D(t) = \frac{C_{susceptible}(t)}{C_{susceptible}(t)} \tag{4}
\]
The airborne infection risk is given by the following equation:

$$P_I = 1 - \exp\left(-\int_0^T \frac{p_i q}{p s D(t)} dt\right)$$  \hspace{1cm} (5)$$

where $P_I$ is the airborne infection risk; $I$ is the number of infectors; $q$ is the quantum generation rate, quanta/s; $p_i$ and $p_s$ are the breathing rates of the infector and susceptible respectively, m$^3$/h; $Q$ is the clean air ventilation rate, m$^3$/h; $D$ is the dilution ratio; $C_{\text{infector}}$ and $C_{\text{susceptible}}$ are the airborne contaminant concentrations exhaled by the infector and inhaled by the susceptible respectively, ppm.

Fig. 5b shows the airborne infection risks at sampling points P1–P7 under different air distributions with various supply airflow rates. The airborne infection risk near the infector (P1–P3) is higher than that far away from the infector (P4–P7). The airborne infection risk at sampling point P1 under displacement ventilation is particularly high (up to 45.2%) because of two reasons. Firstly, the sampling point P1 is close to the infector. Secondly, the contaminant exhaled by the infector is trapped around the infector rather than being dispersed horizontally to the remaining part of the room because of the upward airflow movement under displacement ventilation (Figs. 4a and 5a). The temperature of the exhaled flow is higher than the ambient temperature, therefore the exhaled contaminant would flow upwards because of the buoyancy. The height of the sampling point P7 is similar to the height of the contaminant source and lower than the heights of P1–P6, hence the airborne infection risk at the sampling point P7 are lower than those at the sampling points P1–P6. Under stratum ventilation, the airborne infection risks are 3.0%–9.3%, 0.6%–4.1%, and 0.4%–2.3% at the supply airflow rates of 6 ACH, 9 ACH, and 12 ACH respectively. Under mixing ventilation, the airborne infection risks are 3.9%–9.6%, 2.0%–6.4%, and 1.7%–8.6% at the supply airflow rates of 6 ACH, 9 ACH, and 12 ACH respectively.

Fig. 5c shows that the effects of air distributions and supply airflow rates on the overall airborne infection risk are complicated and non-linear. The overall airborne infection risk is evaluated as the average airborne infection risk of the sampling points P1–P7. Regarding the effect of air distributions, at the supply airflow rates of 6 ACH and 9 ACH, the overall airborne
infection risk is the lowest under stratum ventilation, and the overall airborne infection risk under mixing ventilation is lower than that under displacement ventilation. However, at the supply airflow rate of 12 ACH, although the overall airborne infection risk under stratum ventilation is still the lowest, the overall airborne infection risk under mixing ventilation becomes higher than that under displacement ventilation. Regarding the effect of supply airflow rates, with the increasing supply airflow rate from 6 ACH to 12 ACH, the overall airborne infection risks under stratum ventilation and displacement ventilation decrease from 5.8% to 1.2% and from 10.2% to 3.8% respectively, and the overall airborne infection risk under mixing ventilation first decreases from 7.0% to 4.2% and then increases to 4.4%.

Fig. 5d shows that the effects of air distributions and supply airflow rates on the local airborne infection risk are complicated and non-linear. The local airborne infection risk is evaluated as the peak airborne infection risk of the sampling points P1–P7. Regarding the effect of air distributions, at the supply airflow rate of 6 ACH, the local airborne infection risk under stratum ventilation is similar to that under mixing ventilation and much lower than that under displacement ventilation. At the supply airflow rate of 9 ACH and 12 ACH, the local airborne infection risk under stratum ventilation is the lowest, followed by that under mixing ventilation and that under displacement ventilation. Regarding the effect of supply airflow rates, with the increasing supply airflow rate from 6 ACH to 12 ACH, the local airborne infection risks under stratum ventilation and displacement ventilation decrease from 9.3% to 2.3% and from 45.2% to 13.4% respectively, and the local airborne infection risk under mixing ventilation first decreases from 9.6% to 6.5% and then increases to 8.6%.

It can also be observed that air distributions perform differently regarding the overall and local airborne infection risk controls. For example, at the supply airflow rate of 6 ACH, the overall airborne infection risk under
stratum ventilation is significantly lower than that under mixing ventilation while the local airborne infection risk under stratum ventilation is similar to that under mixing ventilation. At the supply airflow rate of 12 ACH, the overall airborne infection risk under displacement ventilation is lower than that under mixing ventilation while the local airborne infection risk under displacement ventilation is higher than that under mixing ventilation. The mechanisms underlying the complicated variations in the overall and local airborne infection risks under different air distributions with various supply airflow rates are explored in Section 4.

4. Discussion

This study proposes to investigate the airborne infection control mechanisms from two aspects, i.e., the contaminant removal and the contaminant
dispersion. The contaminant removal concerns the average condition in the room. The high contaminant removal ability indicates the mean contaminant concentration in the room is low. The contaminant dispersion concerns the local conditions in the room rather than the average one. The contaminant removal and contaminant dispersion are two different mechanisms of air distribution for airborne infection risk control. The contaminant removal indicates that the exhaled airborne pathogen is removed from the room by the exhausted air. By removing the exhaled airborne pathogen from the room, the mean concentration of the exhaled airborne pathogen in the room is reduced, which reduces the overall airborne infection risk. The contaminant dispersion indicates that the exhaled airborne pathogen is dispersed in the room rather than being trapped in a local area (e.g., the area around the infector). The contaminant dispersion does not reduce the mean concentration of the exhaled airborne pathogen in the room but reduces the peak concentration by making the exhaled airborne pathogen distribute more uniformly in the room. The local airborne infection risk is sensitive to the peak concentration of the exhaled airborne pathogen and can be effectively reduced with the reduced peak concentration of the airborne pathogen. Thus, to effectively control the overall and local airborne infection risks, air distribution should have good abilities of contaminant removal and dispersion respectively. The contaminant removal index is proposed to indicate the contaminant removal ability, which is determined by the contaminant concentrations exhaled by the infector in the exhaust air, in the supply air, and in the breathing zone (Eq. (6)). The contaminant removal index is also termed as the effectiveness of contaminant removal (Cao et al., 2014). A larger contaminant removal index indicates a better contaminant removal ability. The contaminant dispersion index is proposed to indicate the contaminant dispersion ability. The contaminant dispersion index is the standard deviation of the distribution of the contaminant concentration exhaled by the infector (Eq. (7)). The smaller the standard deviation of the distribution of the contaminant concentration, the better the contaminant dispersion ability of air distribution to distribute the contaminant uniformly. Therefore a smaller contaminant dispersion index indicates a better contaminant dispersion ability.

$$CRI = \frac{C_i - C_s}{C_i - C_e}$$

$$CDI = \sqrt{\frac{\sum_{i=1}^{n} (C_i - C_s)^2}{n-1}}$$

where $CRI$ is the contaminant removal index; $CDI$ is the contaminant dispersion index, ppm; $C_e$ is the contaminant concentration in the breathing zone, ppm; $C_s$ is the contaminant concentration in the supply air, ppm; $C_i$ is the contaminant concentration in the exhausted air, ppm; $C_s$ is the contaminant concentration at the $i^{th}$ sampling point, ppm; $C$ is the average contaminant concentration of the $n$ sampling points, ppm.

Fig. 6a shows that at the supply airflow rates of 6 ACH and 9 ACH, the contaminant removal index of stratum ventilation is the largest, followed by that of mixing ventilation and that of displacement ventilation. At the supply airflow rate of 12 ACH, the contaminant removal index of stratum ventilation is the largest, followed by that of displacement ventilation and that of mixing ventilation. Thus, the effect of air distributions on the contaminant removal index is consistent with that of air distributions on the reciprocal of the overall airborne infection risk (Figs. 5c and 6a). Regarding the effect of supply airflow rates (increasing from 6 ACH to 12 ACH), the contaminant removal indices of stratum ventilation and displacement ventilation increase from 1.38 to 4.14 and from 0.74 to 1.26 respectively, while the contaminant removal index of mixing ventilation firstly decreases from 1.01 to 1.38 and then decreases to 1.05. Thus, the effect of supply airflow rates on the contaminant removal index is consistent with that of supply airflow rates on the reciprocal of the overall airborne infection risk (Figs. 5c and 6a). In other words, the contaminant removal well explains the overall airborne infection risk control performance. The larger the contaminant removal ability (indicated by the larger contaminant removal index), the better the overall airborne infection risk control performance (indicated by the lower overall airborne infection risk). This is further confirmed by Fig. 6b that the reciprocal of the overall airborne infection risk is linearly related to the contaminant removal index with the coefficient of determination ($R^2$) of 0.96 regardless of air distributions and supply airflow rates. The relationship between the reciprocal of the overall airborne infection risk and the contaminant removal index indicates that the larger the contaminant removal ability of air distribution, the smaller the overall airborne infection risk. It also indicates that the relationship between the contaminant removal ability of air distribution and the overall airborne infection risk control is nonlinear.

Fig. 6c shows that at the supply airflow rates of 6 ACH - 12 ACH, the contaminant dispersion index of displacement ventilation is generally the largest, followed by that of mixing ventilation and that of stratum ventilation. Thus, the effect of air distributions on the contaminant dispersion index is generally consistent with that of air distributions on the local airborne infection risk (Figs. 5d and 6c). Regarding the effect of supply airflow rates (increasing from 6 ACH to 12 ACH), the contaminant dispersion indices of stratum ventilation and displacement ventilation decrease from 23.3 ppm to 6.7 ppm and from 173.7 ppm to 40.3 ppm respectively, while the contaminant dispersion index of mixing ventilation firstly decreases from 19.7 ppm to 11.8 ppm and then increases to 19.3 ppm. Thus, the effect of supply airflow rates on the contaminant dispersion index is consistent with that of supply airflow rates on the local airborne infection risk (Figs. 5d and 6c). In other words, the contaminant dispersion well explains the local airborne infection risk control performance. The larger the contaminant dispersion ability (indicated by the smaller contaminant dispersion index), the better the local airborne infection risk control performance (indicated by the lower local airborne infection risk). This is further confirmed by Fig. 6d that the local airborne infection risk is quadratically related to the contaminant dispersion index with the coefficient of determination ($R^2$) of 0.99 regardless of air distributions and supply airflow rates.

Air distribution is a main engineering method for airborne infection risk control (REHVA, 2021; Wang et al., 2021). This study contributes to revealing the mechanisms of air distribution for both overall and local airborne infection risk controls. This study finds that the mechanism of air distribution for overall airborne infection risk control is contaminant removal and the mechanism of air distribution for local airborne infection risk is contaminant dispersion. These findings are supported by the high correlation of $R^2$ of the overall and local airborne infection risk and overall airborne infection risk indicates that the air distribution controls the overall airborne infection risk via contaminant removal, and the high correlation of $R^2$ between the contaminant removal index and overall airborne infection risk indicates that the air distribution controls the overall airborne infection risk via contaminant removal and the high correlation of $R^2$ between the contaminant dispersion index and local airborne infection risk indicates that the air distribution controls the local airborne infection risk via contaminant dispersion. These findings provide us a better understanding on how air distribution controls airborne infection risk. These findings can also help to guide the design and operation of air distribution, i.e., air distribution should be designed and operated with high contaminant removal ability (indicated by the contaminant removal index) and high contaminant dispersion ability (indicated by the contaminant dispersion index) for better overall and local airborne infection risk control respectively.

5. Conclusions

The airborne infection risks in a hospital ward under stratum ventilation, displacement ventilation, and mixing ventilation with various supply airflow rates are computed using experimentally validated CFD simulations and the airborne infection risk control mechanisms are discussed. The main findings are summarized as follows.

1. The effects of air distributions and supply airflow rates on both overall and local airborne infection risks are complicated and non-linear.
2. The contaminant removal explains the mechanism for the overall airborne infection risk control. The larger the contaminant removal ability, the lower the overall airborne infection risk. The reciprocal of the overall airborne infection risk is linearly related to the contaminant removal index with the coefficient of determination of 0.96 regardless of air distributions and supply airflow rates.
The contaminant dispersion explains the mechanism for the local airborne infection risk control. The larger the contaminant dispersion ability, the lower the local airborne infection risk. The local airborne infection risk is quadratically related to the contaminant dispersion index with the coefficient of determination of 0.99 regardless of air distributions and supply airflow rates.

CRediT authorship contribution statement
Sheng Zhang: Conceptualization, Formal analysis, Methodology, Writing—original draft, Funding acquisition.
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Declaration of competing interest
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.

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References
Abbas, M., Nunes, T.R., Martinez, R., Zingg, W., Iten, A., Pittet, D., Harbarth, S., 2021. Nosocomial transmission and outbreaks of coronavirus disease 2019: the need to protect both patients and healthcare workers. Antimicrob. Resist. Infect. Control 10 (1), 1–13.
Aganovic, A., Bi, Y., Cao, G., Drangsholt, M., Kurnitski, J., Wargocki, P., 2021. Estimating the impact of indoor relative humidity on SARS-CoV-2 airborne transmission risk using a new modification of the Wells-Riley model. Build. Environ. 205, 108278.
Berlanga, F.A., Olmedo, I., de Adana, M.R., Villafuera, J.M., San José, J.F., Castro, F., 2018. Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms. Energy Build. 177, 207–219.
Bolashikov, Z.D., Melikov, A.K., Kierat, W., Popiołek, Z., Brznd, M., 2012. Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. HVAC&R Res. 18 (4), 602–615.
Brohus, H., 1997. Personal Exposure to Contaminant Sources in Ventilated Rooms. Aalborg University. p. 61 https://vbn.aau.dk/ws/files/316430579/brohus-henrik.pdf.
Fan, Man, Zheng, Fu., Wang, Jia, Wang, Zhaoying, Suo, Hanxiao, Kong, Xiangfei, Li, Han, Guo, M., Xu, P., Xiao, T., He, R., Dai, M., Miller, S.Y., 2020. Review and comparison of HVAC

Desai, P.S., Sawant, N., Keene, A., 2021. On COVID-19-safety ranking of seats in intercontinental commercial aircrafts: a preliminary multiphysics computational perspective.

Liu, Z., Wang, L., Rong, R., Fu, S., Cao, G., Hao, C., 2020. Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward.

Cho, J., 2019. Investigation on the contaminant distribution with improved ventilation system in hospital isolation rooms: effect of supply and exhaust air diffuser configurations. Appl. Therm. Eng. 149, 208-218.

Correia, G., Rodrigues, L., Da Silva, M.G., Gonçalves, T., 2020. Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission. Med. Hypotheses 141, 109781.

Dai, H., Zhao, B., 2020. Association of the infection probability of COVID-19 with ventilation rates in confined spaces. Build. Simul. 13 (6), 1321–1327.

Dao, H., Kim, K., 2022. Behavior of cough droplets emitted from COVID-19 patient in hospital isolation room with different ventilation configurations. Build. Environ. 209, 108649.

Denai, P.S., Sawant, N., Keene, A., 2021. On COVID-19-safety ranking of seats in intercontinental commercial aircrafts: a preliminary multiphysics computational perspective. Build. Simul. 14 (6), 1585-1596.

Fan, Man, Zheng, Fu., Wang, Jia, Wang, Zhaxing, Suo, Hansiao, Kong, Xiangfei, Li, Han, 2022. A review of different ventilation modes on thermal comfort, air quality and virus spread control. Build. Environ. 212, 108831.

Guo, M., Xu, P., Xiao, T., He, R., Dai, M., Miller, S.Y., 2020. Review and comparison of HVAC operation guidelines in different countries during the COVID-19 pandemic. Build. Environ. 187, 107368.

Guo, Y., Qian, H., Sun, Z., Cao, J., Liu, F., Lao, X., Ling, R., Wenschler, L.B., Mo, J., Zhang, Y., 2021. Assessing and controlling infection risk with Wells-Riley model and spatial flow impact factor (SFIF). Sustain. Cities Soc. 67, 102719.

Kong, X., Guo, C., Lin, Z., Duhan, S., He, J., Ren, Y., Ren, J., 2021. Experimental study on the control effect of different ventilation systems on fine particles in a simulated hospital ward. Sustain. Cities Soc. 73, 103102.

Li, C., Tang, H., 2021. Study on ventilation rates and assessment of infection risks of COVID-19 in an outpatient building. J.Build.Eng. 42, 103090.

Li, Y., Ning, Z., Chen, Y., Guo, M., Liu, Y., Gali, N.K., Sun, L., Duhan, Y., Cai, J., Westerdahl, D., Liu, X., 2020. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature 582 (7813), 557–560.

Li, Z., Wang, L., Rong, R., Fu, S., Cao, G., Hao, C., 2020. Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward. Build. Environ. 186, 103733.

Li, Z., Zhang, W., Hu, X., Zhao, Z., Rong, R., Li, J., Li, N., Ding, W., 2021. Potential infection risk assessment of improper bioaerosol experiment operation in one BSL-3 laboratory based on the improved Wells-Riley method. Build. Environ. 201, 107974.

Liu, Z., Li, R., Wu, Y., Ju, R., Gao, N., 2021. Numerical study on the effect of diver divider on the airborne transmission of diseases in canteens. EnergBuild. 248, 111171.

Lu, Y., Lin, Z., 2022. Coughed droplet dispersion pattern in hospital ward under stratum ventilation. Build. Environ. 208, 108602.

Lu, Y., Gladskum, M., Lin, Z., 2020. Reducing the exposure risk in hospital wards by applying stratum ventilation system. Build. Environ. 185, 107204.

Lu, Y., Li, Y., Zhou, H., Lin, J., Zheng, Z., Xu, H., Lin, B., Lin, M., Liu, 2021. Affordable measures to monitor and alarm nosocomial SARS-CoV-2 infection due to poor ventilation. Indoor Air https://doi.org/10.1111/ina.12899.

McKeen, P., Liao, Z., 2022. The influence of airtightness on contaminant spread in MURBs in cold climates. Build. Simul. 15 (2), 249–264.

Nissen, K., Krambrich, J., Akaberli, D., Hoffman, T., Ling, J., Lundkvist, Å., Svensson, L., Salaneck, E., 2020. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. Sci. Rep. 10 (1), 1–9.

Park, S., Choi, Y., Song, D., Kim, E.K., 2021. Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building. Sci. Total Environ. 789, 147764.

REHVA, 2021. How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces. Available https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-guidance.

Rim, D., Novoselac, A., 2009. Transport of particulate and gaseous pollutants in the vicinity of a human body. Build. Environ. 44 (9), 1840–1849.

Rudnick, S.N., Milton, D.K., 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air 13 (3), 237–245.

Srebric, J., Vukovic, V., He, G., Yang, X., 2008. CFD boundary conditions for contaminant dispersion, heat transfer and airflow simulations around human occupants in indoor environments. Build. Environ. 43 (3), 294–302.

Su, W., Yang, B., Melikov, A., Liang, C., Lu, Y., Wang, F., Li, A., Lin, Z., Li, X., Cao, G., Kosonen, R., 2022. Infection probability under different air distribution patterns. Build. Environ. 108555. https://doi.org/10.1016/j.buildenv.2021.108555.

Sun, C., Zhai, Z., 2020. The efficacy of social distance and ventilation effectiveness in preventing COVID-19 transmission. Sustain. Cities Soc. 62, 102390.

Sze To, G.N., Chao, C.Y., 2010. Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. Indoor Air 20 (1), 2–16. https://doi.org/10.1111/j.1600-0668.2009.00821.x.

Wang, J., Huang, J., Feng, Z., Cao, S.J., Haghbaf, P., 2021. Occupant-density-detection based energy efficient ventilation system: prevention of infection transmission. EnergyBuild. 240, 110883.

Xia, C., Liu, W., Liu, L., Cao, S., Ren, Y., 2021. Nonuniform risk assessment methods for personalized ventilation on prevention and control of COVID-19. Kexue Tongbao/Chin. Sci.Bull. 66 (4–5).

Yang, B., Melikov, A.K., Kabashibi, A., Zhang, C., Bauman, F.S., Cao, G., Avbi, H., Wigo, H., Niu, J., Cheong, K.W.D., Tham, K.W., 2019. A review of advanced air distribution methods-theory, practice, limitations and solutions. EnergyBuild. 202, 109595.

Yi, Y., Xu, W., Gupta, J.K., Guity, A., Marmion, P., Manning, A., Gulick, B., Zhang, X., Chen, Q., 2009. Experimental study on displacement and mixing ventilation systems for a patient ward. HVAC&R Res. 15 (6), 1175–1191.

Zhang, S., Lin, Z., 2021. Dilution-based evaluation of airborne infection risk - thorough examination of Wells-Riley model. Build. Environ. 194, 107674.

Zhang, Y., Han, G., Li, A., Olofson, T., Zhang, L., Lei, W., 2021. Adaptive wall-based attachment ventilation: a comparative study on its effectiveness in airborne infection isolation rooms with negative pressure. Engineering https://doi.org/10.1016/j.eng.2020.10.020.

Zhang, S., Ai, Z., Lin, Z., 2021. Occupancy-aided ventilation for both airborne infection risk control and work productivity. Build. Environ. 180, 107506.

Zhang, S., Lu, Y., Niu, D., Lin, Z., 2022. Energy performance index of air distribution: thermal utilization effectiveness. Appl. Energy 118122. https://doi.org/10.1016/j.apenergy.2021.118122.