ABSTRACT
The increasing incidence of airborne transmitted diseases indoors has prompted the attention of studying expiratory droplet dispersion and transport in built environments. Droplet dispersion in a room under the conventional well-mixed and displacement ventilation is simulated. In this work, a source (i.e. a patient) and a receptor (i.e the susceptible object) were located in a mechanical ventilated room. This study evaluated droplet dispersion and mixing under well-mixing and displacement ventilation scheme. Two droplet nuclei sizes, 0.01 and 10 µm, are selected as they represent very fine and coarse droplets. The flow field is modeled using k-ε RNG model. A new Eulerian drift-flux methodology is employed to model droplet phase. Under the conventional ventilation scheme, both fine and coarse droplets are homogeneously dispersed within approximately 50 s. Droplet nuclei exhibit distinctive dispersion behavior, particularly for low airflow microenvironment. After 210 s of droplet emission, gravitational settling influences the dispersion for 10 µm droplets, and concentration gradient can still be observed for displacement ventilation.

KEYWORDS
Dispersion, Expiratory Droplets, Eulerian Model, Mixing

INTRODUCTION
Transmission of airborne disease is a function of the concentration of respirable infectious particles in air and the contact time. When a contagious individual coughs or sneezes, droplets containing infectious particles (bacteria, viruses) are released. The larger ones fall to the floor within a few meters. Smaller droplets remain airborne long enough that the moist coating of saliva and mucus evaporate, leaving a residual dry nucleus of the droplet, that may include one or more bacteria or viruses (referred to droplet nuclei). Depending on the original (and final) size, droplet nuclei can remain suspended in air for several hours, hence they can travel over long distances, distribute widely throughout indoors, and lead to airborne transmitted infections.

The quantity inhaled is the ultimate factor determining the probability of infection. For an occupant inside an enclosure, the inhalation dose (or called intake dose) depends on both temporal and spatial droplet nuclei concentration. In a ventilated enclosure, it depends on many aerosol physical characteristics and environmental factors including droplet size, density, ventilation scheme, and relative source-to-susceptible location, etc. The ventilation scheme is the most important parameter influencing the aerosol transport characteristics indoors (Li et al. 2007). The other key factor affecting droplet nuclei transport is the size. It has been reported that expiratory droplets can be classified as large and fine aerosols. Those large droplets do not become true airborne as they settle to the floor rapidly after emission. Due to the low settling velocity, fine aerosols remain airborne for prolonged periods and may create a potential for long-range infections (Tellier 2006). The key objectives of the present work are (i) to apply the new Eulerian approach to study droplet dispersion and transport in a ventilated room, and (ii) to highlight the influence of droplet sizes and ventilation scheme on mixing characteristics.
CFD MODELING

To investigate the droplet nuclei dispersion and mixing in a ventilated environment, an enclosure with two occupants (the heat sources) is selected. Two popular ventilation configurations; well-mixed and displacement schemes are studied. Besides, two source-to-receptor orientations are considered; in one case one occupant (the droplet source) faces directly to the receptor (face-to-face orientation); while in another case the source faces directly to one wall (face-to-wall orientation). The outline of face-to-wall orientation of well-mixed ventilation is shown in Figure 1. Table 1 shows the details of the room geometry, the velocity and the thermal boundary conditions adapted. To simply the model, the droplets are assumed trapped once they touch any surfaces and do not resuspend or break-up. This assumption is valid as the droplets will relax their speeds rapidly (see below) and attain to reach the air speed surrounded.

Renormalization Group (RNG) $k-\varepsilon$ turbulent model is adopted here to simulate the airflow. The RNG $k-\varepsilon$ model is more appropriate for indoor airflow simulation, and better agreement between simulated results and measured data has been achieved compared to the standard $k-\varepsilon$ and other turbulence or laminar models (Chen et al. 1995).

A generic commercial CFD code FLUENT was used to simulate the airflow. The PISO algorithm was employed to couple the pressure and velocity fields. Grid independent tests were performed and the optimal grid densities for the well-mixed and displacement ventilation geometries are 404,000 and 375,000 cells respectively. Since two dummy heat sources (occupants) are involved, there are buoyancy flows around the occupants. Here, air density is defined as a function of temperature by a piecewise-linear function. The simulation was performed on an SGI Onyx 3800 shared server.

A simplified Eulerian drift-flux model has been developed to take full advantage of the extremely low volume fraction of indoor particles (Chen et al. 2006). The term “drift-flux” (or drift velocity) stands for particle flux (or velocity) caused by effects other than convection, i.e. gravitational settling and diffusion for the current work. The advantage of this approach is the feasibility of incorporating other external forces i.e. electrostatic into the model. As the convective velocity of the particle phase is the same as the air phase, the complexity of the two-phase flow system is greatly reduced. The governing equation for particle transport in turbulent flow field is given as:

$$\frac{\partial C_i}{\partial t} + \nabla \cdot \left( \mathbf{u} C_i + \mathbf{v}_i C_i \right) = \nabla \cdot \left( D_i \nabla C_i \right) + S_{C_i}$$

(1)

where $\mathbf{u}$ is the air phase velocity vector, $C_i$ is the particle mass concentration, kg m$^{-3}$ (or number concentration, m$^{-3}$) of particle size group $i$ (hereafter the subscription $i$ denotes particle size group), $\mathbf{v}_i$ is the particle settling velocity, $\varepsilon_{ij}$ is the particle eddy diffusivity, and $D_i$ is the Brownian diffusion coefficient and $S_{C_i}$ is the mass concentration source term. The drift-flux methodology is incorporated into Fluent by a user-written sub-program.

Equation (1) can be solved analytically to obtain the particle deposition velocity, $v_{d,j}$. The only required input is the friction velocity, $u^*$, which is defined as $u^* = \sqrt{\tau_w/\rho}$, where $\tau_w$ is the wall shear stress and $\rho$ is the density of air. The expression for the particle wall flux, $J_{d,j}$, is given as:

$$J_{d,j} = v_{d,j} \cdot C_{b,j}$$

(2)

$C_{b,j}$ is taken as the concentration at the first near-wall cell.

A model room of 4.7 m (L) × 3.7 m (W) × 2.7 m (H) is used to model droplet dispersion transport and exposure risk under two common ventilation schemes; well-mixed and displacement ventilations. Two heated model persons face each other and one emits droplets lasting 0.5 s while the other is the receptor.

The performance of the new Eulerian model is compared with a Lagrangian approach, as discrete phase tracking has been employed to solve many types of two-phase engineering problems for more
than a few decades. The Lagrangian particle tracking is carried out by FLUENT built-in features. The equation of motion of a small aerosol particle can be written as:

\[
\frac{du_{i,j}}{dt} = \left( u_i - u_j \right) + \frac{\tau}{\tau} + \frac{\xi(t)}{\rho} + \frac{g \left( \rho_p - \rho \right)}{\rho_p}
\]

where \( u_i \) and \( u_j \) are the velocity of the particle and fluid respectively, \( \tau \) is the particle relaxation time (Lai and Nazaroff, 2000), \( \xi(t) \) is the Brownian force per unit mass, \( \rho_p \) and \( \rho \) are the particle and air density respectively, and \( g \) is the gravitational acceleration. In the following section, some Eulerian and Lagrangian predictions will be presented side-by-side. For the Lagrangian approach, a sampling plane must be defined prior to counting the particles. Here, the droplets within 1.535 to 1.545 m (for breathing plane) and 1.745 to 1.755 m (for mid-plane) are selected. The purpose of including the Lagrangian approach is to compare the results qualitatively only. It must be emphasized here that direct quantitative comparison of these two approaches is impossible as the variables and governing equations solved are different.

RESULTS AND DISCUSSION

Figure 2 shows the dispersion at 50 s for the two ventilation schemes at the mid-plane; under the well-mixed scheme, 0.01 \( \mu \)m droplets are well-mixed, whereas large concentration gradient can still be observed under the displacement ventilation. In fact, the droplets do not disperse to most regions of the room until 210 s (refers to Figure 3). Under such a single emission event studied here, droplets under displacement ventilation take approximately 14 times longer than in the case of the well-mixed ventilation to achieve moderate room dispersion.

Some salient features regarding the two approaches are worth discussion. First, under the Lagrangian methodology each particle has a unique ID, and hence the position for each particle can be tracked throughout the entire simulation domain and time. In risk exposure applications, this feature seems attractive only for some cases such as to investigate the individual “contribution” of multiple sources. For a single source, particle tracking feature is not important most of the time. Instead, for many exposure assessments, the spatial and temporal concentration levels are the vital piece of information needed. In these figures, a 1-cm thick "slice" is chosen and particles enclosed in the slice are counted. If a thicker slice is chosen, it can not represent the correct spatial concentration; on the other hand, if the slice is too thin, there may be no particle contained. The selection is, however, quite arbitrary.

CONCLUSIONS

An alternative Eulerian drift-flux model is adopted to simulate dispersion of droplet nuclei in a ventilated room. Two particle sizes (0.01 and 10 \( \mu \)m) are chosen to mimic very fine and coarse droplet nuclei. Results show that both Lagrangian and drift-flux approaches give similar concentration profiles. Inferring from the results presented, it can be observed that for the well-mixed ventilation scheme, the dispersion pattern is dominated by the high velocity airflow, and the different between droplet sizes is not obvious. The droplets are homogeneously mixed within one minute. When the global airflow speed is lower, the distinctive characteristics of coarse size start to appear. Ten micrometer droplets begin to settle at the lower region of the room under displacement ventilation.

REFERENCES

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Figure 1. Geometry of the test room for face-to-face orientation.

![Figure 1](image)

Table 1. Boundary conditions.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location (m)</th>
<th>Size (m)</th>
<th>Temperature (K)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>0 0 0 0 4.5 3.5 2.7</td>
<td>- -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Well-Mixed inlet (a)</td>
<td>4.5 1.75 2.1 0 0.4 0.4</td>
<td>237 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement inlet (b)</td>
<td>4.3 1.75 0 0.2 0.3 1</td>
<td>292 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust (c)</td>
<td>0.2 1.75 2.7 0 0.4 0.4</td>
<td>- -</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model (Source)</td>
<td>1.58 1.75 0</td>
<td>- - -</td>
<td>- -</td>
<td></td>
</tr>
<tr>
<td>Model (Receptor)</td>
<td>1.48 1.75 0</td>
<td>- - -</td>
<td>- -</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Eulerian plots at mid-plane for 0.01 µm droplets at 50 s (a) displacement ventilation; (b) well-mixed ventilation.
Figure 3. Lagrangian and Eulerian plots at mid-plane under displacement ventilation (a) 0.01 μm at 210 s and (b) 10 μm at 210 s.