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A hybrid model for investigating transient particle transport in enclosed environments

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A B S T R A C T

It is important to accurately model person-to-person particle transport in mechanical ventilation spaces to create and maintain a healthy indoor environment. The present study introduces a hybrid DES-Lagrangian and RANS-Eulerian model for simulating transient particle transport in enclosed environments; this hybrid model can ensure the accuracy and reduce the computing cost. Our study estimated two key time constants for the model that are important parameters for reducing the computing costs. The two time constants estimated were verified by airflow data from both an office and an aircraft cabin case. This study also conducted experiments in the first-class cabin of an MD-82 commercial airliner with heated manikins to validate the hybrid model. A pulse particle source was applied at the mouth of an index manikin to simulate a cough. The particle concentrations versus time were measured at the breathing zone of the other manikins. The trend of particle concentrations versus time predicted by the hybrid model agrees with the experimental data. Therefore, the proposed hybrid model can be used for investigating transient particle transport in enclosed environments.

1. Introduction

There is strong evidence of an association between indoor airflow patterns and the spread of infectious diseases, such as tuberculosis, influenza, and severe acute respiratory syndrome (SARS) [1]. Breathing, coughing, talking, and sneezing by an infected person can generate pathogen-carrying particles and can cause the transmission of infectious diseases [2,3]. Furthermore, infectious disease transmission in commercial aircraft cabins where passengers are in close proximity has become a major health issue [4]. Exhaled pathogen-containing particles generated by an infected passenger can disseminate throughout the cabin and cause infections in fellow passengers [5,6]. Therefore, it is important to accurately model the person-to-person particle transport in mechanical ventilated spaces in order to improve air distribution design to reduce the infection risk.

In recent years, Computational Fluid Dynamics (CFD) has been widely used in modeling airflow field and particle transport in enclosed environments, such as buildings [7], aircraft cabins [8], and hospital rooms [9]. For airflow modeling, there are several turbulence models such as Reynolds-averaged Navier–Stokes (RANS) models, Large Eddy Simulation (LES), and Detached Eddy Simulation (DES), which have that has been reviewed and tested [10,11]. For particle modeling, Eulerian and Lagrangian are two popular methods. The Eulerian method often uses the drift flux model for considering the slippage between particle phase and fluid (air) phase. This model performed well in modeling indoor particle dispersion [12–14]. The Lagrangian method with the Discrete Random Walk (DRW) model has also performed very well in modeling and analyzing the particle transport and dispersion [15–17]. Most of the studies mentioned above focused on steady-state particle transport processes. However, particle transport processes can be in an unsteady state. Wang et al. [18] have tested different combinations of the airflow and particle models for steady- and unsteady-state cases. For steady-state airflow conditions, they preferred the RANS model with the Eulerian method due to the reasonable accuracy and low computing cost associated with the model. For unsteady-state airflow conditions, Wang et al. recommended the DES model with the Lagrangian method due to its relatively high accuracy. The reason for using DES rather than RANS model is that RANS model fails to predict correct transient airflow [11]. Moreover, when the airflow field is still developing, the Lagrangian method may have better accuracy than the Eulerian method since it accounts for more physics of airflow and particle

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Nomenclature

C_c	Cunningham coefficient caused by slippage
C_D	Drag coefficient
d_p	Particle diameter
d_0	Diameter of the mouth
$F(t)$	Airflow field of the room
$\overrightarrow{F}_a$	Other forces
$\overrightarrow{g}$	Gravitational acceleration vector
k	Turbulence kinetic energy
L	Distance from the mouth to a solid surface in the front
Q	Airflow rate
Re	Reynolds number
S_c	Generating rate of the particle source
s	Distance from the mouth
s^*	Distance that a cough can affect the surround flow
$s_{\overline{U_m}}$	Distance from the mouth corresponding to $\overline{U_m}$
t	Time
t_{release}	Duration of coughing
t_{decay}	Decay time when the $\overline{U_m}$ decreases to the surrounding value
t_{travel}	Traveling time needed for the coughing jet peak travel to position $s_{\overline{U_m}}$
$t_{\text{DES-Lagrangian}}$	Computing time when using DES-Lagrangian for the hybrid model
$t_{\text{RANS-Eulerian}}$	Computing time when using RANS-Eulerian for the hybrid model
$T_{\text{hybrid}}/T_{\text{DES-Lagrangian}}$	Ratio of the computing time by the hybrid model to the DES-Lagrangian model
$\overrightarrow{u}_a$	Velocity vector of air
u_j	Averaged fluid (air) velocity
$\overrightarrow{u}_p$	Velocity vector of the particle
u_{sj}	Gravitational settling velocity of particles
$U_m(s)$	Jet velocity at distance s
$\overline{U_m}$	Average velocity along the s^*
U_r	Reference room air velocity
U_0	Initial cough velocity
V	Volume of the room
η	Error
λ	Mean free path of the air molecules
μ	Fluid viscosity
ξ_i	Normal random number
ρ	Air density
ρ_p	Particle density
τ	Room time constant
τ^*	Local time constant
τ_p	Particle relaxation time

motion [18]. But if the DES with Lagrangian model is applied for studying coughing, talking, and sneezing among persons in an enclosed environment, it requires considerable computing cost.

Thus, it is worthwhile to develop a model that can not only ensure the accuracy but also reduce the computing cost. It should be noticed that coughing, sneezing, or talking are unsteady-state and may have a significant impact on airflow distribution only in the first few seconds. But after the effect of the coughing, talking, and sneezing on the airflow is damped, the airflow can be regarded as steady-state. Then RANS with the Eulerian model can be applied to reduce the computing cost [18].

To further reduce the computing cost, one solution is to use a RANS model as the initial field for a DES model. Then the DES model can be used to calculate accurate results within a very short period of time. Now the question is how long the DES simulations should be performed in order to completely eliminate the effects of RANS modeling. In addition, if the DES is applied to study coughing, how short should the transient simulation be so that the steady-state modeling afterward will still give accurate results? This investigation set out to identify the two time constants and test the hybrid model for transient particle distributions in an airliner cabin.

2. Model determination

To identify the two time constants, this study used the RANS model for steady-state flows and the DES model for unsteady-state flows. Similar to in previous research, we used the Eulerian and Lagrangian methods for particle transport under steady-state and unsteady-state, respectively. This section details the flow and particle models used as well as the procedure to determine the two time constants.

2.1. Steady-state airflow conditions

2.1.1. Airflow and turbulence model

For steady-state flows, the renormalization group (RNG) k-ε model [19] is applied to calculate the airflow and turbulence. It has the best overall performance among all RANS models for enclosed environments [10]. The equations for RNG k-ε model can be found in the Fluent manual [20].

2.1.2. Particle transport model

For steady-state flows, the Eulerian drift flux model is applied to calculate the particle dispersion. The drift flux model considers the slippage between particle phase and fluid (air) phase, which takes the effect of the gravitational settling into consideration:

$$\frac{\partial\left[\left(u_j+u_{sj}\right)C\right]}{\partial x_j} = \frac{\partial}{\partial x_j}\cdot\left(\frac{\upsilon_t}{\sigma_C}\frac{\partial C}{\partial x_j}\right)+S_C \tag{1}$$

where u_j is the averaged fluid (air) velocity; υ_t the turbulent kinetic viscosity; σ_c the turbulent Schmidt number, which is usually equal to 1.0 [12]; and S_c the generating rate of the particle source. The u_{sj} in the equation is the gravitational settling velocity of the particles, which can be calculated by:

$$u_{sj} = \tau_p g_j \tag{2}$$

where τ_p is the particle relaxation time. The τ_p can be calculated by:

$$\tau_p = \frac{C_c\rho_p d_p^2}{18\mu} \tag{3}$$

where C_c is the Cunningham coefficient caused by slippage. The C_c can be calculated by [21]:

$$C_c = 1+\frac{\lambda}{d_p}\left(2.514+0.8\times\exp\left(-0.55\frac{d_p}{\lambda}\right)\right) \tag{4}$$

where λ is the mean free path of the air molecules.

2.2. Unsteady-state airflow conditions

2.2.1. Airflow and turbulence model

For unsteady-state flows, the DES Realizable k-ε model [22] is applied to predict the airflow and turbulence. The reason for using