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Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces

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Abstract

The computational fluid dynamics (CFD) methods have been widely used in modeling particle transport and distribution in enclosed spaces. Generally, the particle models can be classified as either Eulerian or Lagrangian methods while each has its own pros and cons. This investigation is to compare the two modeling methods with an emphasis on their performance of predicting particle concentration distributions in ventilated spaces. Both the Eulerian and Lagrangian models under examination were performed based on the same airflow field calculated by solving the RANS equations with the k–ε turbulence model. The numerical results obtained with the two methods were compared with the experimental data. The comparison shows that both of the methods can well predict the steady-state particle concentration distribution, while the Lagrangian method was computationally more demanding. The two models were further compared in predicting the transient dispersion of the particles from a coughing passenger in a section of airliner cabin. In the unsteady state condition, the Lagrangian method performed better than the Eulerian method.

Keywords: Particle; Eulerian method; Lagrangian method; CFD; Indoor environment; Airliner cabin

1. Introduction

Suspended particles can cause many human health problems and are identified as a major pollutant in the air (Mølhave et al., 2000; Mendell et al., 2002; Schneider et al., 2003). When particles carried virus of infectious diseases or microorganisms traveling in the air, they can spread the diseases. The SARS outbreak in 2003 and the new threat of bird flu those days have increased our concern of infectious disease transmission in enclosed spaces, such as in buildings and transport vehicles. Meanwhile, the transport mechanism of the aerosol is complicated and not yet fully understood. Therefore, the study of particle transport and distribution in enclosed spaces has been an important topic in the field of air quality and public health studies.

As particulate matter is suspended in the air, the particle transportation and distribution are highly associated with the airflow motion and the turbulence. Hence, the computational fluid dynamics (CFD) is the most suitable modeling approach to study the spatial distributions of particles in enclosed spaces. Generally, there are two methods of modeling particle transport in CFD simulations,

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the Eulerian and the Lagrangian method. The Eulerian method treats the particle phase as a continuum and develops its conservation equations on a control volume basis and in a similar form as that for the fluid phase. The Lagrangian method considers particles as a discrete phase and tracks the pathway of each individual particle. By studying the statistics of particle trajectories, the Lagrangian method is also able to calculate the particle concentration and other phase data. Within each kind of the particle models, there are many different models to address various characteristics of particle motion and dispersion. The development of each method, from the simplest models to the most sophisticated ones, has been described and compared throughout the literature from different perspectives (e.g., Shirolkar et al., 1996; Loth, 2000; Lakehal, 2002).

To choose the Eulerian method or the Lagrangian method for certain problem depends highly on the objective and characteristics of the problem under examination. The Eulerian method has gained its popularity on studying particle concentration distributions in indoor environments (Murakami et al., 1992; Zhao et al., 2004, 2005). The Lagrangian method is mainly used to predict the overall particle dispersion pattern (Béghein et al., 2005) and the temporal development of the mean concentration (Lu et al., 1996; Zhang and Chen, 2004). But the capability of the Lagrangian method on predicting the concentration distributions of particles has not been well explored.

Recently, we have used a Lagrangian method to predict the particle concentration distributions in ventilated rooms and have compared the numerical results with experimental data (Zhang and Chen, 2006). The Lagrangian method can predict the detailed particle distributions, while it required considerable computational effort, which may limit its application. Furthermore, Loomans and Lemaire (2002) claimed that the Lagrangian method can be more precise than the Eulerian in predicting particle distribution in a room, but they did not provide sufficient evidence with experimental validation. Riddle et al. (2004) concluded that their Lagrangian method gave better results than an Eulerian one in predicting dispersion of gas pollutant around buildings. However, the two models used by Riddle et al. were not based on the same flow model, so it is very difficult to judge if and how much the advantage was brought by the flow models. The above review has posted an interesting question: if or in what situations, the Lagrangian method could perform better than the Eulerian method in predicting the particle concentration distributions in enclosed spaces? This investigation therefore aimed to compare an Eulerian and a Lagrangian method by emphasizing on their capabilities of predicting particle distributions in enclosed spaces.

2. Research methodology

The CFD was used to predict both airflow fields and particle concentration distributions. This study adopted Reynolds averaged Navier–Stokes (RANS) equations with the standard k–ε turbulence model (Launder and Spalding, 1972) to predict the airflow field. The popular k–ε model has been successfully applied to simulate indoor airflow fields (Chen and Zhang, 2005; Chen, 1995). Since the focus of this study was to compare the performance of different particle models, the turbulence model for airflow is not detailed here. The readers can refer to Versteeg and Malalasekera (1995) about the fundamentals of CFD modeling of fluid flow and turbulence.

For particle modeling in an enclosed space, the particle volume fraction is generally low. Thus the effect of particles on the turbulent flow is negligible, and the interaction between the carrier air and the particles can be treated as one-way coupling that is from flow to particles not vice versa. In addition, the particle size is the most important control parameter for determining the particle dynamics such as deposition. In the current study, the particle diameters considered are 0.3–1 μm, the corresponding particle deposition velocity V_d is on the order of 10^{-5}–10^{-6} (m/s) in ventilated chambers (Lai, 2002; Lai and Nazaroff, 2005). Considering the particle loss coefficient for deposition β:

$$\beta = V_\mathrm{d} A / V, \tag{1}$$

where A is the area of room inner surface and V the volume. The β is on the order of 10^{-2}–10^{-1} (h^{-1}) that is about two-magnitude order lower than air exchange rate (h^{-1}) in ventilated rooms. Therefore, the particle deposition was neglected for the particle sizes studied in this paper. When particle deposition becomes important, appropriate deposition models must be implemented. Otherwise, the numerical prediction on particle concentration distribution cannot be accurate.

The one-way coupling and the neglect of deposition have been used in both Eulerian and Lagrangian modeling for this investigation.