Numerical Investigation of the Wall Effect on Airborne Particle Dispersion in a Test Chamber

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**ABSTRACT**

Numerical investigations of the transport and distribution of airborne particles in a test chamber were carried out with drift-flux model. Although factors such as the configuration of the flow field and gravitational settling can influence the distribution of particle concentration, the results show that the walls can play an important role in particle dispersion when the velocity gradient of air flow at the walls is high. The high gradient of the air flow velocity at the walls can lead to particle accumulation near the walls, which can significantly improve the particle concentration. The walls can also influence the particle distribution in vertical space, along with gravitational settling.

**Keywords:** Drift-flux model; Wall effect; Indoor airborne particle; Transport; Distribution.

**INTRODUCTION**

The airborne particles have been recognized as one of the most important risk in atmospheric environment (US EPA, 2004; Jin et al., 2007; Buonanno et al., 2009; Huboyo et al., 2011; Cheng et al., 2012). As humans spend more and more time indoors nowadays (up to 90%), long-term exposure to indoor airborne particles can cause severe health problem. As a result, studies on transport and distribution of indoor aerosol particles have been one of the great interests of many researchers.

A good understanding of particle transport is crucial for controlling contaminant particle concentration in indoor environments. As a powerful tool, computational fluid dynamics (CFD) method is widely used in studying indoor airborne particle dispersion and deposition. In order to make accurate prediction of the motion of the indoor particles, many models have been developed by researchers (Holmberg and Li, 1998; Lai and Nazaroff, 2000; Chang et al., 2006; Lai and Chen, 2007; Hussein et al., 2011). With these developed models, many numerical studies on particle distribution and deposition have been carried out. Among these studies, the gravitational settling and deposition is one of the main topics. Such as Murakami et al. (1992) studied the gravitational sediment of the particles and its effect on the property of particle diffusion, Zhao and Wu (2006) numerically studied particle deposition onto rough walls in a ventilation duct with an Eulerian model, and Zhang and Chen (2009) studied particle deposition onto indoor surface with a Lagrangian model, etc. One another main topic is studies on the particle dispersion in different configurations of one or several rooms. Such as Gao et al. (2009) studied particle transport between flats in high-rise residential buildings, Lai et al. (2008) studied particle distribution in a two-zone chamber, and Zhao and Guan (2007) studied particle dispersion in a personalized ventilated room under different air supply volumes to investigate human exposure to particles, Zhang and Chen (2007) numerically simulated particle distribution in an enclosed room with both Eulerian and Lagrangian methods, etc. Some other studies focused on the indoor particle dispersion for different ventilation modes. Such as Gao and Niu (2007) used the drift-flux model to investigate the deposition rates and human exposures to particles from two different sources with three typical ventilation systems of mixing ventilation (MV), displacement ventilation (DV), and under-floor air distribution (UFAD).

For all these previous numerical studies, the walls were usually considered as a boundary for particle deposition. Although Gao and Niu (2007) studied the aerosol particle deposition on the walls and a nominal particle concentration on the boundary was obtained, no one investigated the effect of wall existing (including ceiling and floor) on the particle transport and distribution together with the flow field in the whole space such as the near wall region. Studies in two-phase flow showed the existing of walls can effectively influence the particle concentration in near wall...
region (Marchioli et al., 2003). Therefore, it is necessary to set out a detailed investigation of the wall effect on transport and distribution of indoor airborne particles.

In this paper, the transport and the distribution of the airborne aerosol particles for different sizes in a test chamber were numerically investigated with the drift-flux model. The effect of the walls on dispersion of indoor airborne particles was mainly discussed, together with the experimental results obtained by Jin et al. (2009).

**MATHEMATICAL MODEL**

**Drift-Flux Model**

In this paper, the standard k-ε model is adopted to simulate the airflow field. For nano-scale particles, the particles can follow the turbulent flow field closely. For larger particles such as the particle diameter less than 10 μm, the particles can also follow the flow field well when the Reynolds number of the gas flow is not very high. Thus the inertia effect on particle transport for particle size in this range is often neglected and particles in this size range are usually used as tracer in PIV or LDV measurement of flow field. In this paper, the transport of particles with particle size less than 5 μm were investigated and the drift-flux model is adopted to simulate the motion of particle phase without considering the effect of the particle inertia,

\[
\frac{\partial \rho_p}{\partial t} + \frac{\partial (\rho_p u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( D_p + D_s \right) \frac{\partial \rho_p}{\partial x_i} \right] + \frac{\partial}{\partial x_i} \left[ \left( \frac{\partial \rho_p}{\partial x_i} \right) v_s \right]
\]

In which, \( m_i \) is the dimensionless particle concentration for particle size \( k \). \( m_i = C_i/C_{i0} \), where \( C_i \) is the particle number density for size \( k \); \( C_{i0} \) is the characteristic particle number density for size \( k \), and the particle concentration at the inlet is set as the characteristic concentration in this paper; \( u_i \) is the local airflow velocities in three directions respectively, the subscript \( i \) represents the three directions in Cartesian coordinates; \( D_p \) is the Brownian diffusion coefficient; \( D_s \) is the turbulent diffusion coefficient; and \( v_s \) is the gravitational settling velocity of the particle,

\[
v_s = 3.62 \left( \frac{d_p^3}{\mu} \right) \rho_p - \rho_a \beta \frac{g}{\rho_p}
\]

where \( d_p \) is the diameter of the particle; \( \rho_p \) and \( \rho_a \) is the material density of the particle and the air respectively; the coefficient \( \beta \) depends on the airflow field surrounding the particles, for spherical particles in steady flows \( \beta = 24/Re \) and \( Re = \frac{d_p v_p}{\mu} \), \( \beta \) depends on the shape of the particles, for spherical particles \( \beta = 1 \). Supposing the forces acting on a freely falling spherical particle with a uniform velocity are gravity and stokes drag force, one can derived the expression of \( v_s \) with Newton’s second laws

\[
v_s \approx 0.54 \frac{d_p^3 (\rho_p - \rho_a)}{\mu}
\]

where \( \mu \) is the dynamic viscosity of the air.

**Boundary Conditions**

Accounting for concentration loss due to the deposition of the particles on the walls, the deposition flux is defined as \( J = v_s C_{cell} = (D_p + \epsilon_p) \left( \frac{\partial C}{\partial y} \right) + \nu C_{cell} \), where \( C_{cell} \) is the particle concentration on the first neighbor cell of the boundary; \( \epsilon_p \) is turbulent diffusivity of the air flow field (Lai and Nazaroff, 2000). A nominal particle concentration on the boundary is defined as \( C_{wall} \) (Gao and Niu, 2007):

\[
C_{wall} = C_{cell} - C_{cell} \left( \frac{v_s - iv} \right) \frac{\delta y}{D_p + D_s}
\]

where \( \delta y \) is the height of the first neighbor cell; \( v_s \) is the gravitational settling velocity of the particles; \( i \) is used to characterize the wall surface orientation \((i = 0 \text{ for a vertical surface}; \ i = 1 \text{ for an upward facing horizontal surface}; \ i = -1 \text{ for a downward facing horizontal surface})\); \( v_d \) is the deposition velocity of the particles on the boundary solid surface. With the assumption that the deposition flux is one-dimensional and constant in the concentration boundary layer, and the particle eddy diffusivity equals the fluid turbulent viscosity, the dimensionless deposition velocity \( v_d^* \) can be expressed by the following equation:

\[
v_d^* = \begin{cases} \frac{v_d}{u^*} & \text{upward surface,} \\ \frac{v_d}{u^*} - 1 & \text{downward surface,} \\ \frac{v_d}{u^*} & \text{vertical surface,} \end{cases}
\]

where \( v_d = v_d^* u^* ; \ i = \frac{1}{v_d} \int dC_{cell}^* \left( \frac{v_d}{C_{cell}^*} \right) dy^* ; \ v_d^* = \frac{v_d}{u^*} ; \ u^* \) is the friction velocity, \( u^* = \sqrt{\frac{\mu}{\rho_a}} \); \( r^* = (d_p/2)(u^*/v) \). The detailed description on the deposition velocity and particle concentration on the boundary can also be found in the ref. (Gao and Niu, 2007).

**NUMERICAL SIMULATION**

Schematic diagram of the flow configuration is shown in Fig. 1, which was the same as the test chamber in the experiment (Jin, 2009). The size of the flow configuration was set as \( x \times y \times z = 1 \times 1 \times 0.3 \) m. One inlet was fixed on the right hand side. Three different outlets were available for three different cases respectively, only one of the outlets was used for one case. The initial dimensionless particle concentration was set as \( 0 \) in the flow field (inside the test chamber) and at the inlet. The inflow air velocity was set the same as that in the experiment, in which two different velocities of 0.5 m/s and 1.5 m/s were adopted respectively. Particles with different diameters of 0.3 μm, 0.5 μm, 1.0 μm, 3.0 μm and 5.0 μm were released into the flow field at the inlet after the air flow field simulation was
converged. The material density of the particles is set as 2.1 × 10^3 kg/m^3.

The inflow velocity is 0.5 m/s, the numerical results fit well with the experimental results (as shown in Fig. 3). Both the time dependent rising process and the final steady value of the particle concentration for different sizes are accurately predicted with numerical methods. Furthermore, the difference in the time-dependent rising ratio of the particle concentration among different sizes is clearly obtained by numerical simulation. Some factors can reduce the accuracy of the numerical prediction, such as the sharply transforming flow field. Fig. 4 shows the time-dependent increasing process of the particle concentration in case that the outlet O2 was opened with the same inflow velocity of 0.5 m/s. The difference in the time-dependent variation ratio for different particle sizes is not as clearly predicted as that when outlet O1 is opened. It seems the model may decrease the accuracy when the air flow varies drastically. The reason should be the neglect of the particles' independent convective terms in the air flow. Although not all results for different cases have the same accuracy as that shown in Fig. 3, the drift-flux model can reasonably simulate the transport of indoor airborne particles well.

**The Wall Effect for Different Structures of the Flow Field**

A 2D gas flow field does not necessarily lead to a 2D distribution of the particle concentration. Fig. 5 shows the contour of velocity magnitude in cross-sections y = 0, x = 0.13 and x = 0, when outlet O1 is opened and inflow velocity is 1.5 m/s. It can be found that the iso-line of the velocity magnitude is nearly perpendicular to the upper or bottom boundary, which means the gas flow field is nearly 2D. In spite of the approximate 2D flow filed, the distribution of the particle concentration appears far from 2D case. Fig. 6 shows the contour of the particle concentration in the case that outlet O1 is open and inflow velocity is 1.5 m/s. The concentration near the upper and bottom faces is apparently higher than the corresponding internal region, especially in the region around the main stream of the airflow. For those walls far from the main stream region, the wall effect is not so obvious, such as the vertical lateral faces (as shown in Figs. 6(b) and 6(c)). It indicates that when the air strongly flows through the walls, the walls can obviously affect the distribution of the particle concentration. This phenomenon can be explained with the high gradient of velocity adjacent to the wall region. At this region of boundary layer, the velocity in the main stream of the flow field rapidly decreases to 0. The particles accumulate quickly in the region of low velocity and then disperse transversely with the turbulent diffusion. Similar phenomenon appears when outlets O2 and O3 are open, respectively (as shown in Fig. 7). Fig. 7(a) shows the concentration of the particle with diameter 0.3 µm in the face x = 0 when the inflow velocity is 0.5 m/s and outlet O2 is open. The concentration near the upper or bottom wall is usually higher than corresponding internal region except for the central core region. The concentration distribution makes a convex shape at this region. It is because the main stream of the airflow makes a curve in the central core region, and the cooperation of the centrifugal effect and the viscous force makes this happen. This convex shape disappears if the main stream of the flow doesn’t curve very much such as in the cross section of x = 0.13 (as shown in Fig. 7(b)). When the main stream of the air flow changes its trajectory sharply with inflow velocity 1.5 m/s and outlet O3 open, the wall effect is even more evident.
The increase of particle size usually leads to increase in gravitational settling of particles. For very tiny particles, the gravitational settling doesn’t play an important role in particle transport. But for particles larger than 1.0 µm, the gravitational settling comes to be a more and more important factor. As a result, the distribution of particle concentration varies in the mid-plane in z direction (z = 0) when particle diameter is larger than 1 µm (as shown in Fig. 8). Under this circumstance, the walls influence the particle transport together with the gravitational settling. The particle distribution appears quite different for different particles in vertical space. The iso-line contour of particle concentration of particles $d_p = 1.0$ µm (as shown in Fig. 8(c)) differs apparently from those $d_p = 0.3$ µm and 0.5 µm (as shown in Figs. 8(a) and 8(b)). Due to the gravitational settling of the particles, the coverage of high particle concentration reduces even more obviously when particle diameter $d_p = 5.0$ µm (as shown in

![Image](image1.jpg)

Fig. 2. The structure of the flow field with inflow velocity 0.5 m/s.
Fig. 3. Comparison of time-dependent particle concentration at different measuring points between numerical results and experimental data (outlet O1, inflow air velocity 0.5 m/s).

Fig. 4. Comparison of time-dependent concentration for particles with different sizes between numerical results and experimental data (outlet O2, inflow air velocity 0.5 m/s and measuring point (3,3)).

Although the gravitational settling influences the particle distribution for particle larger than 1 µm in central plane in vertical direction, the particle distribution in x and y direction shows the walls play an important role in particle concentration in near wall region. Fig. 9 shows the distribution of particle concentration in the cross-section of y = 0.25. It can be observed the concentration in the bottom region is a little higher because of the gravitational settling when particle diameter is 1 µm (as shown in Fig. 9(a)). The particle concentration is higher than in the central region and a wider high concentration region appears near the walls. For large particles with diameter 3.0 and 5.0 µm, the gravitational settling is much more apparent (as shown in Figs. 9(b) and 9(c)). In spite of the wall effect on the particle distribution, the region of high concentration reduces obviously near the upper wall. For those regions with high particle concentration near the upper wall, it can be observed the convection of the air flow field is stronger than in other regions, which means a higher gradient of velocity adjacent to the walls in these regions.

Although the gravitational settling starts to appear for particles with diameter 1.0 µm, it does not always appear for all circumstances. It depends on the relative importance between the gravitation and some other factors, such as the convection of the flow field. The distribution of particle concentration is central symmetry in z direction when outlet O1 is open and inflow velocity is 1.5 m/s (as shown in Fig. 10), no gravitational settling can be observed and the wall effect on particle distribution near the walls is still very obvious. It shows the gravitational settling is controlled by both gravitation (i.e., particle diameter) and the flow field. The gravitational settling does not appear even when the particle diameter is greater than 1.0 µm if the convection of the flow field is strong enough.

CONCLUSION

Numerical investigation on transport and distribution of airborne particles in a test chamber were carried out with drift-flux model. The validation tests show the model can reasonably predict the transport of the fine indoor particles well. Then the wall effect on the distribution of airborne particles was numerically studied.

The results show the walls can obviously affect the distribution of the particle concentration when the air flows
Fig. 5. Contour of velocity magnitude in cross-sections (outlet O1, inflow air velocity 1.5 m/s).

Fig. 6. Distribution of particle concentration in cross-sections (outlet O1, inflow air velocity 1.5 m/s and particle diameter 0.3 μm).
Fig. 7. Distribution of particle concentration in cross-sections (particle diameter 0.3 μm).

Fig. 8. Distribution of particle concentration in the mid-plane of z = 0 (Outlet O3 and inflow velocity 0.5 m/s).
Fig. 9. Distribution of particle concentration in cross-section of y = 0.25 (Outlet 03 and inflow velocity 0.5 m/s).

Fig. 10. Distribution of particle concentration in cross-sections (Outlet 01, inflow velocity 1.5 m/s and particle diameter 1.0 µm)

through the walls with a high gradient of velocity adjacent to the walls. The accumulation of particles in the boundary layer can change the distribution of particles obviously. Those walls with low velocity gradient have little effect on the distribution of particles.

When the particle diameter is greater than 1.0 µm, the walls influence the transport and distribution of particles together with the gravitational settling in vertical space. No apparent gravitational settling can be observed when the particle diameter is greater than 1.0 µm if the convection of the flow field is strong enough.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of Natural Science Fund of China (NSFC, No: 10502044, 10772162) and the major projects on control and rectification of water body pollution (No. 2009ZX07424-001). The
valuable help made to this paper by Prof. Naiping Gao at Tongji University is also specifically acknowledged.

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Received for review, April 26, 2012
Accepted, September 2, 2012