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Particle deposition in indoor environments: Analysis of influencing factors

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Abstract

In this paper, several factors influencing particle deposition in indoor environments are analyzed with an analytical model and a three-dimensional drift flux model combined with the particle deposition boundary conditions for wall surfaces. The influences of flow conditions near the wall surfaces, surface roughness and particle concentration distribution on particle deposition indoors are studied. By modeling particle deposition onto surfaces with the analytical model, it is found that larger friction velocity near the wall surfaces and rougher surface may lead to larger particle deposition velocity when the particle size is small, but when particle size is large enough (the range is up to the actual friction velocity and in this study it is about 1–5 μm), the influence of the friction velocity and roughness could be neglected. Furthermore, the three-dimensional numerical simulations indicate that particle concentration distribution may be very different even for the same particle source and air change rate, which cause a different deposited particle flux. As the particle concentration distribution may not be uniform in most cases, especially for the ventilated rooms, it is important to incorporate particle concentration distribution when analyzing particle deposition in indoor environments. Some suggestions or rules for particle deposition controlling are also presented based on the analysis.

Keywords: Aerosol; Particle; Deposition; Indoor air quality (IAQ); Indoor environment; Ventilation

1. Introduction

Modern people spend most of their lives in the indoor environment which implies that indoor air quality (IAQ) has become more important than ever before. Particulate matter (PM) is a ubiquitous pollutant indoor and outdoor around the world and aerosol particles are regarded as significant pollutant sources in the indoor environment. One fate of aerosol particles in indoor air is deposition onto surfaces. This process is very important because deposited particles may damage the electronic equipment and artworks. Besides, particles deposited onto indoor surfaces might be re-suspended and pollute indoor environment. One should ensure as little as possible particles deposited if such hazardous material is released/generated indoor. Knowledge of particle deposition indoors is therefore important for indoor air quality study.

Previous studies of particle deposition indoors is mainly focused on mean deposition velocity and mean deposition rate of particles, by both experimental methods (for example, [1–15]) and theoretical methods (for example, [7,16–19]) which are useful and suitable for a lumped parameter study and analysis of indoor deposited particles as a whole. Studies on particle deposition together with particle distribution indoors with numerical methods have also been reported [20–24]. Reviewing these work shows that particle deposition velocity may differ much for different indoor environments. Lai has summarized published measured data of particle deposition and related experimental conditions [25]. He found that scattering of the data among different studies is quite significant and he pointed out that these discrepancies may attribute to different particle generation or incomplete measuring parameters. Zhao et al. further found that even for the same particle source and ventilation rate, the average particle deposition velocity may differ significantly in different ventilation rooms [22]. As the complexity and importance of particle deposition in indoor environments, the influencing factors of particle deposition deserve more attention and study. The main purpose of this paper is therefore to analyze several main

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factors influencing particle deposition in indoor environments, which could be air flow near wall surfaces (represented by friction velocity), wall surface characteristics (roughness) and particle spatial distribution according to previous studies. As measurement of some important parameters is hard to perform, for example, the flow conditions near wall surfaces, surface roughness and particle spatial distribution (specially for larger particles), this study tends to adopt an analytical and numerical model for the analysis, with the assistance of measured data for validation.

2. Method

2.1. Three-layer analytical model

The authors have developed a three-layer analytical model based on the one by Lai and Nazaroff [26] to incorporate turbophoresis (Zhao and Wu [27]). Using the correlation by Caporaloni et al. [28] to model the turbophoretic velocity, the relationship of particle and air wall normal fluctuating velocity intensity by Johansen [29], and relation to express the particle eddy (turbulent) diffusivity ε_p by Hinze [30], dimensionless particle deposition velocity could be deduced as:

$$\upsilon_d^+ = [Sc^{-1} + (\frac{\tau_L}{\tau_p + \tau_L})\upsilon_t^+]\frac{dC^+}{dy^+} + \{i\upsilon_s^+ + \tau^+ \frac{d[(\frac{\tau_L}{\tau_p + \tau_L})\overline{\upsilon_y'^2}^+]}{dy^+}\}C^+, \quad (1)$$

where υ_d^+ is dimensionless particle deposition velocity, Sc is Schmidt number (ratio of fluid molecular viscosity υ to particle Brownian diffusivity D), τ_p and τ^+ is the particle relaxation time and its dimensionless format respectively, τ_L is the Lagrangian timescale of the fluid (air), υ_t^+ is dimensionless fluid turbulent viscosity, C^+ is dimensionless particle concentration, y^+ is dimensionless normal distance to the surface, υ_s^+ is the dimensionless settling velocity, and i is used to characterize the orientation of the surface, i.e., for an upward facing horizontal surface (floor), $i = 1$; for a downward facing horizontal surface (ceiling), $i = -1$; for a vertical surface, $i = 0$, $\bar{\upsilon}_y'^{2+}$ is dimensionless air wall normal fluctuating velocity intensity. All these variables could be found in the earlier paper [27] and thus not repeated here. With the expression of the Lagrangian timescale of the fluid (air) τ_L given by Johansen [29] and expression of the dimensionless air wall normal fluctuating velocity intensity $\overline{v_y'^2}^+$ given by Guha [31], which related these two parameters as function of the dimensionless normal distance to the wall (y^+), Eq. (1) is an ordinary partial equation (ODE) with the assistance of the fitted equation of υ_t. Thus an analytical three-layer model incorporating turbophoresis is built up and the particle deposition onto smooth walls could be modeled with corresponding boundary conditions.

When predicting particle deposition onto rough walls, the shift of turbulent boundary layer due to wall roughness should be considered, that is, the virtual origin of the velocity profile is shifted by a distance, e, away from the walls. Thus the effect of "interception" was accounted for by assuming that a particle is captured when it reaches the effective roughness height. Traditional treatment is to shift the velocity boundary layer a distance that is a constant ratio of the effective roughness height (for example, $0.55k$ is widely used by [31–35]) away from the walls. However, the turbulent flow over rough walls could be classified as three different regimes according to the value of roughness Reynolds number (or called dimensionless roughness), k^+, that is, hydraulically smooth, transition and completely rough regime of turbulent boundary layer. For each regime, the thickness of separated free shear layer behind the roughness is different and thus the shifted distance of turbulent boundary layer should not be a constant ratio of roughness (Zhao and Wu [36]). Based on the measured data by Wan [37] and Grass [38], the shifted distance of the virtual origin of the velocity profile, e, could be fitted as:

$$\begin{aligned}
\frac{e^+}{k^+} &= 0 && k^+ < 3 && \text{Hydraulically smooth}\\
\frac{e^+}{k^+} &= 0.3219\ln(k^+) - 0.3456, && 3 < k^+ < 30 && \text{Transition}\\
\frac{e^+}{k^+} &= 0.0835\ln(k^+) + 0.4652, && 30 < k^+ < 70 &&\\
\frac{e^+}{k^+} &= 0.82 && k^+ > 70 && \text{Completely rough}
\end{aligned} \quad (2)$$

where:

$$e^+ = \frac{eu^*}{\upsilon}, \quad k^+ = \frac{ku^*}{\upsilon}$$

To solve the above model for both smooth and rough walls, the fluid (air) turbulent viscosity, υ_t, is calculated by the correlation of Johansen [29] in this study:

$$\begin{aligned}
\upsilon_t &= \left(\frac{y^+}{11.15}\right)^3, && y^+ < 3\\
\upsilon_t &= \left(\frac{y^+}{11.4}\right)^2 - 0.049774, && y^+ \in [3, \ 52.108]\\
\upsilon_t &= 0.4y^+, && y^+ > 52.108
\end{aligned} \quad (3)$$

The boundary conditions are:

$$\begin{aligned} &y^+ = r^+, && C^+ = 0, \quad \text{smooth wall} \\ &y^+ = r^+ + k^+ - e^+, && C^+ = 0, \quad \text{rough wall} \\ &y^+ = 200, && C^+ = 1 \end{aligned} \tag{4}$$

Eq. (1) is adopted for both smooth and rough walls. The detail of solving the equation could be found in Zhao and Wu [27] and thus not repeated here.

It should be pointed out that the present model incorporates Brownian and turbulent diffusion, turbophoresis and gravitational setting. Although the electrostatic and thermophoresis effect is easily to be incorporated into this model, they are not taken into account in this study as: particles indoors are not charged artificially by diffusion or filed charging, the most possible charged mechanism is static electrification which is a uncertain mechanism and could not make the particle highly charged in indoor environment; in most conditions the temperature difference in indoor environments (not more than 10 °C in the whole indoor spaces) only lead a negligible thermal force compared with diffusion and drag force, except for the space near a very hot (cool) surface such as heat radiators attached to walls.

2.2. Drift flux model combined with particle deposition boundary conditions

Indoor particle spatial distribution is significantly decided by indoor air flow, which is usually turbulence. And for ventilated room, the complicated boundary condition of air supply openings is another key parameter influencing indoor air flow.

To calculate the three-dimensional and non-isothermal turbulent airflow in ventilated rooms quickly and correctly, a well validated simplified methodology combined with N-point air supply opening model [39] and a zero equation turbulence model [40] are applied. For indoor aerosol particles distribution simulation, drift flux model is employed. The drift flux model is a Eularian method that integrates the gravitational settling effects of particles into the concentration transportation equation. It is an improvement of the traditional transportation model of contaminant concentration by adding the drift flux term into the particle concentration equation, which is caused by the velocity slippage of particle and air due to drag force. Especially, the particle deposition boundary conditions for walls are developed based on the analytical expression of deposition velocity by Lai and Nazaroff [26]. Here Lai and Nazaroff's model is adopted because this model neglects turbophoresis and thus has analytical solution, which makes it easy to be incorporated with CFD simulation. As turbophoresis play a very limit role on particle deposition in indoor environment, it is reasonable to adopt this model. Zhao and Wu have proved that the result by this model is similar to that by complicated model with turbophoresis for indoor environments [27]. The key input parameter for calculating particle deposition velocity and related particle flux to the wall is the friction velocity of walls, which could be easily calculated based on the numerical results of wall shear stress. And then the deposition particle flux at each point (indicated by near wall area of each mesh in numerical calculation, dA) of the walls could be calculated by:

$$J_{\mathrm{w-d}A} = V_{\mathrm{d-d}A} C_{\mathrm{n-d}A} \mathrm{d}A \tag{5}$$

where $V_{\mathrm{d-d}A}$ is the deposition velocity of particles for each position; $C_{\mathrm{n-d}A}$ is the particle concentration at grids adjacent to walls, dA is the wall area corresponding to each adjacent control volume.

Thus influence of particle spatial distribution on particle deposition could be identified by this method with the assistance of three-dimensional numerical simulations. The details of the drift flux model combined with the particle deposition boundary conditions of wall surfaces could be found in Zhao et al. [22] and thus not repeated here.

2.3. Validation of the analytical model

Fig. 1 shows comparison of simulated results of particle dimensionless deposition velocity onto smooth walls with the measured data of Liu and Agarwal [41], which is widely used for model validation. The simulated results agree well with the measured data and the "S" shape curve of deposition velocity versus particle relaxation time is well simulated. More comparison of the results by the analytical model with experiments could be found in Zhao and Wu [27]. The agreements are well for vertical walls and upward walls (floor), while the discrepancy of downward wall (ceiling) is significant. However, as both the experiment [42] and model simulation [26,43] show that the deposition velocity onto vertical and floor is much larger than that onto ceiling (about 1–2 orders of magnitude larger), this discrepancy would not influence the analysis significantly.

Fig. 2 further shows the comparison of the simulated deposition velocity with measurement for rough wall cases. It indicates that the analytical model could simulate agreeable results for a wide range of roughness for rough walls. It should be pointed out that the actual wall roughness could be very different, resulting different shifted distance of velocity and concentration boundary layer, and thus Eq. (2) need to be adjusted accordingly. It is the reason why the predicted result according to Eq. (2) is still not satisfactory and thus we have to choose $e^+ = 0.97k^+$ to optimize the agreement between model predictions and measurements in Fig. 2(b). Due to the lack of measured shifted distance of boundary layer for different wall roughness types (specially for actual

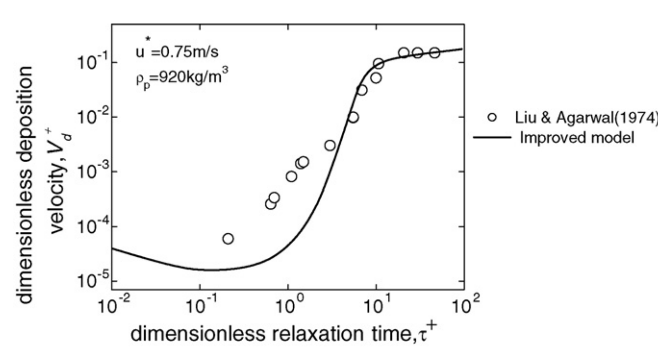

Fig. 1. Comparison of simulated particle deposition velocity with measurement (smooth wall case).

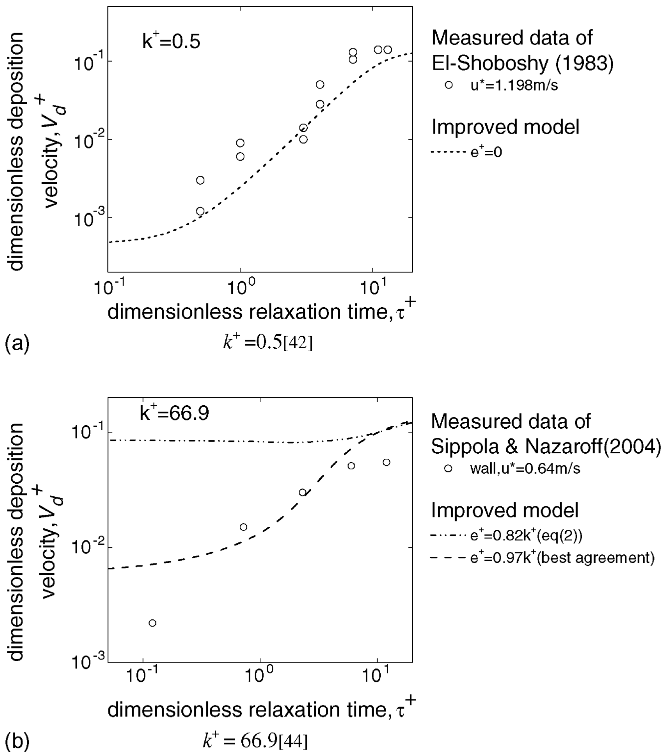

Fig. 2. Comparison of simulated particle deposition velocity with measurement (rough wall case [42,44]).

complicated wall roughness), Eq. (2) is fitted based on measurement of Wan [37] and Grass [38], where the roughness is formed by uniformly distributed steel balls of 3, 6 and 9.66 mm diameter, respectively [37]; and sand of 2 mm diameter and round pebbles of 9 mm diameter [38]. More comparison of the results by the analytical model with experiments could be found in Zhao and Wu [36]. However, the rule of the particle deposition would not change at certain kind of roughness although the accurate value of the shifted distance might be different for different kind of roughness. Therefore Eq. (2) is still adopted to predict the deposition velocity of the particles onto rough walls in the following study.

2.4. Validation of the numerical model

To validate the numerical model for simulating particle spatial distribution indoors, the measured data in a model room by Chen et al. [24] is adopted. The model room geometry is length × width × height = 0.8 m × 0.4 m × 0.4 m. Its inlet and outlet are of the same size, 0.04 m × 0.04 m and both of them are symmetrical with the center plane $Y = 0.2$ m, See Fig. 3. The particle density is 1400 kg/m^3. Particle concentration is normalized by the inlet concentration and thus the inlet concentration of particle is 1.0. Chen et al. measured the airflow velocity and particle concentration with a phase Doppler anemometry (PDA) system. Fig. 4(a) shows the comparison of simulated velocity with measured data, while Fig. 4(b) shows the comparison of particle concentration. The particle size is 10 μm, which is suitable to validate the drift flux model as the drift flux may be dominant for particles of this size. The results show that both the airflow

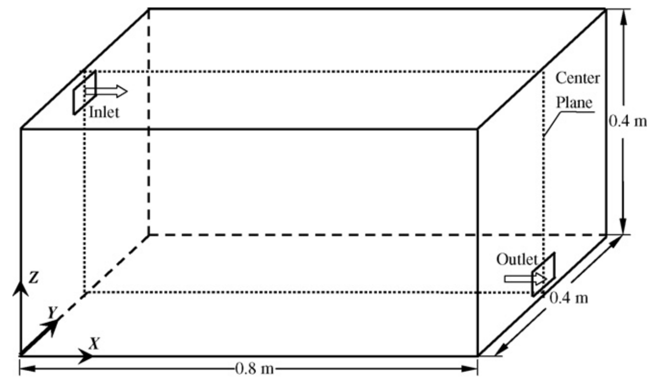

Fig. 3. Schematic of the ventilation chamber for validation of numerical model [24].

and particle concentration distribution could be well simulated by the presented drift flux model combined with the particle deposition boundary conditions.

3. Analysis of factors influencing particle deposition indoors

3.1. Influence of friction velocity

Friction velocity, which is defined as the square root of the wall shear stress over air density, could stand for near wall flow conditions since it is decided by near wall velocity gradient. According to the analytical model, friction velocity affects the particle inertia and thus decides the particle deposition significantly. For instance, airflow in ventilation ducts has larger friction velocity which implies a larger inertia, resulting stronger particle deposition.

As the velocity in the ventilation room would be different due to different air change rate, the friction velocity would also be different, which influences the deposition velocity onto the surfaces. According to study of Lai and Nazaroff [26], the friction velocity in the room is usually in the range of several centimeters per seconds (0.1–3.0 cm/s). To analyze the influence of the friction velocity, here the deposition velocity is calculated when the friction velocity is in the range of 0.1–10 cm/s. It should be pointed that turbophoresis play a very limit role on particle deposition in this case because the friction velocity is very small, which makes the result of our model similar to the result of the model by Lai and Nazaroff [26]. Fig. 5 shows the predicted result by the model at different friction velocities and measured data of Xu et al. [14] in which case four mixing fans with different speeds is used to change the velocity in the test room. The measured data are almost totally in this range and agrees well with the predicted result. The area-weighted deposition velocity (or mean deposition velocity), $V_{d,total}$, is calculated by:

$$V_{d,total} = \frac{V_{d,wall} \cdot A_{wall} + V_{d,ceiling} \cdot A_{ceiling} + V_{d,floor} \cdot A_{floor}}{A_{total}}, \tag{6}$$

where A_{wall}, $A_{ceiling}$ and A_{floor} are the areas of the vertical walls, ceiling, floor, respectively, and A_{total} is the total area of the sur-

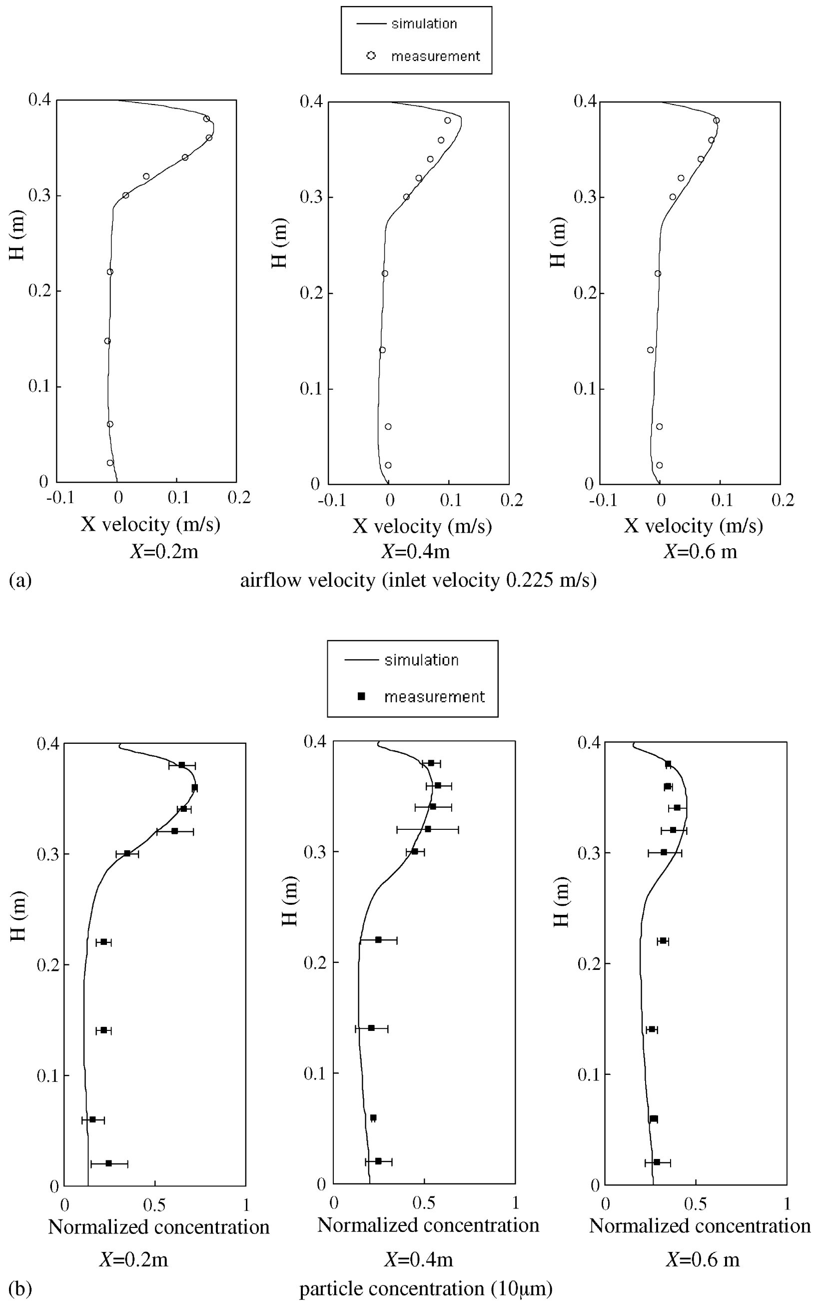

Fig. 4. Comparison of simulated airflow velocity and particle concentration distribution with measurement (different locations at center plane).

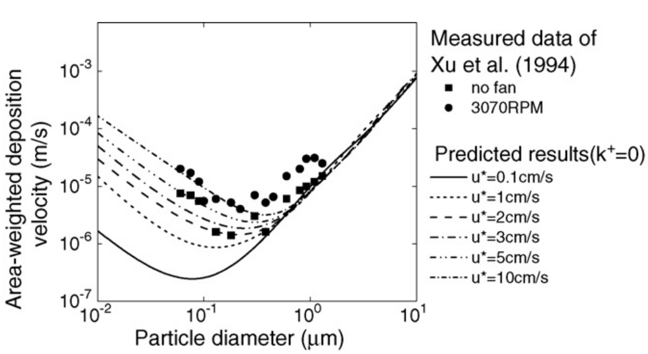

Fig. 5. Comparison of the predicted result and measured data of Xu et al. [14] at different friction velocities.

faces (sum of $A_{\rm wall}$, $A_{\rm ceiling}$ and $A_{\rm floor}$); $V_{\rm d,wall}$, $V_{\rm d,ceiling}$ and $V_{\rm d,floor}$ are the deposition velocities to the vertical walls, ceiling and floor, respectively. It could be found that when the particle size is small, the area-weighted deposition velocity grows larger as the friction velocity grows larger, but when particle size is large enough (aerodynamic diameter larger than 1 μm), the friction velocity won't influence the deposition velocity, just as that of model prediction and published measurement. The cause of this phenomenon is that Brown and turbulent diffusion controls particle deposition when the particle size is small enough, while the particle concentration gradient near the wall surface would be enhanced at larger friction velocity due to the decrease of the thickness of particle concentration boundary layer ($y^+ = 200$ is the upper limit of integration in the boundary conditions of Eq. (1) and as friction velocity grows, the thickness of particle concentration boundary layer becomes thiner since it is 200 υ/u^*), which makes the diffusion enhanced. However, when the particle size is large enough, the gravitational settling plays the most important role which is only related to particle size, and thus the influence of the friction velocity is negligible. Larger friction velocity usually implies larger air flow velocity due to the existence of larger velocity gradient near the wall surfaces. Thus in small size particle range, larger deposition velocity is usually observed in indoor environments with larger air change or ventilation rate, just as the experiments by Nomura et al. [8], Cheng [15] and Xu et al. [14] shown.

As discussed above, if the hazardous material released indoor is mainly built up by large particles (aerodynamic diameter larger than 1 μm), the friction velocity, or the ventilation volume, has little influence on particles deposition velocity in the room, therefore the deposited particle flux would become smaller as the ventilation volume is getting larger, which makes the concentration of the particles smaller. But if the hazardous material is mainly built up by small particles (aerodynamic diameter smaller than 1 μm), as the ventilation volume increased, the deposition velocity would become larger while the concentration of the particles become smaller, therefore in this case the relationship between the deposited particle flux and the ventilation volume is not as clear as that for large particles. Consequently, larger ventilation volume is suggested to control large particles deposition, while for small particles, a most suitable ventilation volume may exist, which may need a more detailed analysis to aid the control method decision. For instance, the numerical model which could analyze particle concentration distribution together with deposition velocity may be helpful. This will be shown in the following subsection.

3.2. *Influence of wall roughness*

The effective roughness height k could stand for wall roughness conditions. According to the analytical model, roughness height affects the concentration profile of the particle and thus decides the particle deposition significantly.

Fig. 6 shows the predicted result by the model at different roughness heights (the effective roughness height is 0–1600 μm, which is in a wide range) and measured data of Abadie et al. [1] who studied five common surface materials used in the room, including smooth wallpaper, rough wallpaper, carpet, linoleum and glazing, among which the roughness height of carpet is largest and that of glazing and linoleum is smallest. Here the friction velocity is chosen as 2 cm/s which makes the simulated results fit best with the measured data when the surface is almost smooth (linoleum surface). The measured data are almost totally in this range and agrees well with the predicted result. The area-weighted deposition velocity grows larger as the roughness height grows larger when the particle size is small. The reason is the roughness enhances the particle concentration gradient near the wall as this reduces the thickness of particle concentration boundary layer and thus reduces the particle transfer resistance to the wall surfaces equivalently, which serves as the dominant influencing factor on particle deposition, while the Brown and turbulent diffusion are also enhanced due to the enlargement of particle concentration gradient. When particle size is larger (aerodynamic diameter larger than 5 μm), the gravitational settling plays the most important role. Thus the influence of the surface roughness is negligible.

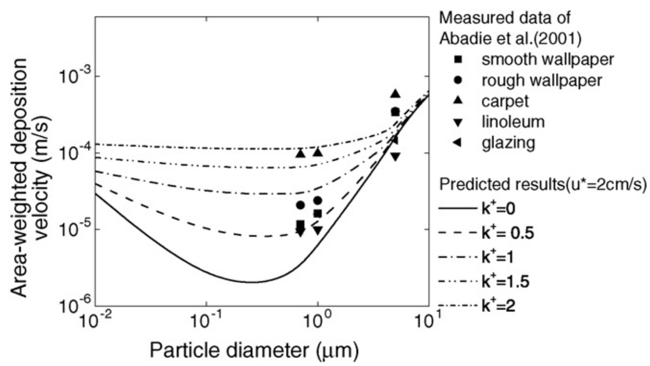

Fig. 6. Comparison of the predicted result and measured data of Abadie et al. [1] at different roughness.

As discussed above, when large particles (aerodynamic diameter larger than 5 μm) are released/generated in the room, the surface material has little influence on the deposited particle flux. But for small particles (aerodynamic diameter smaller than 5 μm), smoother surface material is suggested as small particle deposition is sensitive to surface roughness. Thus for the cases where small particles deposition need to be controlled carefully, for example, the clean rooms, smooth surfaces indoor are adopted.

3.3. *Influence of particle spatial distribution*

To analyze the influence of particle spatial distribution on particle deposition, a full-scale room with two different ventilation modes (one ceiling supply and the other bottom-side supply) is selected. As shown in Fig. 7, the room geometry is $L(X) \times H(Y) \times W(Z) = 4\,\text{m} \times 3\,\text{m} \times 3\,\text{m}$. The ceiling supply case is ventilated by one grille diffuser on the ceiling ($0.2\,\text{m}(X) \times 0.2\,\text{m}(Z)$) and two grille outlets on two side walls ($0.2\,\text{m}(Y) \times 0.2\,\text{m}(Z)$). The bottom-side supply case is ventilated by a displacement diffuser ($0.4\,\text{m}(Z) \times 1\,\text{m}(Y)$) and a grille outlet on the ceiling ($0.2\,\text{m}(X) \times 0.2\,\text{m}(Z)$). Both the inlets and outlets are symmetrical about the center plane in XY plane ($Z = 1.5$ m). The two cases have the same air supply volume rate (288 m^3/h, corresponding air change rate is 8 ACH). Particle sources are also the same for the two cases and assumed to be the particle generation by a person indoor, with 10^5 particles/min generating rate of each size of particle (0.01, 0.1, 0.5, 1, 2.5, 5, and 10 μm, which are also assumed to be aerodynamic diameter) for simplification. The location of the particle source is 1.05 m high and in the center plane ($Z = 1.5$ m). Thus the conditions are similar so that the results are comparable. All the surfaces are assumed to be smooth.

The grid numbers calculated are $44(X) \times 33(Y) \times 34(Z)$ for both bottom-side supply and ceiling supply cases. Grid independence test is conducted by calculating the same case with finer

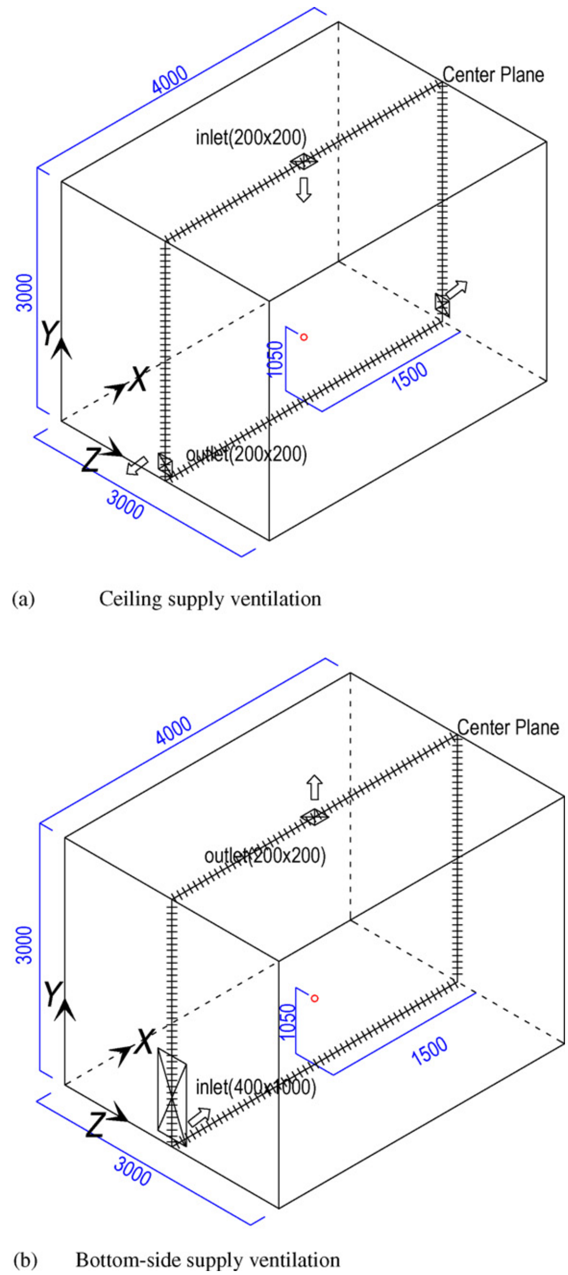

Fig. 7. Schematic figure of the room with two ventilation modes.

grids (twice denser in each direction) and finding no change of the results. The convergence criterion is set as the maximum residual of the governing equations less than 10^{-6}.

Figs. 8 and 9 shows the comparisons of particle spatial distribution and deposited particle flux at different ventilation modes. It could be found that when particle size is small, the deposited particle flux of ceiling supply case is about 5 times larger than that of bottom-side supply case. This because that diffusion plays the most important role in this range (0.01–1.0 μm), where the differences among the deposition velocity onto the three orientation surfaces could be neglected, and thus the deposited particle flux are mainly decided by the concentration near all surfaces. Fig. 8 shows that the particle concentration of the ceiling supply ventilation case is larger than that of bottom-side supply ventilation, which leads larger deposited particle flux. Another reason that ceiling supply case has much larger deposited particle flux is that this case has larger friction velocities, where the average friction velocity of ceiling supply case is 3 cm/s and bottom-side supply case is only 1 cm/s. When particle sizes are large enough and the gravitational settling would play the most important role, which makes the deposition velocity onto the floor is much larger than that onto the other surfaces, the concentration near the floor of the ceiling supply ventilation becomes the dominant factor deciding particle deposition flux. For this particle size range (2.5–10 μm), the deposited particle flux of ceiling supply case is about 2–3 times larger than that of bottom-side supply case. The difference becomes smaller because the influence of the friction velocity to the area-averaged deposition velocity are not obvious when the particle size is larger since gravitational settling will play the most important role and thus only the concentration near floor decides the particle deposition flux.

By the analysis above, one could get a general rule for indoor particle deposition control: with the purpose of reducing the deposited particle flux, for small particles (aerodynamic diameter smaller than 1 μm), the air flow pattern which would reduce the friction velocities is suggested; while for large particles (aerodynamic diameter larger than 1 μm) the air flow pattern which would reduce the concentration near the floor is suggested, for example, the bottom-side supply ventilation mode may be suitable for this case.

4. Discussions

As discussed before, several factors influencing particle deposition in indoor environments, including flow conditions near the wall surfaces (here using the friction velocity to represent near wall flow condition), surface roughness and particle concentration distribution, are analyzed. The electrostatic field and thermophoresis effect are not taken into account in this study. For most indoor environments, particles indoors are not charged artificially by diffusion or filed charging, the most possible charged mechanism is static electrification which is a uncertain mechanism and could not make the particle highly charged. And in most conditions the temperature difference in indoor environments (not more than 10 °C in the whole indoor spaces) only lead a negligible thermal force compared with diffusion and drag force, except for the space near a very hot (cool) surface such as heat radiators attached to walls. Thus it is suitable not to incorporate these two factors in this study.

As the wall roughness is always irregular and complicated actually, it is hard to deduce a universal rule for the shifted distance of velocity boundary layer theoretically. This study adopted effective roughness of uniform distributed balls for different cases. Whereas the cases presented in this study shows the treatment is validated for most cases from different literatures, knowledge on roughness structure need to be further investigated, which may be helpful for understanding a suitable value of shifted distance of velocity boundary layer. And for actual cases, the analytical model could be employed as the same manner presented in this study as long as the actual shifted distance of velocity boundary layer could be measured.

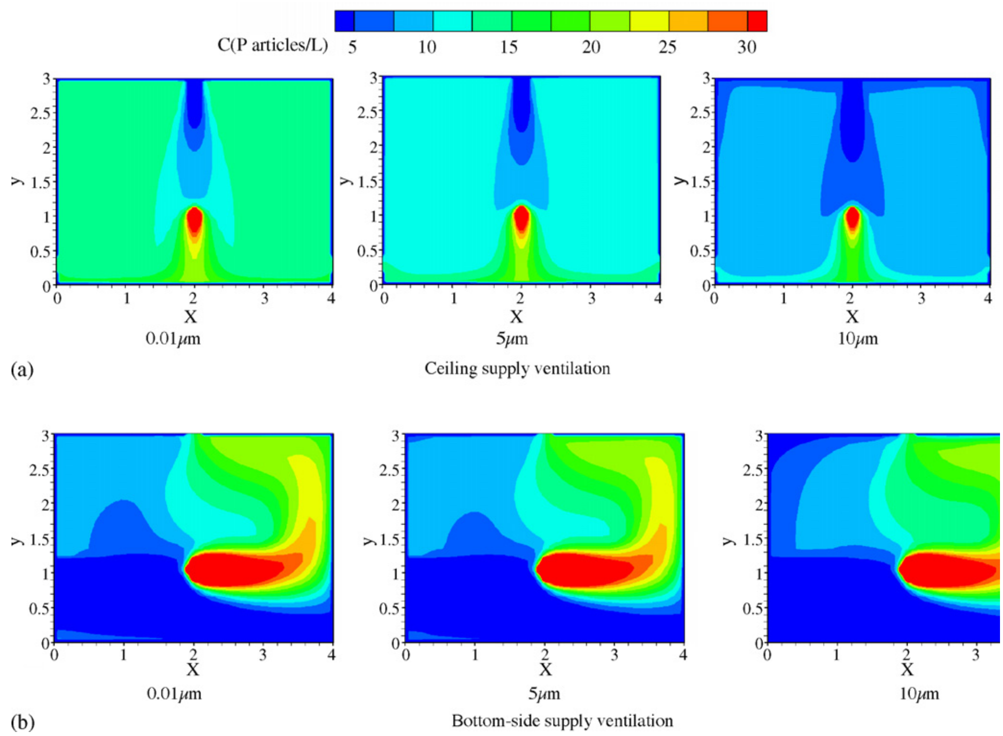

Fig. 8. The particle spatial distribution at different particle sizes and ventilation methods in center plane ($Z = 1.5$ m).

The presented three-dimensional numerical simulations indicate that particle concentration distribution may differ much even for the same particle source and air change rate, which cause a different deposited particle flux to walls. As the particle concentration distribution may not be uniform in most cases, especially for the ventilated rooms where ventilation is used for controlling indoor air quality, it is important to incorporate particle concentration distribution when analyzing particle deposition in indoor environments.

Above analysis on influencing particle deposition indoor could be the basic for particulate matter control in indoor environment. As the modeling method is easy to apply for actual cases, one could perform particle pollution control method decision efficiently in this way. And the presented modeling method could be easily extended to real situation. For a mechanical ventilated room, the particle distribution and deposition could be easily analyzed by the validated three-dimensional numerical simulations, just as the case shown above. For a natural ventilated room, once the friction velocity is known, which is mainly decided by the air change rate, the deposition velocity could be calculated easily; therefore the particle deposition could be easily analyzed. To evaluate the friction velocity in such indoor environment, one could adjust the similar method suggested by White [45] for ducts, or the method by Lai and Nazaroff [26] or even the measurement. The particle distribution in the room could be analyzed by the CFD method or zonal model, which may get rough concentration distribution with less computational time.

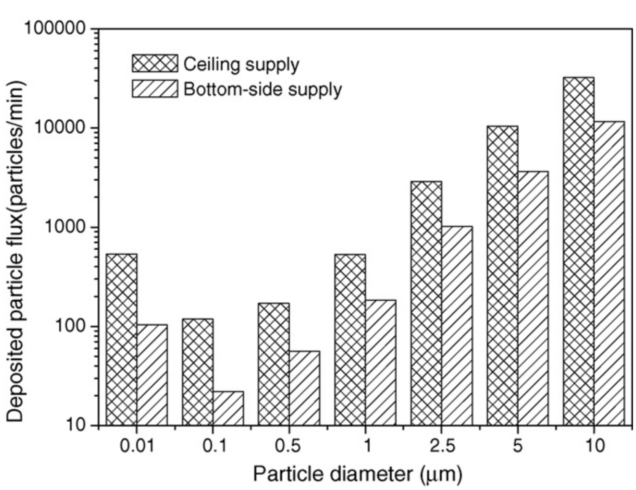

Fig. 9. The deposited particle flux onto the total surfaces of the room at different particle sizes and ventilation modes.

5. Conclusions

In this study, the influences of air flow conditions near the wall surfaces, surface roughness and particle concentration distribution on particle deposition in indoor environments are analyzed with an analytical model and a three-dimensional drift flux model combined with the particle deposition boundary conditions for wall surfaces. The following conclusions may be drawn based on the presented results:

(1) As the particle size grows larger, the area-weighted particle deposition velocity first grows smaller due to weakening of the diffusion and then becomes larger due to enhancement of the gravitational settling.

(2) When the particle size is small, the area-weighted particle deposition velocity grows larger as the friction velocity grows larger, but when particle size is large enough (aerodynamic diameter larger than 1 μm), the friction velocity won't influence the area-weighted deposition velocity. Therefore larger ventilation volume is suggested for large particles while there may be a most suitable ventilation volume for small particles.

(3) The area-weighted particle deposition velocity grows larger as the roughness height grows larger when the particle size is small, but when particle aerodynamic diameter is larger than a constant (when friction velocity is 2 cm/s, it is about 5 μm as shown in this study), the roughness height won't influence the area-weighted deposition velocity. Smoother surface is suggested for small particles deposition control.

(4) The deposited particle flux is very different under different particle spatial distribution. For small particles (aerodynamic diameter smaller than 1 μm), the deposited particle flux is decided by the concentration near all wall surfaces and the friction velocity, therefore the air flow pattern which would reduce the friction velocities is suggested. While for large particles (aerodynamic diameter larger than 1 μm), the deposited particle flux is mainly decided by the concentration near the floor, and thus the air flow pattern which would reduce the concentration near the floor is suggested.

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