

# COMPUTATION OF AIRFLOW-DRIVEN RE-ENTRAINMENT OF FINE PM IN CONVENTIONALLY-VENTILATED CLEAN ROOM

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## ABSTRACT

Detailed airflow pattern and particulate contamination characteristics, induced by dump-type air supply in a full-scaled conventionally-ventilated clean room, are investigated numerically. Standard k-epsilon turbulence model is applied to calculate velocity vector, turbulent intensity etc. mainly due to the adoption of large ACH which results in high turbulence indoors. Based on the criterion proposed by Murakami et al, small-slip model in Euler framework advanced by S. L. Soo is applied to characterize particulate diffusion. Test data from an in-site observation are used to define boundary conditions, and releasing rate of contaminant on interior surface from literature is used to define source strength.

In general, floor surface is an important sink of airborne particles and re-entrainment is rare due to large adhesion force, especially for micron-sized aerosol particles generating indoors through a variety of mechanisms. However, under the condition of strong supply jet flow required for dilution purpose in clean room, phenomenon of deterioration in cleanliness is confirmed both by numerical investigation and by experimental test.

The airborne cleanliness of a conventionally-ventilated clean room is dependent not only on the quantity and quality of air supplied to the room but also the interrelationship between airflow and generation mode of contamination. For some specific location and strength of contaminant source, it should be recognized that the type and layout pattern of air supply devices will influence the air movement in clean room and hence its cleanliness.

## KEYWORDS

Airborne cleanliness, Dump-type air supply, Re-entrainment

## INTRODUCTION

The ability to predict and analyze the particulate matter (PM) is crucial for designing clean room and maintaining their efficiency to meet high level cleanliness required by relevant codes. The knowledge of the airflow characteristics as well as turbulent intensity which is responsible for the PM dispersion is very meaningful from the viewpoint of the control of the cleanliness level. However such accurate measurements and theoretical computation are hard to obtain. As experimental investigations are long and tedious, the numerical simulation can be viewed as an efficient alternative. Computational Fluid Dynamics (CFD) is more and more attractive in studying and evaluating turbulent flow to properly design the air distribution and to optimize the process arrangement (Lei 2001, Zhao et al. 2004, Zhao and Wu 2005). Visualizing and eliminating the paths of possible contaminant flow in some process industries, such as pharmaceutical manufacturing, where airborne fine particles and droplets within the diameter range of submicron is prevalent, are critical to guarantee the quality of products.

Non-unidirectional or turbulently-ventilated airflow is widely adopted in cleanliness class ISO6~9 mainly due to its low capital and running cost. Dump-type air supply through ceiling diffusers with Air Change per Hour (ACH) 10~60 and air extract grilles on the side walls are the general method of ventilation used in conventionally ventilated clean rooms. Theoretically the air velocity suggested is sufficient to

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remove any contaminant generated into the air through mixing and dilution. However, air vortex caused by obstructions and entrainment of contaminant by strong airflow interaction with interior surfaces in practical situation, even in "at rest" condition (no personnel presence), will play a significant role in establishing of higher contamination concentration.

Meanwhile, the transport mechanism of aerosol particles is complicated and not yet fully understood. Their behavior is closely associated with the airflow motion and the turbulence (Zhang and Chen 2007). Mathematically, there are two treatments of PM movements: the Euler-Euler method and Euler-Lagrange method (Gao and Niu 2007). The former method has been justified by many researchers in clean room environment where fine aerosol particles are assumed to be passive based on the criterion proposed by Murakami et al (Murakami et al. 1992). One-way coupling between particles and airstreams in a dilute dispersed phase flow in which particle movements are determined by the state of the airflow is feasible due to the particle Stokes number way smaller than 1 and particle volume fraction indoors below  $10^{-9}$  (Li et al. 2005). In this paper, one of the simplified Eulerian methods, i.e. a Small Slip Model (SSM) advanced by S. L. Soo (Zhou 1993) is applied to characterize particulate diffusion and distribution. As an alternative to drift-flue model, the SSM can easily incorporate Brownian and turbulent diffusion when the gravitational settlement effect is negligible, with particle diameter of interest in this paper smaller than  $4.5\mu\text{m}$ . Comparison between numerical results and in-situ observation data shows good agreement. Also drawn from the simulation results is the need to optimize air supply type and layout pattern according to ACH and contaminant source characteristics.

## MATHEMATICAL MODLES

### Small Slip Model

In Eulerian framework, the particle-phase can be statistically assumed as a continuum when particle size significant smaller than Kolmogorov micro scale and enough particles in each computational cell. The basic viewpoint of SSM is that the time-averaged inter-phase slip is the diffusion of particle phase relative to the mixture. In nature, this method generalizes the concept of multi-component single phase fluid into multi-phase mixture. So the slip velocity of particle relative to the fluid is the result of diffusion drift, i.e.,

$$-\rho_p(u_{p,i} - u_i) = D_p \frac{\partial \rho_p}{\partial x_i} \quad (1)$$

In multi-phase flow, the continuity equation of particle phase is:

$$\frac{\partial \rho_p}{\partial t} + \frac{\partial}{\partial x_i}(\rho_p u_{p,i}) = 0 \quad (2)$$

Combining Eqn. (1) and (2), it yields,

$$\frac{\partial \rho_p}{\partial t} + \frac{\partial}{\partial x_i}(\rho_p u_i) = \frac{\partial}{\partial x_i} \left( D_p \frac{\partial \rho_p}{\partial x_i} \right) \quad (3)$$

Where  $\rho_p = N_p m_p$ ,

In dilute dispersed phase flow, coagulation from collision between individual particles is negligible and phase change is not considered either (Friedlander 2000). So the mass of individual particle remains constant, then  $\rho_p$  can be replaced by  $N_p$ . Eqn. (3) can be transformed into Eqn. (4) with particle source term  $S_p$ .

$$\frac{\partial N_p}{\partial t} + \frac{\partial}{\partial x_i} (N_p u_i) = \frac{\partial}{\partial x_i} (D_p \frac{\partial N_p}{\partial x_i}) + S_p \quad (4)$$

### Airflow Model

The turbulence model used is the standard k-epsilon turbulence model, since this model has been found to generate reasonable accuracy for clean room air flow. The governing equation for airflow in clean room can be written in a general form as follows:

$$\nabla \cdot (\rho \bar{u} \phi - \Gamma_\phi \nabla \phi) = S_\phi \quad (5)$$

Derivation of the basic equations and details of  $\phi$ ,  $\Gamma_\phi$  and  $S_\phi$  may be found in many textbook on the subject, such as Versteeg and Malalasekera (Versteeg and Malalasekera 1995). Eqn. (5) can be solved by the semi-implicit method for pressure linked equation (SIMPLE) algorithm, which was described by Patankar (Patankar 1980). The standard log-law wall functions of Launder and Spalding are used for the next-to-surface grid points.

### Particle Boundary Condition

Although the amount of deposited particle is usually much smaller than that of particles exhausted by ventilation, the net transport of particle toward internal room surface may influence the particle distribution. With the assumption that the flux is one-dimensional and constant in the concentration boundary layer and the particle eddy diffusivity equals the fluid turbulent viscosity, the modified form of Fick's law accounts for the effect of Brownian and turbulent diffusion:

$$J = -(D + \varepsilon_p) \frac{\partial N_p}{\partial n} \quad (6)$$

## CASE AND RESULT

### Case description

Figure1. shows the schematic of a full-scale clean room for simulation and measurement with geometry: L(X)×W(Y)×H(Z)=3.0m×2.2m×2.5m. The ceiling diffuser grille is 0.5m×0.5m and the two sidewall exhaust grilles are 0.4m(X)×0.4m(Y). The dimensions of the working table and the cabinet are 1.2m(X)×0.6m(Y)×0.8m(Z) and 0.8m(X)×0.4m(Y)×1.8m(Z) respectively. Based on the in-situ observation, the ACH is 55 and supply air temperature is 15.2°C. The surrounding adjacent rooms are so air-conditioned as this room that adiabatic wall thermal condition is assumed. Particle source is assumed to be particles generated from the floor under "at rest" condition and is modeled as a "source volume" regarded as transparent for the fluid flow. Literature (Xu 1998, Chen 2003) suggest that particle generating rate of floor is within the range of (0.3~4.5) × 10<sup>4</sup> min<sup>-1</sup>·(m<sup>2</sup> floor)<sup>-1</sup>. 1.25×10<sup>4</sup> min<sup>-1</sup>·(m<sup>2</sup> floor)<sup>-1</sup> is obtained through trial and error procedure by fitting simulated result with experimental data for this clean room investigated.

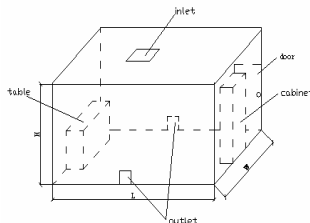


Figure 1. Schematic figure of the clean room investigated

## Grid Independence

A fine contracting grid has been used near the inlet and outlets to capture the flow, thermal and contaminant characteristics in the boundary layer. The computation has been performed using a non-uniform grid of  $80 \times 60 \times 76$  after ascertaining grid independence of the solution. A well-validated in-house code (Chen 2004) has been used as the simulation tool.

## Numerical Result

Figure 1a shows the airflow field of the simulation of two orthogonal vertical planes (left and right) and one horizontal section (center). Both measurement and simulation predict greatest velocity near the diffuser. The supply jet impinges directly with on the floor very small deflection angle due to the large outflow momentum, diffuses in all directions and rises along the side of the obstacles and the walls of the room. Recirculation consisting of downward supply jet and rising flow near the walls is observed. Dead zones, located in the four corners near the obstacles (table and cabinet) and a swirl just above the table appear in Figure 1a (left and center).

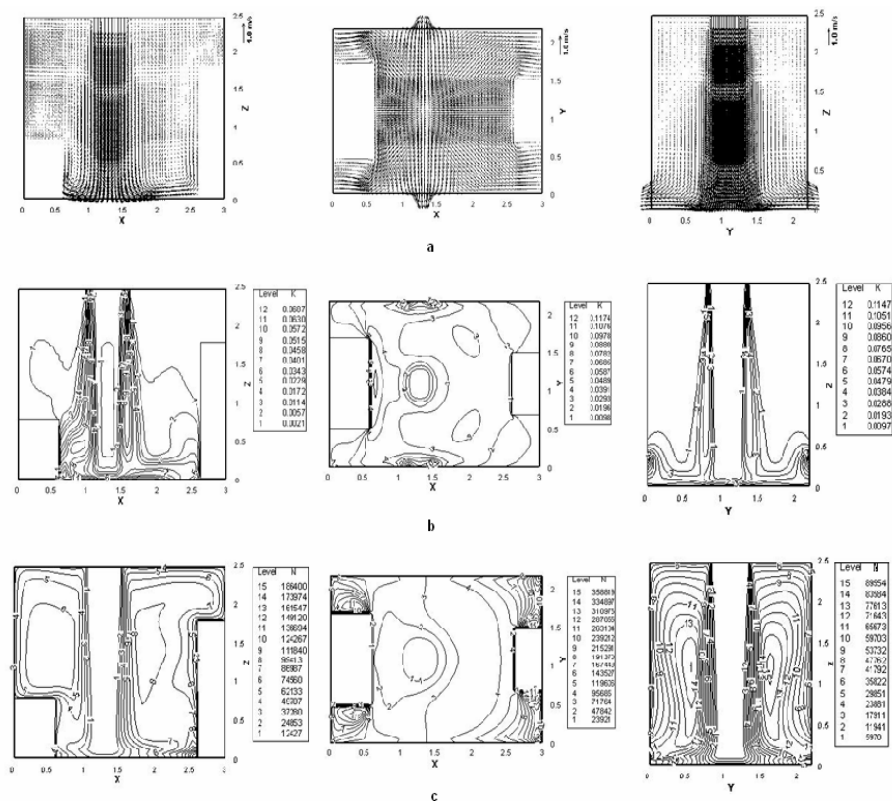


Figure 2. Velocity vector (a), turbulent kinetic energy (b) and concentration (c) for plane Y=1.1m (left), plane Z=0.2m (center) and plane X=1.3m (right)

Obviously, these recirculation zones should be taken into consideration at the time of installation of

equipments. The swirling airflow will increase the residence time of particles and thus hinders their suitable evacuation (in Figure1c). High concentration zones adjacent to the jet, located half height of the room, correspond to the two big recirculation zones. The direct strong impingement of supply jet on the floor will accelerate the corrosion and shedding of surface material. In the meanwhile, entrainment of deposited (turbulent diffusion) and generated (heterogeneous surface reaction) particles into the upward flow will deteriorate the cleanliness level. Turbulence kinetic energy appears to be larger on the edge of jet flow and near the exhaust grilles (in Figure1b). In these areas, particles motion will be subject to turbulent diffusion.

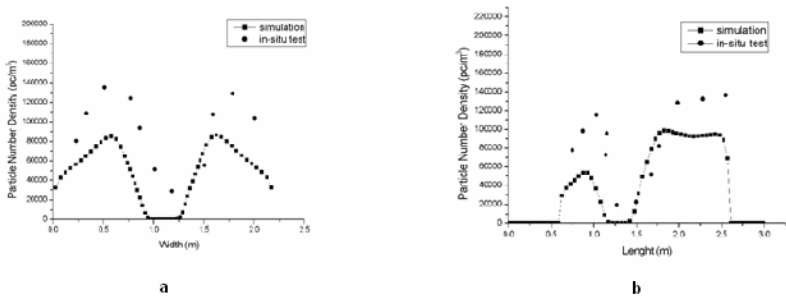


Figure 3. Comparison of concentration between simulation and measurement along width (a) and length (b) direction: (a) through position ( $x=1.3\text{m}$ ,  $z=0.6\text{m}$ ) (b) through position ( $y=1.1\text{m}$ ,  $z=0.6\text{m}$ )

Figure3 shows the comparison of simulation and full-scale experiment (particle size:  $0.3\sim 3.0\mu\text{m}$ ). The agreement between the measured and simulated results is acceptable due to the uncertainty involved in in-situ observation. Some intervening factors are not as controllable as in laboratory environment. Besides, the inefficiency of the adopted turbulence model in non-isotropic domain, and the imprecision of the match in turbulence property at the supply inlet in simulation and measure also account for the difference. However, the trend of data distribution correspond each other well.

## CONCLUSIONS

Numerical approach has been used to investigate the airflow and concentration field in a conventionally ventilated clean room. Main features of the airflow and contaminant distribution, including recirculation zone, stagnation areas etc., have been visualized for the analysis of the airflow structure where detriment to cleanliness will be caused.

Because of the inherent particle properties in advection and turbulent diffusion dominant area, pseudo-fluid SSL particle model can be applied to account for airflow effects on contaminant distribution. But the suitability of concentration gradient boundary condition needs to be further confirmed. And improvement should be done to better analyze near-wall behavior of particles.

Dump-type air supply jet with high velocity can be a major reason behind the deterioration of the cleanliness in the room when contaminant releasing from the floor due to a variety of mechanism, e.g. wear and aging of floor material, heterogeneous reaction between gaseous contaminant with floor surface. To maintain high ACH needed, multiple ceiling supply diffusers can be arranged to join jet streams with the aim of minimizing recirculation region and decreasing impingement strength, so re-entrainment and accumulation of contaminants can be minimized.

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### Nomenclature

$D$	Brownian diffusivity	$t$	time
$D_p$	particle diffusivity	$u$	airflow velocity
$J$	deposition flux	$u_p$	particle velocity
$m_p$	particle mass	$x_i$	coordinate in tensor notation
$n$	wall normal direction	$\rho_p$	particle density
$N_p$	particle number concentration	$\varepsilon_p$	particle eddy diffusivity

## REFERENCES

1. Lei TKG (2001) "Use of computational fluid dynamics applications in cleanroom design", J IEST, Vol. 44, 30-34.
2. Zhao B, Cao L, Li X, Yang X, Huang D (2004) "Comparison of Indoor environment of a locally concentrated clean room at dynamic and steady status by numerical method" J IEST, Vol.47, 94-100.
3. Zhao B. and Wu J. (2005) "Numerical investigation of particle diffusion in a clean room" Indoor and Built Environment, Vol. 14, 469-479
4. Zhang Z. and Chen Q. (2007) "Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces", Atmospheric Environment, in press.
5. Gao N.P. and Niu J.L. (2007) "Modelling particle dispersion and deposition in indoor environment", Atmospheric Environment, in press.
6. Murakami S, Kato S, Nagano S, Tanaka Y (1992) "Diffusion characteristics of airborne particles with gravitational settling in a convection-dominant indoor flow field", ASHRAE Transaction, Vol. 98, 82-97.
7. Li K.Q., Gong G.C., Tang G.F., Zou S.H. (2005) "An improving particle model", Proceedings of the 5<sup>th</sup> International Conference on Indoor Air Quality and Climate, Vol.2, 2009-2013.
8. Zhou L.X. (1993) "Theory and modelling of turbulent gas-particle flows and combustion", published by Science Press, (in Chinese).
9. Friedlander S.K. (2000) "Smoke, dust and haze", published by Oxford University Press.
10. Versteeg H.K. and Malalasekera W. (1995) "An introduction to computational fluid dynamics", published by Pearson Education Limited.
11. Patankar S.V. (1980) "Numerical heat transfer and fluid flow", published by Hemisphere.
12. Xu Z.L (2003) "Theory of air cleaning technology", published by Science Press, (in Chinese).
13. Chen L.X. (2003) "Design and construction of clean room", published by Chemical Industry Press, (in Chinese).
14. Chen K., Gong G.C., Tang G.F. (2004) "Distribution sensitivity of particle contamination to ceiling exhaust openings pattern under traditional displacement ventilation: a numerical investigation", Proceedings of Built Environment and Public Health, 378-384.