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A Study on Diffusion Property of Airborne Particles in Clean Room

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1. ABSTRACT

Based on a k-ε equation turbulence model, 3-D numerical simulation was performed to evaluate diffusion property of airborne particles when gravity sedimentation was taken into account. Based on the results, ventilation efficiency was obtained for each particle size of the airborne particles. Also, by considering weighted average velocity of wind velocity,diffusion velocity given by random numbers, and density of particles and flow resistance associated with density difference of fluid, the diffusion of airborne particles was obtained from numerical simulation, and the validity was evaluated.

2. INTRODUCTION

In a general clean room, fine particles with particle size of less than 1μm are deposited on wafer primarily by Brown diffusion and gravity. Liu and Ahn (1987) assumed additivity of deposition velocity[1] by diffusion and gravity and estimated deposition velocity. Also, they used correlation equation for mass transfer[2] obtained by Sparrow and Geiger (1985) to a wafer, which is placed perpendicularly to air flow. We measured[3] the number of particles deposited on wafer surface using visualization method by argon laser and confirmed the validity of the hypothesis of Liu and Ahn.

On the other hand, to plan an effective contamination control within a cleanroom, it is important to quantitatively analyze and predict diffusion property of airborne particles.Murakami and Kato[4] studied air flow property and contaminant diffusion property in various conventional flow type clean rooms.

In the present study, numerical simulation was performed on diffusion property of airborne particles when gravity sedimentation was taken into account, and ventilation efficiency for each particle size of airborne particles was obtained and discussed. The diffusion property of airborne particles was obtained by numerical simulation considering weighted average velocity of wind velocity by numerical simulation, diffusion velocity given by random numbers, density of particles and flow resistance associated with density difference of fluid, and the validity was evaluated.

3. MODEL ROOM ANALYZED

Figure 1 and Table 1 show the configuration of the analyzed model room. The model room was designed in simple form in order to facilitate the determination of diffusion property of airborne particles.The model room has a size of 4.2×3.0×2.7m (W×D×H) ,and an obstacle with size of 0.6×0.4×0.8m (W×D×H) is placed in it.

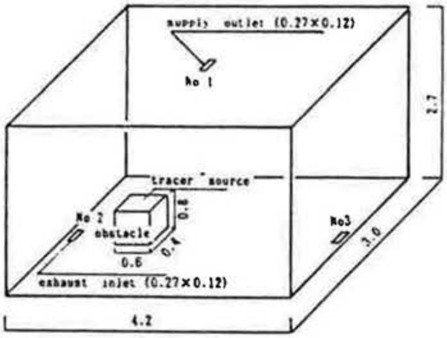


Figure 1 Room Model(unit:m)

Each of the supply outlet and the exhaust inlet has size of 0.12×0.27m, and there are provided one supplyoutlet and two exhaust inlets. The outlet temperature was set to room temperature.

Table 1 Specifications of model clean room used

Dimension of Plan [M × M]	Height of Ceiling [M]	Direction of Supply Air	Number of Exhaust Inlet s	Supply Air Velocity [M / S]	Return Air Velocity [M / S]	Number of Air Changes [/ H]
4.2×3.0	2.7	↓	2	2	1	6.9

4. CASES ANALYZED

The types of analysis are shown in Table 2. For numerical analysis of diffusion property of airborne particles, it was assumed as follows:

When it is assumed that there are passive contaminants, particle loss due to aggregation and deposition, change in particle size distribution and gravity sedimentation are neglected. It is also assumed that the airborne particles are transported together with air flow as an integrity.

In case gravity sedimentation is taken into account, particle loss due to aggregation and deposition and changes of particle size distribution are neglected, and it is assumed that, on floor surface and on upper surface of the object, airborne particles are steadily deposited and piled on floor surface by concentration flux due to sedimentation and are separated and removed from the air.

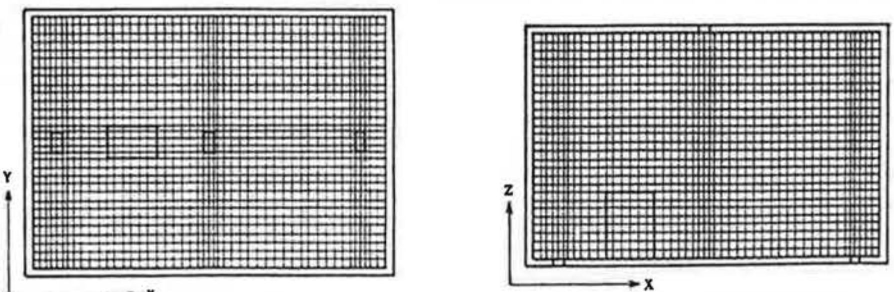
Table 2 Specifications for Cases Analyzed

CASES		1		2		3	
numerical simulation		S1	S2	S1	S2	S1	S2
supply outlet NO 1	air volume (m^3/h)	234	←	←	←	←	←
	velocity (m/s)	2.0	←	←	←	←	←
exhaust inlet NO 2,3	air volume (m^3/h)	117	←	←	←	←	←
	velocity (m/s)	1.0	←	←	←	←	←
Particle size of source (μm)		——	passiv	0.5	100.0	0.5	100.0

5. NUMERICAL SIMULATION

1) CASE 1

For analysis, 3-D numerical simulation was performed based on a k-ε



horizontal plane : 50(X)×33(Y) meshes   vertical plane : 50(X)×29(Z) meshes

Figure 2 Mesh dividing system

Table 3 Model equation

CASE 1

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial}{\partial x_i}\left(\frac{P}{\rho} + \frac{2}{3}k\right) + \frac{\partial}{\partial x_j}\left\{\nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\}$$

here $\nu_t = C_\mu \frac{k^2}{\varepsilon}$

$$\frac{\partial k}{\partial t} + \frac{\partial u_j k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + \nu_t S - \varepsilon$$

here $S = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial u_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_1 \nu_t \frac{\varepsilon}{k} S - \nu_t C_2 \frac{\varepsilon^2}{k}$$

$$\frac{\partial C}{\partial t} + \frac{\partial u_j C}{\partial x_j} = \frac{\partial}{\partial x_j}\left\{\frac{\nu_t}{\sigma_c}\frac{\partial C}{\partial x_j}\right\}$$

$\sigma_k = 1.0$ $\sigma_\varepsilon = 1.3$ $\sigma_c = 1.0$
$C_\mu = 0.09$ $C_1 = 1.44$ $C_2 = 1.92$

CASE 2

$$\frac{\partial C}{\partial t} + \frac{\partial u_j C}{\partial x_j} + \frac{\partial CV}{\partial x_3} = \frac{\partial}{\partial x_j}\left\{\frac{\nu_t}{\sigma_c}\frac{\partial C}{\partial x_j}\right\}$$

CASE 3

$x_i^{n+1} = x_i^n + U_i \Delta t$ $U_{i,dif} = \frac{1}{\Delta t} B_{ran} \eta_i \sqrt{4\Delta t\, U_t}$

$y_i^{n+1} = y_i^n + V_i \Delta t$ $V_{i,dif} = \frac{1}{\Delta t} B_{ran} \eta_i \sqrt{4\Delta t\, V_t}$

$z_i^{n+1} = z_i^n + W_i \Delta t$ $W_{i,dif} = \frac{1}{\Delta t} B_{ran} \eta_i \sqrt{4\Delta t\, W_t}$

Table 4 Boundary Conditions for Numerical Simulation

Supply Outlet boundary:	$u_t = 0.0$, $u_n = u_{out}$, $k = 0.005$, $C = 0.0$ suffix t: tangential component suffix n: normal component u_{out}: outlet velocity
Exhaust Inlet:	$u_t = 0.0$, $u_n = u_{in}$, $\partial k/\partial n = 0.0$ $\partial \varepsilon/\partial n = 0.0$, $\partial C/\partial n = 0.0$ u_{in}: Exhaust inlet velocity
Wall boundary:	$\partial u_t/\partial n_{wall} = m u_{t,wall}/h$, $u_n = 0.0$ $\partial k/\partial n = 0.0$, $\partial C/\partial n = 0.0$ $\varepsilon_{wall} = (C_\mu k_{wall}^{3/2})/(C_\mu^{1/4}\kappa h)$ h: Length from the wall surface to the center of the adjacent cell m: 1/7 κ: 0.4, von Karman constant

Table 5 Gravity sendimentation velocity for particle size (density 1 g/cm³)

Particle size (μm)	0.8	100
Gravity sendimentation velocity (m/s)	2.32×10^{-5}	2.48×10^{1}

equation turbulence model. Basic equations based on k-ε model are: equation of motion, simultaneous equation, transport equation for turbulent energy kand turbulance dissipation ε and concentration diffusion equation.

Basic equations are summarized in Table 4. Figure 2 shows mesh division used for analysis. SMAC method was used for analysis of air flow property. For difference apporoximation, forward difference was used for time, central difference for space, and windward difference for advection term. For analysis of concentration distribution property of airborne particles, SIMPLE method was used. For difference approximation, back-ward difference was used for time, central difference for space, and windward difference for advection term.

The number of mesh divisions was: [50(X)×33(Y)] for horizontal cross-section, and [50(X)×29(Z)] for vertical direction.

2) CASE 2

Basic equations of Case 1 were used, and gravity sedimentation was taken into account for concentration diffusion equation as shown in Table 3. In the present analysis, density of 1 g/cm³(assuming polystyrene standard particle) as gravity sedimentation velocity of airborne particles as shown in Table 5.

3) CASE 3

Considering weighted average velocity of wind velocity, diffusion velocity given by random numbers,particle density and flow resistance associated with density difference of fluid obtained from basic equations of Case 1,the diffusion property of airborne particles was obtained. In the present analysis, density of 1 g/cm³(assuming polystyrene standard particle) as gravity sedimentation velocity of airborne particles as shown in Table 5.

6. ANALYSIS BY MEANS OF NUMERICAL SIMULATION

1) Air flow property

Figure 3 and Figure 4 show air flow distribution by numerical simulation and the air flow distribution based on the experiment[5]. The aspects measured over the entire experiment are reproduced by the simulation. The outlet jet reaches floor surface without being attenuated very much and flows toward every direction. The air flow directed to an obstacle goes upward along wall of the obstacle and is induced by the outlet jet at upper portion of the obstacle and forms vortex.

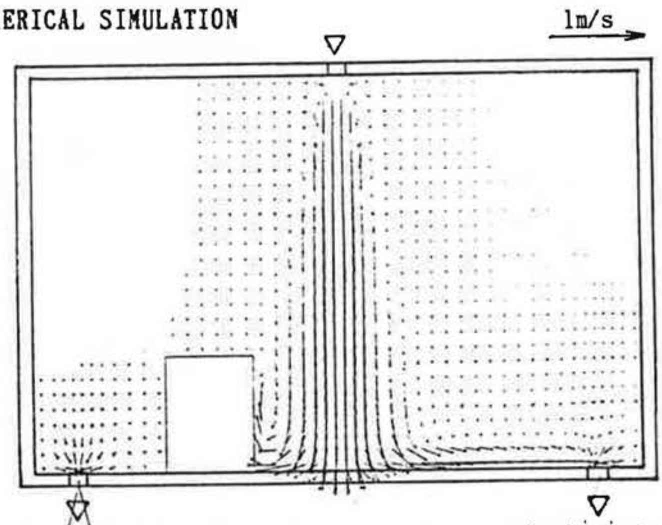


Figure 3 Velocity vectors given by numerical simulation

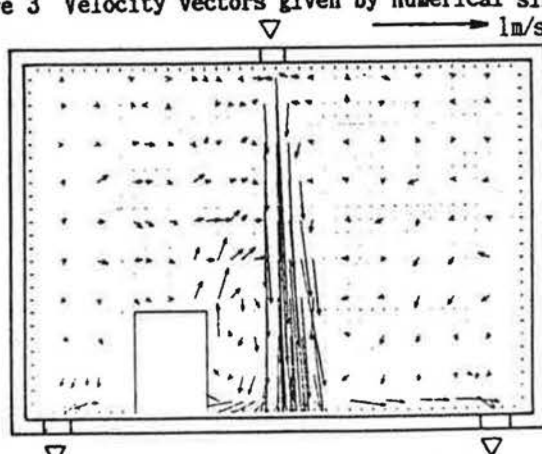


Figure 4 Velocity vectors given by model experiment

2) Concentration distribution property (CASE 1 and CASE 2)

Concentration distribution property of airborne particles is given in Figure 5 for CASE 1-S2, in Figure 6 for CASE 2-S1, and in Figure 7 for CASE 2-S2. The concentration is instantaneous uniform diffusion concentration and is turned to non-dimensional. In both CASE1-S1 and CASE2-S1, air flow is induced by outletjet at the upper portion of the obstacle and forms vortex, and high concentration region with non-dimensional concentration of 2 or more stagnates around the obstacle. In CASE 2-S2, inlet concentration is 0, and it is considered that most of the generated particles are not removed from the room and are deposited and piled on floor surface.

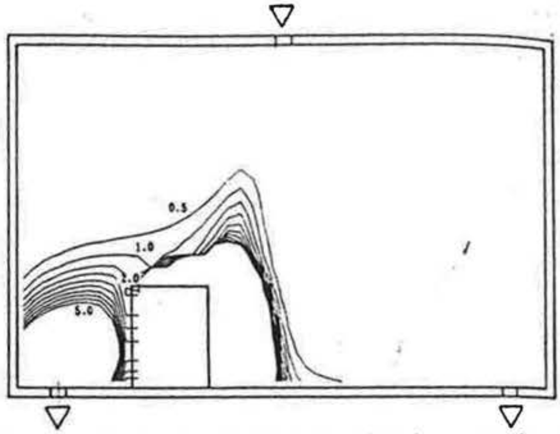


Figure 5 Contaminant distribution by numerical simulation (CASE 1 S2)

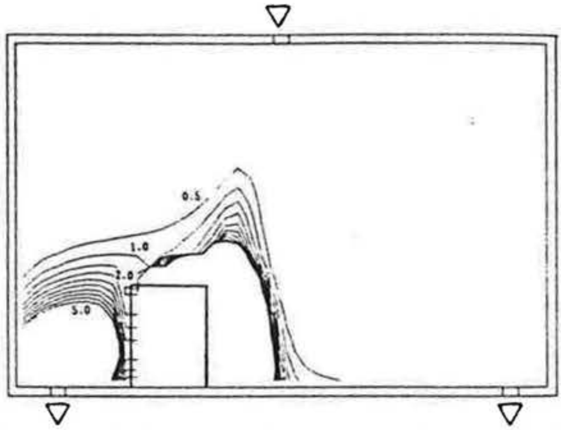


Figure 6 Contaminant distribution by numerical simulation (CASE 2 S1)

3) Concentration distribution property (CASE 3)

The airborne particle distribution property is shown in Figure 7 for CASE 3-S1, and in Figure 8 for CASE 3-S2. In both cases, the gravity sedimentation velocity shown in Table 5 is given as initial velocity of the particles. In CASE 3-S1, the air flow is induced by the outlet jet

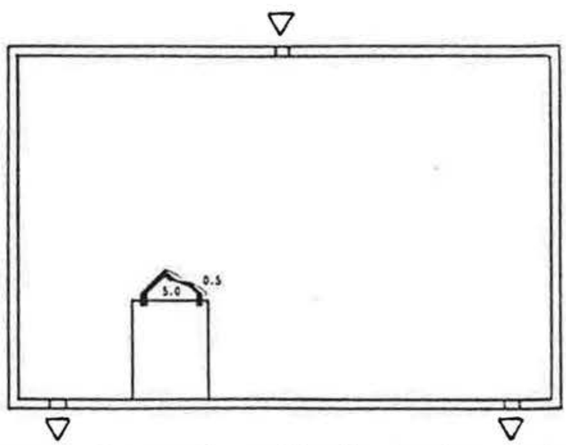


Figure 7 Contaminant distribution by numerical simulation (CASE 2 S2)

over upper portion of the obstacle and forms vortex. The particles are caught in the vortex, diffused, and sucked into the inlet. In CASE 3-S2, gravity sedimentation is superior to diffusion, and no diffusion occurs.

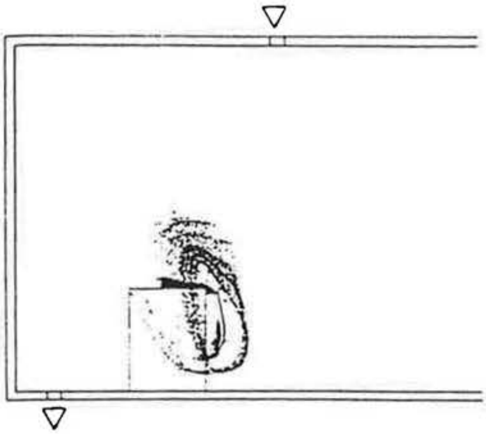


Figure 8 Contaminant distribution by numerical simulation (CASE 3 S1)

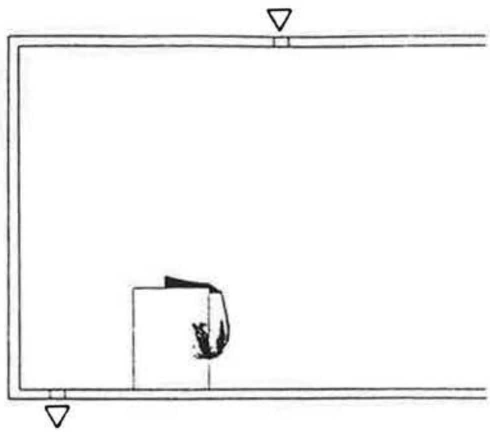


Figure 9 Contaminant distribution by numerical simulation (CASE 3 S2)

7. DISCUSSION

Table 5 shows ventilation efficiency index, in which room average concentration obtained from CASE 1-S2, CASE 2-S1 and CASE 2-S2 is standardize by instantaneous uniform diffusion and defined. When comparison is made between CASE 1-S2 where passive contaminants are supposed to be present and CASE2-S1 where particle size is $0.5\mu m$ and gravity sedimentation occurs, there is no substantial difference in ventilation efficiency index. Because inlet concentration is 0 in CASE 2-S2, it is considered that most of the generated particles are not removed from the room and are deposited and piled on floor surface.

Table 5 Ventilation Efficiency Index

CASE	CASE1-S2	CASE2-S1	CASE2-S2
Ventilation Efficiency Index	0.2200	0.2196	0.0008

8. CONCLUSION

The diffusion property of airborne particles was evaluated by numerical simulation in the case where gravity sedimentation occurs. The results were as follows:

(1) Even when gravity sedimentation is considered, the diffusion property was almost the same as in the simulation where passive contaminants were supposed to exist. In case particle size was as large as 100 μm, the airborne particles did not diffuse from the room almost at all and were deposited and piled on floor surface. Thus, room concentration distribution shows entirely different aspect.

(2) When weighted average velocity of wind velocity obtained by numerical simulation, diffusion velocity given by random number, and flow resistance associated with density difference between particle and fluid are taken into account, numerical simulation of airborne particle diffusion is effective for identifying the behavior of particles, but it is necessary to make some improvements in order to quantitatively determine the diffusion property of the airborne particles.

NOMENCLATURE

C_μ、C_1、C_2	= empirical constants in k-ε turbulence model
C	= mean contaminant concentration
h	= length from the solid wall surface to the center of the adjacent fluid cell
k	= turbulence kinetic energy
P	= mean pressure
ε	= turbulence dissipation rate
κ	= von Karman constant, 0.4
ρ	= fluid density
ν	= molecular kinematic viscosity
ν_t	= eddy kinematic viscosity
X_P	= position of particle in X direction
Y_P	= position of particle in Y direction
Z_P	= position of particle in Z direction
U_P	= moving velocity of particle in X direction
V_P	= moving velocity of particle in Y direction
W_P	= moving velocity of particle in Y direction
Δt	= time step
B_{max}	= rate of change movable by diffusion
η_1	= rate of change defined by random number
U_f	= average diffusion velocity in X direction
V_f	= average diffusion velocity in Y direction
W_f	= average diffusion velocity in Z direction

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