International Journal of the Physical Sciences Vol. 5(14), pp. 2150-2160, 4 November, 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

The effect of air supply and air exhaust locations on particle restraint and removal in a laboratory utilizing a Lagrangian particle-tracking method

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Accepted 18 August, 2010

The effect of air supply and air exhaust locations on the efficiency of restraining particles from entering the laboratory and the efficiency of particle removal from the laboratory were investigated by simulating the flow conditions, accompanied by a Lagrangian particle-tracking method to calculate the trajectories of the particles in the laboratory. Three cases with air supplied from different locations in the laboratory were used to investigate the restraint and removal effects in the study. The results indicate that for the case with air supplied from the air supply located on the ceiling near the door, the efficiency of restraining particles from entering the laboratory is the best among the three cases. However, for the particle removal efficiency, the case with the air supplied from the air supply located on the ceiling in the center of the laboratory possesses the best removal performance. For the case with air supplied from the air supply located on the ceiling far away from the door, the particle restraint and removal efficiencies are not obvious. By tracing and calculating the trajectories of micro-particles in time, the particle restraint and removal effects can be explicitly indicated by calculating the amount of particles that enter or leave the laboratory.

Key words: Particle, air supply, air exhaust, Lagrangian, restraint, removal effects.

INRODUCTION

Due to the increasing number of people spending most of their time in an indoor environment, indoor air quality (IAQ) and the prediction of indoor pollution levels have become more important subjects for health risks. With science and technology developing, the semiconductor, aerospace, electro-optical, medicine and precision-manufacture industries, among others want to precisely control any kind of pollution in their working spaces. Ventilation of indoor space may have serious influence on the precision of experimental results or the manufacture of products. Unsuitable ventilation can even change the risk level of surgery in an operation room. In an indoor environment, particles are regarded as pollutant sources. Particle deposition may damage the human body and equipment. Therefore, the behavior of pollutant particles and the design of ventilation systems must be further evaluated. A proper ventilation system can not only restrain the pollutant particles from entering the indoor space but also remove the pollutant particles from that space efficiently.

Over the past few years, using ventilation systems to

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Nomenclature: $\vec{V}$,Flow velocity; $\vec{V}_p$,particle velocity; p , pressure; k ,turbulent kinetic energy; ε , dissipation; ρ , fluid density; ρ_p, particle density; μ , fluid viscosity; μ_t, eddy viscosity; G_k, production rate of kinetic energy; m_p, particle mass; g, gravity; Re, Reynold number ; x_p, y_p, z_p, particle displacement ; A_p , particle cross-sectional area; C_D , drag coefficient; $C_{1\varepsilon}, C_{2\varepsilon}, \sigma_k, \sigma_\varepsilon, C_\mu$ constants of turbulent modeling.

remove pollution has been investigated by some researchers who studied the mean deposition velocity and the mean deposition rate of particles in the indoor environments. These velocities concern the indoor particle concentration and explain the predominant role of indoor particle pollution, subjects that are useful and suitable for study and analysis of indoor deposited particles (Abadie et al., 2001; Howard-Reed et al., 2003; Bouilly and Limam, 2005; He et al., 2005). Sippola and Nazaroff (2003) measured the particle deposition on the floors, walls and ceilings of experimental duct surfaces and these experimental results have been applied to understanding particle exposure evaluations. Lai (2002), Zhao et al. (2004) and Chen et al. (2006) investigated the particle deposition and particle distribution indoors with numerical methods and the numerical results were compared with experimentally measured data. It was shown that the particle deposition velocity varies under different indoor environments in their results. Loomans and Lemaire (2002), Zhang and Chen (2006) and Narayanan et al. (2003) studied the problem of the Euler and Lagrange approaches to calculate the particle contaminant distribution in a room using numerical simulation. They used a CFD program with a Lagrangian particle-tracking method to predict the particle dispersion and concentration distribution in ventilated rooms. Sippola and Nazaroff (2004) measured the particle deposition rates on the ceiling, walls and the floor in steel ducts. The deposition rate on the floor is much greater than the deposition rates on walls or on the ceiling. Gao and Niu (2007) used the drift-flux model to predict the distribution of particle concentration in the isothermal flow. It was shown that the larger the particle size, the lower the human exposure. Nazaroff (2004) and Zhao and Wu (2007) investigated some factors that can affect particle deposition in indoor environments. They indicated that as the particle size grows larger, the particle deposition velocity first grows smaller and then becomes larger. The deposited particle flux is very different for different particle spatial distributions. The influence of the particle dispersion characteristics was investigated by many scholars (Chow et al., 2006; Zhao and Guan, 2007; Yongson et al., 2007). They indicated that the factors of particle sizes, air supply volume and ventilation modes have significant influence on particle dispersion in personalized ventilated rooms. Memarzadeh and Jiang (2000) and Qian et al. (2008) used ventilation systems in hospital rooms to reduce the risk of airborne transmissible diseases. Cases with high exhaust grilles vent out more particles than low exhaust systems for the particle release points considered in low to medium air changes per hour (ACH) values.

Most of the studies investigated the distribution of pollution in an indoor space by calculating the distribution of the gaseous concentration to simulate the dispersion and deposition of pollutant particles inside an indoor space. For smaller pollutant particles, the distribution of the pollution is similar to the distribution of the gaseous concentration inside the indoor space. However, for larger pollutant particles, due to the gravitational effects on the particles, the dispersion and deposition of the particles cannot be directly simulated by calculating the distribution of the gaseous concentration. For larger pollutant particles, the materials and the sizes of the particles can seriously affect the distribution of the pollutant particles. These effects cannot be investigated by directly solving the mass transport equation and calculating the distribution of the gaseous concentration. In this study, a Lagrangian particle-tracking method, which solves the particle motion equation, was used to analyze the particle dispersion and deposition in a laboratory with a negative pressure gradient in order to investigate the effects of air supply locations on the rates of restraining particles from entering the laboratory and the rates of particle removal from the laboratory. Generally, the Lagrangian method may be ensure statistically stable results. And the Lagrangian method is attractive if interests are in the particle dispersion.

PHYSICAL MODEL

Geometry of the physical model

This study investigated the particle restraint and removal effects under the influence of different locations of the air supply in a laboratory. The physical model used in the study possesses a front room and a laboratory as shown in Figure 1. Between the front room and the laboratory, there is a door for incoming and outgoing researchers. The width and height of the door are 1 and 2.2 m, respectively. In the front room, there is an air supply and an air exhaust. The length and width of air supply and air exhaust in the front room are0.6 and 0.1 m, respectively. The length and width of the air supplies in the laboratory are1.6 and 0.6 m, respectively. The length and width of the air exhausts in the laboratory are1.2 and 0.4 m, respectively.

The particles are release from the air supply of the front room to simulate the pollution distribution in the rooms. The values of the physical parameters in the study are an air density of 1.225 kg/m^3, a viscosity of 1.789 × 10^{-5} kg/ms, a particle diameter of 10 µm, and a particle density of1550 kg/m^3. The geometry of the physical model shown in Figure 1 has realistic dimensions of a laboratory similar to the national laboratory animal center in Taiwan. The door opening and closing sequence and the corresponding period are shown in Figure 2. During period I (from t= 0 to 240 s), the particles were ejected from the air supply of the front room and were uniformly distributed over the front room. During period II (from t = 240 to 270 s), the door was opened for 30 s. Then, the door was closed during period III (from t = 270 to 300 s). During period IV (from t = 300 to 360 s) and period V

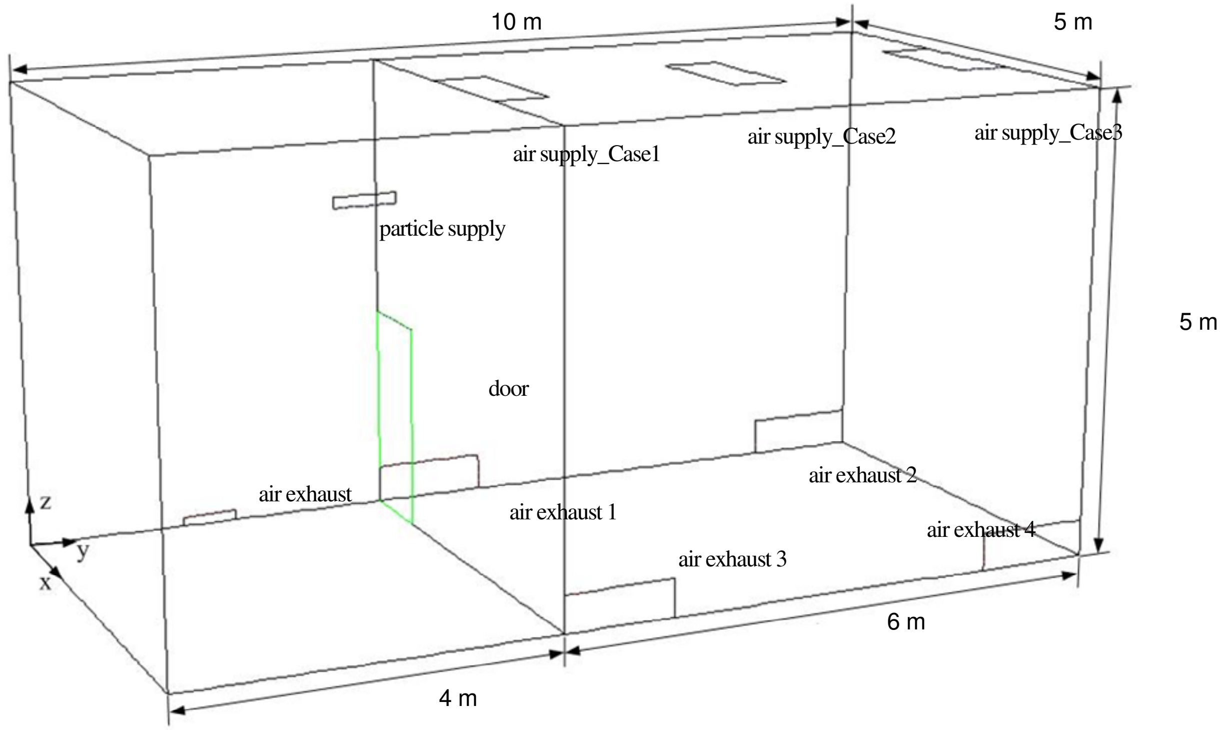

Figure 1. Geometry of the physical model.

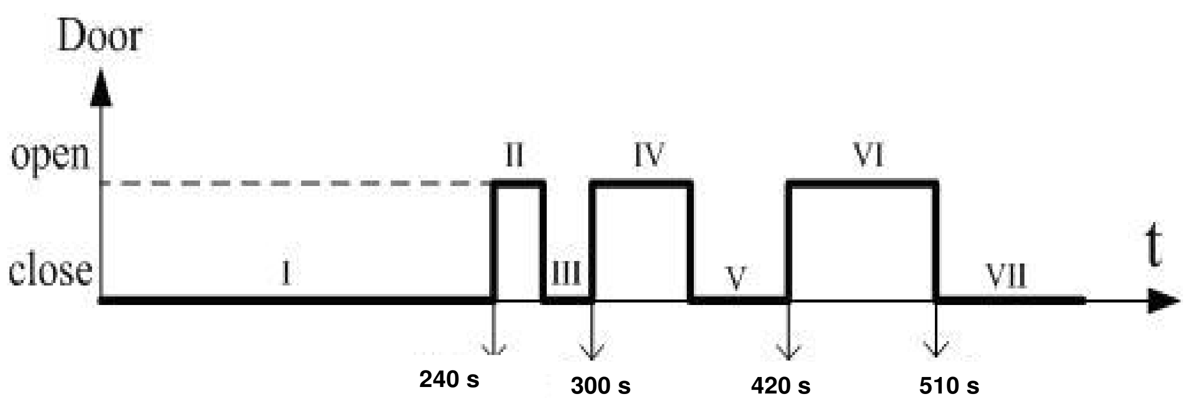

Figure 2. The door opening and closing sequence and the corresponding period.

(from t = 360 to 420 s), the door was respectively reopened and closed again. During period VI (from t = 420 to 510 s), the door was reopened for 90 s and at t= 510 s the door was closed again one more.

ASSUMPTION OF THE PHYSICAL MODEL

In order to simplify the physical characteristics considered in this study, the following assumptions are made:

1. The fluid in the front room and laboratory is incompressible.
2. There is no heat source in the physical domain. The temperature and buoyancy effects can be neglected, but the gravity on the pollutant particles is considered.
3. The equipment in the front room and the laboratory do not affect the airflow in the physical domain.
4. The door between the front room and the laboratory is airtight. The air cannot leak out from the door while the door is closed.

In order to investigate the influence of the air supply locations on the particle restraint and removal effects, three cases where the air moves from the different air supply to the laboratory were investigated in this study. In Case 1, the air is supplied to the laboratory from the air supply on the ceiling very close to the door.

In Case 2, the air is supplied from the air supply on the ceiling in the center of the laboratory. In Case 3, the air is supplied from the air supply on the ceiling far away from the door; all cases are as shown in Figure 1. Due to the character of the flow conditions within the physical domain, a $k-\omega$ turbulent model was used in the simulation. The governing equations used in this study are listed as follows:

Continuity equation:

$$\nabla \cdot \vec{V} = 0 \qquad (1)$$

Momentum equation:

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\mu}\nabla^2 \cdot \vec{V} + \vec{g} \qquad (2)$$

Standard $k-\omega$ turbulent kinematic energy equation:

$$\frac{\partial}{\partial t}(\rho k) + \nabla(\rho k\vec{V}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k - \rho\varepsilon \qquad (3)$$

Dissipation equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla(\rho\varepsilon\vec{V}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (4)$$

Particle motion equation:

$$m_p\frac{d\vec{V}_p}{dt} = \frac{1}{2}C_D A_p \rho_p(\vec{V}-\vec{V}_p)\sqrt{(\vec{V}-\vec{V}_p)\cdot(\vec{V}-\vec{V}_p)} + m_p\nabla g \qquad (5)$$

Where $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, and

$$\begin{cases} C_D = \frac{24}{Re}\left(1+\frac{3}{16}Re\right)^{0.5}, Re \le 1000 \\ C_D = 0.44 \quad ,Re > 1000 \end{cases}$$

In this paper, the boundary conditions of the physical model are as follows:

1. At each air exhaust, the boundary condition of $\partial p/\partial n = 0$ was used, where n is a unit normal vector to the surface of each air exhaust. The gauge pressures of air exhaust in the front room and air exhausts in the laboratory were 0 and -15 pa, respectively. This pressure difference caused negative pressure gradients to exist between the laboratory and the ambient environment and between the front room and the laboratory. The negative pressure gradient between the laboratory and the ambient environment could prevent pollution infiltration and the pressure gradient between the front room and the laboratory caused the air to pass through the door and flow into the laboratory while the door was open.
2. The no-slip boundary condition was applied to the surface of the door and the walls of the rooms.
3. The slip grid boundary condition was applied to the door while the door was opening.
4. The air velocity from the air supply in the front room is 0.5 m/s and the air velocity from the air supply in the laboratory is 0.54 m/s. These flow velocities can result in12 ACH (air changes per hour).
5. The particles were released from the air supply in the front room. The mass flow rate of the particles was 6×10^{-13}kg/s.

RESULTS AND DISCUSSION

This study investigated the restraint efficiency for the particles entering the laboratory and the removal efficiency of the particles from the laboratory under the influence of the different air supply locations and the door open and close periods. Due to lower air pressure in the laboratory in comparison with that in the front room, when the door was open, some particles in the front room were brought into the laboratory by the airstream flowing from the front room to the laboratory. The amount of particles passing through the door was affected by the air flow conditions, which were dominated by the locations of the air supply and air exhaust in the laboratory. Otherwise, the particles existing in the laboratory could also be removed from the laboratory by the air exhausts installed in the four corners of the laboratory. The amount of particles that could be removed from the laboratory was also dependent on the air flow conditions in the laboratory. Based on these reasons, sequential and alternating door opening and closing sequences were applied to investigate the amount of particles brought into the laboratory and removed from the laboratory, respectively, under the influence of different locations of the air supply.

The flowing state of the airflow

Three different cases with the air supplied from different air supply locations were used to investigate the particle restraint and removal efficiency under the influence of different air supply locations. The distributions of particles and the flow conditions of the airflow in the physical domain when the door was open or closed are shown in Figures 3a and b. In case 1, while the door was closed, the air is supplied from the air supply near the door on the ceiling and a jet flow moving from the air supply on the ceiling to the ground was formed near the front wall. When the air hit the ground, the air was induced to move either in the x- or y-direction. The air moving in the y-direction formed a large recirculation, rotating in the counter-clockwise direction and almost occupied the space between the front wall and the rear wall. However, the air moving in the x-direction formed two circulations moving from the jet flow to the left and right walls, as shown in Figure 3a. In Case 1, while the door was open, most of the particles just entering the laboratory through the door could be removed by air exhaust 1 through the air circulation moving from the jet flow to the right wall, as shown in Figure 3b. The rest of the particles were blown

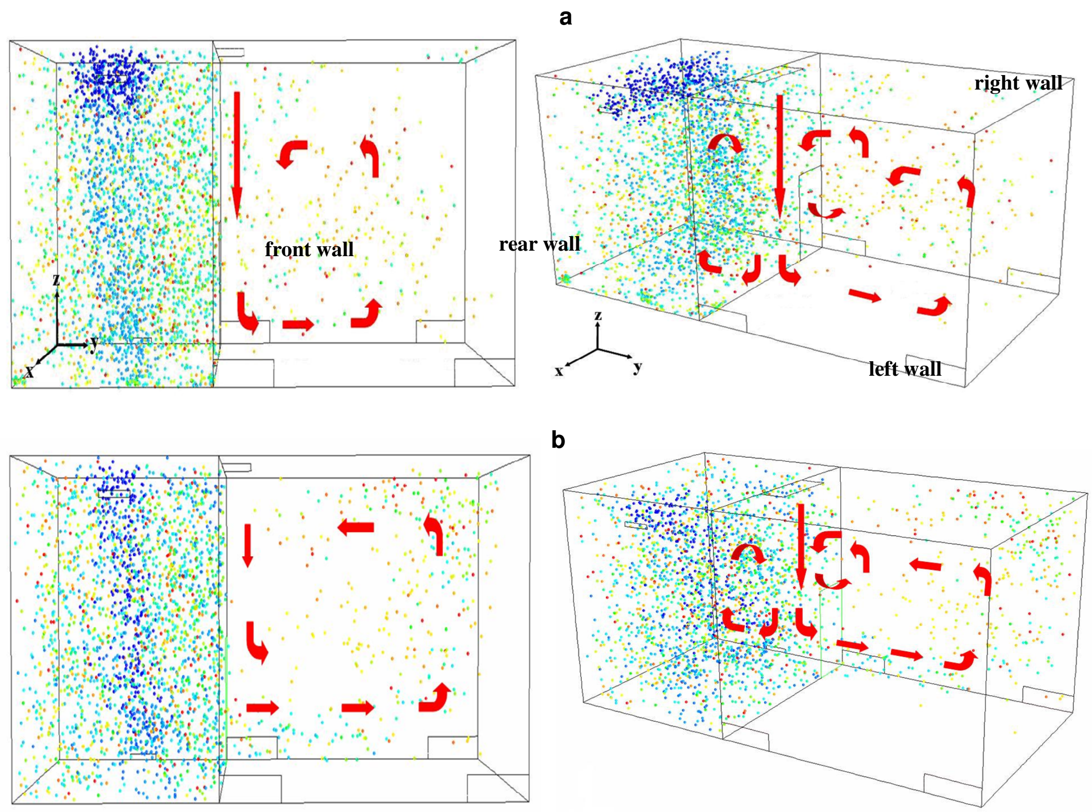

Figure 3. The distributions of particles and the airflow while the door is (a) closed and (b) opened in Case 1.

down to the ground of the laboratory and moved with the large recirculation traveling from the front wall to the rear wall. Then, the particles gradually flew up with the counter-clockwise rotating recirculation and even reached the ceiling of the laboratory. As a result, the particle removal effect from the air exhausts in the corners was not obvious. Otherwise, the removal efficiency of particles while the door was open was better than that while the door was closed because most of the particles just entering the laboratory through the door can be removed by air exhaust 1.

In Case 2, the air was supplied from the air supply in the center of the laboratory on the ceiling and a jet flow moving from the air supply on the ceiling to the ground was formed in the center of the laboratory. The distributions of particles and the flow conditions in the physical domain while the door was opened or closed are shown in Figures 4a and b. When the air hits the ground, the air was induced to symmetrically move in radial directions and formed symmetrical circulations rotating in the counter-clockwise direction moving from the jet flow to the surrounding walls as shown in Figure 4. In Case 2, while the door was opened, due to lack of horizontal rotating circulation moving in the x-direction near the door, the particle removal effect through air exhaust 1 was worse than that in Case 1. The rest of the particles were gradually blown upwards with the symmetrical circulations and gradually disperse to fill the entire space of the laboratory. While the door was closed, the particles could move with the airflow in the laboratory and be effectively removed by the four air exhausts in the corners in comparison with those in case 1. In other words, the removal efficiency of particles in Case 2 is much better than that in Case 1 while the door is closed.

The flow conditions in Case 3 are similar to the flow conditions in case 1, but the two flow conditions are symmetrical to the vertical cross section in the center of the laboratory. The distributions of particles and the flow conditions in the physical domain while the door was open or closed are shown in Figures 5a and b. In Case 3, while the door was open, the direction of movement of the large recirculation in the laboratory was opposite to that of the airflow passing through the door. This phenomenon led the particles just entering the laboratory to be pushed upwards and move towards the rear wall with the recirculation. As a result, the removal efficiency of particles from air exhaust 1 was also worse than that in Case 1. While the door was closed, although the particles could spread efficiently inside the laboratory, it was hard for the airflow to carry them to be removed by the air exhausts. In other words, the removal efficiency of particles in Case 3 was worse than that in Case 2 while

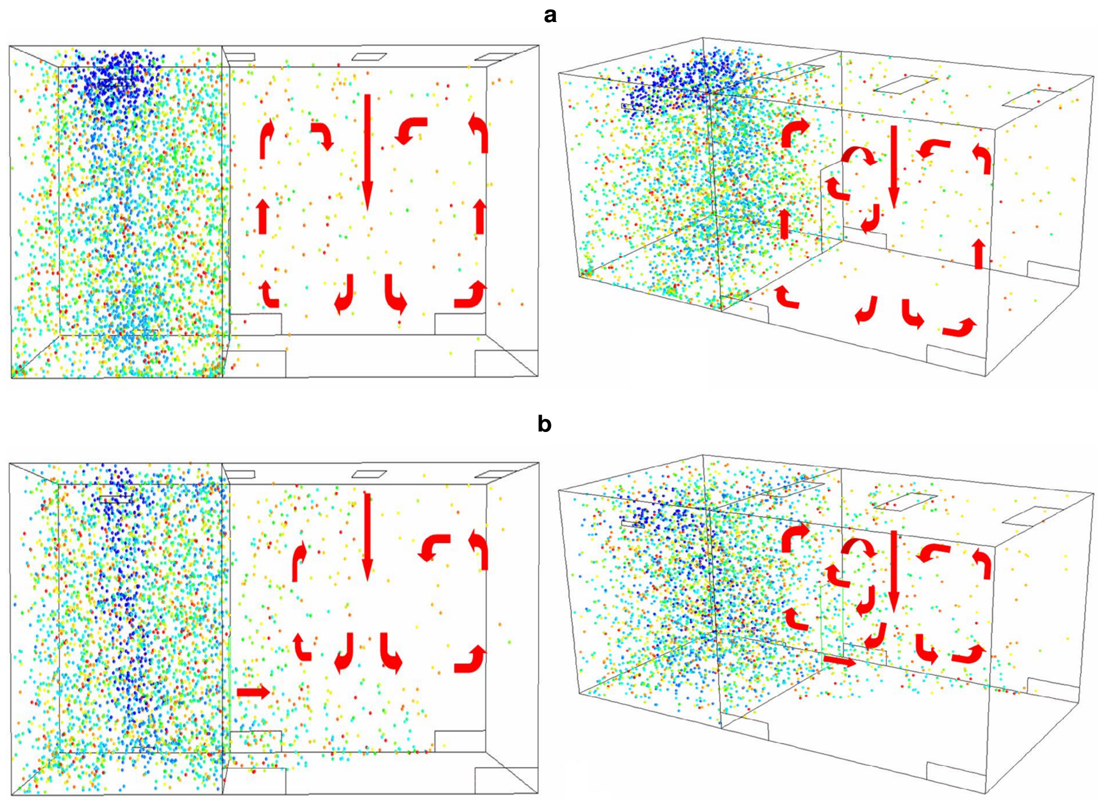

Figure 4. The distributions of particles and the airflow while the door is (a) closed and (b) opened in Case 2.

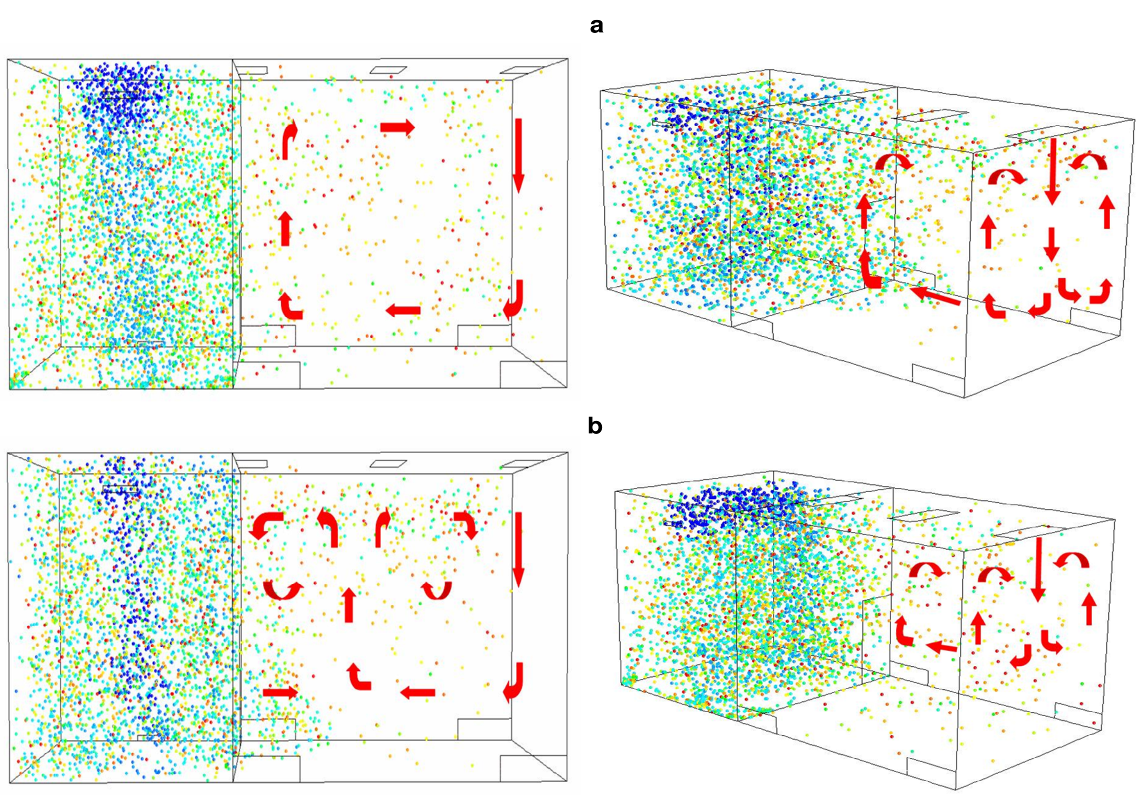

Figure 5. The distributions of particles and the airflow while the door is (a) closed and (b) opened in Case 3.

Table 1. The statistics of the restraint rate.

Period	Time (s)	Amount of particles passing through the door N_p			Amount of particles in the front room N_f			Restrained rate (%) R_{res}		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
I	0 - 240	0	0	0	2386	2261	2413	100.0	100.0	100.0
II	240 - 270	218	211	321	2673	2524	2702	91.84	91.64	88.12
III	270 - 300	0	0	0	2904	2772	2937	100.0	100.0	100.0
IV	300 - 360	267	331	411	3228	3287	3445	91.73	89.93	88.07
V	360 - 420	0	0	0	3881	3788	3927	100.0	100.0	100.0
VI	420 - 510	671	816	741	4467	4685	4111	84.98	82.58	81.98
VII	510 - 600	0	0	0	5280	5252	5299	100.0	100.0	100.0
	Total	1176	1358	1473	5280	5252	5299	77.73	74.14	72.20

the door was closed.

The effect of airflow in the laboratory on the restraint rate of particles

The restraint rate of particles (R_{res} %) is defined as|(1-N_p/N_f) × 100, where N_p is the amount of particles passing through the door during the door opening period and N_f is the amount of particles in the front room at the initial of the door opening period. The restraint rate can be used to evaluate the possibility of the particles remaining in the front room. A high restraint rate indicates that the possibility of particles in the front room entering the laboratory is low. The statistics of the restraint rates for the three cases are listed in Table 1. From the table, it can be seen that while the door was open in period II, IV and VI, the corresponding restraint rate of R_{res} Case 1 was the best among the three cases. The reason is that the jet flow supplied from the air supply near the door has an air curtain effect, which can obstruct the particles in the front room from entering the laboratory. However, in Case 3, the air was supplied from the air supply far away from the door and the flow intensity of the resultant large recirculation near the door was much weaker than that in Case 1. As a result, the corresponding restraint rate R_{res} of Case 3 was the smallest among the three cases.

In the complete process, in Cases 1, 2 and 3, the total N_f are 5280, 5252 and 5299; the total N_p are 1176, 1358 and 1473 and the total R_{res} are 77.73, 74.14 and 72.20%, respectively. The comparative diagram of the restraint rates of particles in the three cases is shown in Figure 6.

The effect of airflow in the laboratory on the removal rate of particles

The remove rate of particles (R_{res} %) is defined as N_r/N_f) × 100, where N_r is the amount of particles removed during the door opening period and N_f is the amount of particles in the laboratory at the initial of the door opening period. The statistics of the removal rates for the three cases are listed in Table 2. From the table, it can be seen that while the door was closed, the particle removal rate in Case 2 was the best among the three cases. However, while the door was open, the particle removal rate in Case 1 had the best performance among the three cases. During the period while the door was closed, most of the particles were carried to disperse to the ceiling by the large recirculation in the laboratory in Cases 1 and 3. Thus, the amount of particles removed from the air exhausts in the corners was not large in the two cases. In Case 2, the particles could be easily carried to fill the space in the laboratory by the radially symmetric distributed circulations in the laboratory. Thus, more particles could be removed from the air exhausts in the corners and the particle removal rate in Case 2 was the best during this period. However, during the period while the door was open, in Case 1, the particles just passing through the door to enter the laboratory could be easily removed through exhaust 1 by the horizontal circulation near the right wall. Thus, the particle removal performance in case 1 was the best during these periods. In Case 3, the particles just entering the laboratory tend to be carried to move upwards to the ceiling by the large recirculation in the laboratory. Thus,

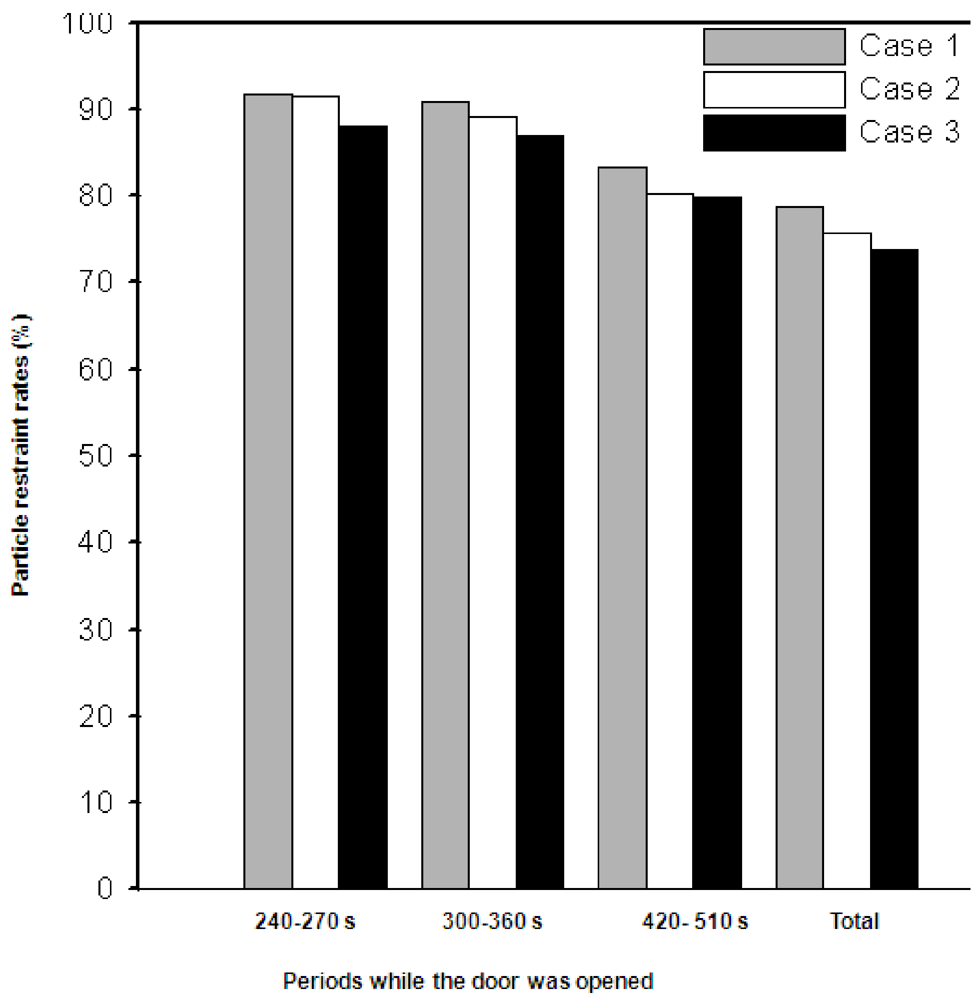

Figure 6. The comparison of restraint rates of particles in the three cases.

Table 2. The statistics of the removal rate.

Period	Time (s)	Amount of removed particles N_r			Amount of the particles in the laboratory N_l			Removal rate (%) R_{rem}		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
I	0 - 240	0	0	0	0	0	0	0.00	0.00	0.00
II	240 - 270	104	75	131	218	211	321	43.70	35.33	40.81
III	270 - 300	19	29	41	134	136	190	14.18	21.32	21.58
IV	300 - 360	206	198	173	382	438	560	53.93	45.21	30.89
V	360 - 420	65	92	121	176	240	387	36.93	38.33	31.27
VI	420 - 510	411	469	457	782	964	1007	52.56	48.65	45.38
VII	510 - 600	96	260	116	371	495	550	25.88	52.53	21.09
	Total	901	1123	1039	1176	1358	1473	76.62	82.70	70.54

the amount of particles to be removed from the air exhausts in the corners was the smallest and the particle removal rate was also the smallest among the cases.

In the complete process, in Cases 1, 2 and 3, the total N_f are 1176, 1358 and 1473 and the total N_r are 901, 1123 and 1039 respectively. The corresponding total R_{rem} are 76.62 82.70 and 70.54% in the three cases, respectively. Case 2 possesses the best particle removal

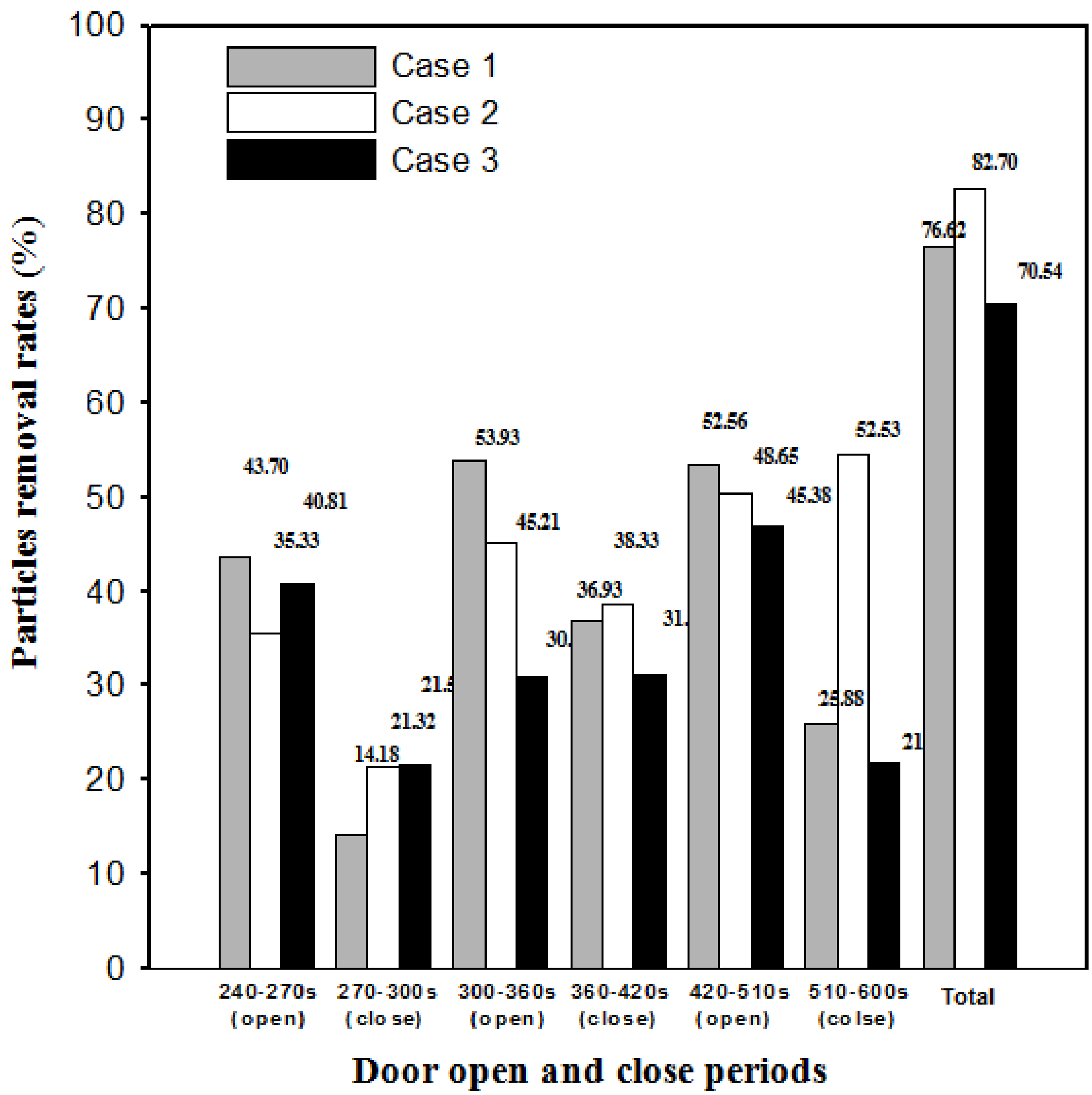

Figure 7. The comparison of removal rates of particles in the three cases.

performance. The comparative diagram of the removal rates of particle of the three cases is shown in Figure 7.

The particle removal effect by each air exhaust

Table 3 lists the statistics of the removal rate by each air exhaust. Due to the fact that air exhaust 1 was located very close to the door, the particles just passing through the door could be easily carried to be removed through Air exhaust 1 by the airflow in the laboratory. Thus, while the door was open, the amount of particles removed from Air exhaust 1 was greater than that from the other air exhausts. The rest of the particles were carried to move in the laboratory by the inertial force of the airflow from the front room passing through the door and the circulations in the laboratory. Thus, most of the rest of the particles were carried to move towards the rear wall of the laboratory and the amount of particles removed by Air exhaust 2 was greater than those removed from Air exhaust 3 and Air exhaust 4. Over time, the particles in the laboratory gradually diffused around the space in the laboratory, but only a few particles were removed by Exhausts 3 and 4 in Cases 2 and 3. In Case 2, only a few particles were removed by Exhausts 3 and 4. While the door was closed, the distribution of the particles was affected only by the airflow in the laboratory. During the entire process, most of the particles were distributed near the right wall. Consequently, most of the removed particles were removed by Air exhausts 1 and 2, especially by Air exhaust 1.

In the complete process, the total particles removed through Air exhausts 1, 2, 3 and 4 in Case 1 are 766 (65.14%), 126 (10.71%), 2 (0.17%) and 7 (0.60%); in

Table 3. The statistics of the removal of particles by each air exhaust.

Period	Time (s)	Amount of removed particles in Case 1				Amount of removed particles in Case 2				Amount of removed particles in Case 3			
		Air exhaust				Air exhaust				Air exhaust			
		1	2	3	4	1	2	3	4	1	2	3	4
I	0 - 240	0	0	0	0	0	0	0	0	0	0	0	0
II	240 - 270	104	0	0	0	75	0	0	0	131	0	0	0
III	270 - 300	10	9	0	0	29	0	0	0	41	0	0	0
IV	300 - 360	188	18	0	0	197	1	0	0	159	14	0	0
V	360 - 420	50	15	0	0	73	18	1	0	105	16	0	0
VI	420 - 510	353	51	0	7	412	40	15	2	376	63	13	5
VII	510 - 600	61	33	2	0	188	63	9	0	59	41	3	13
	Total	766	126	2	7	974	122	25	2	871	134	16	18

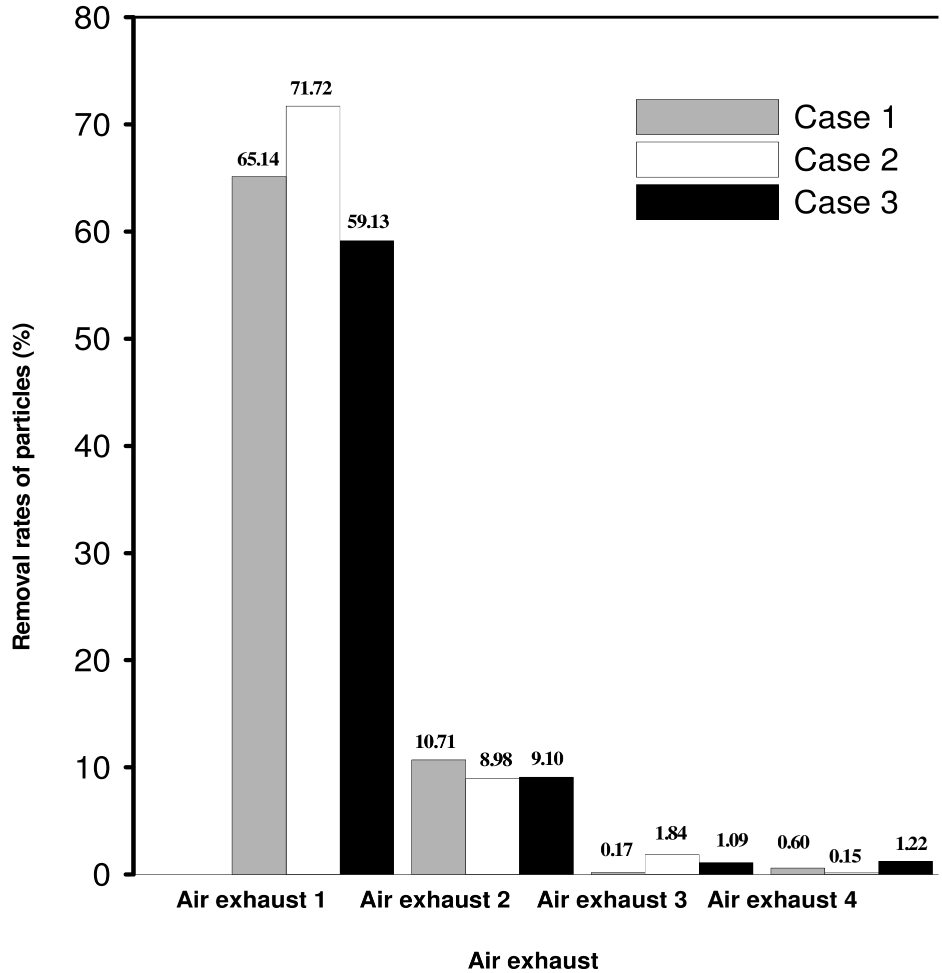

Figure 8. The comparison of removal rates in each case by each outlet.

Case 2, they are 974 (71.72%), 122 (8.98%), 25 (1.84%) and 2 (0.15%) and in Case 3, they are 871 (59.13%), 134 (9.10%), 16 (1.09%) and 18 (1.22%) respectively. Figure 8 is the comparative diagram of removal rates of each case by each air exhaust. According to these figures, it can be seen that most of the particles were removed through Air exhausts 1 and 2 in each case. The resulting flow condition in case 3 could make the particles in the laboratory efficiently diffuses around the room. Therefore, the amount of particles removed from air exhaust 3 and 4 in case 3 were greater than those in Cases 1 and 2. If the air is supplied from the air supply very near the door, Air exhausts 3 and 4 can be uninstalled. When the air is supplied from the air supply in the center of the lab, only Exhaust 4 can be neglected. Air exhausts 3 and 4 were still effective when the air was supplied from the air supply near the rear wall.

Conclusion

The effects of air supply and air exhaust locations on the efficiency of restraining particles from entering the laboratory and the efficiency of particle removal from the laboratory were investigated by simulating the flow conditions accompanied by a Lagrangian particle-tracking method. When the air supply is installed near the door on the ceiling, the supplied airflow may form an air curtain effect to obstruct the particles from entering the laboratory. Thus, the particle restraint rate is the best in this case. With the air supply gradually moved away from the door, the air curtain effect also gradually becomes weaker and the particle restraint rate also gradually decreases. When the air supply is installed in the center of the laboratory on the ceiling, airflow with radially symmetric distributed circulations is formed in the laboratory. The particles in the laboratory can be easily carried to uniformly fill the space in the laboratory by the airflow. Thus, the particles can also be more uniformly removed from the air exhausts in the corners in comparison with the other cases. In the case with the air supply located away from the door, both the particle removal and restraint effects are the worst among the cases. Utilizing the Lagrangian particle-tracking method can explicitly and precisely indicate the particle restraint and removal effects in the laboratory and the gravity effect of the particles can also be taken into account in the analysis. This research could be providing a reference in the design of the similar air condition environment.

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