Numerical Study of the Effect of Ventilation Pattern on Coarse, Fine, and Very Fine Particulate Matter Removal in Partitioned Indoor Environment

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ABSTRACT

An indoor size-dependent particulate matter (PM) transport approach is developed to investigate coarse PM (PM_{10}), fine PM ($PM_{2.5}$), and very fine PM (PM_1) removal behaviors in a ventilated partitioned indoor environment. The approach adopts the Eulerian large eddy simulation of turbulent flow and the Lagrangian particle trajectory tracking to solve the continuous airflow phase and the discrete particle phase, respectively. Model verification, including sensitivity tests of grid resolution and particle numbers, is conducted by comparison with the full-size experiments conducted previously. Good agreement with the measured mass concentrations is found. Numerical scenario simulations of the effect of ventilation patterns on PM removal are performed by using three common ventilation patterns (piston displacement, mixing, and cross-flow displacement ventilation) with a measured indoor PM_{10} profile in the Taipei metropolis as the initial condition. The temporal variations of suspended PM_{10} , $PM_{2.5}$, and PM_1 mass concentrations and particle removal mechanisms are discussed. The simulated results show that for all the of the three ventilation patterns, $PM_{2.5}$ and PM_1 are much more difficult to remove than PM_{10} . From the purpose of health protection for indoor occupants, it is not enough to only use the PM_{10} level as the indoor PM index. Indoor $PM_{2.5}$ and PM_1 levels should be also considered. Cross-flow displacement ventilation is more effective to remove all PM_{10} , $PM_{2.5}$, and PM_1 than

the other ventilation patterns. Displacement ventilation would result in more escaped particles and less deposited particles than mixing ventilation.

INTRODUCTION

Several epidemiological studies^{1–3} conducted in different countries have reported that particulate matter (PM) with aerodynamic diameter smaller than $10\ \mu\text{m}$ (PM_{10}), especially the finer particle fraction of PM_{10} , such as $PM_{2.5}$ ($<2.5\ \mu\text{m}$) and PM_1 ($<1\ \mu\text{m}$), can penetrate deep into the respiratory tract and, therefore, have a negative impact on human health condition, such as an increase in mortality¹ and asthma.² These findings attract more attention to the investigation of transport behavior of PM. Moreover, people nowadays spend a significant amount of their time in the indoor environment, such as homes, offices, and transport vehicles. The provision of low indoor PM levels in these indoor environments is, thus, crucial. However, in many large Asian cities, such as Taipei, Tokyo, Japan, and Hong Kong, People's Republic of China, because of the living habits and cooking style, indoor PM_{10} and $PM_{2.5}$ levels have been found to be approximately two to four times higher than those in homes in Western countries.⁴ As a result, there is a high demand in Asia for research on indoor air cleaning procedures against PM_{10} , $PM_{2.5}$, and PM_1 .

Natural or mechanical ventilation has played an essential role in diluting and removing pollutants emitted by indoor sources. Ventilation is an air mass transfer process by which clean outdoor air is brought to an indoor space and stale air is removed.⁵ This clean outdoor air is either mixed with the air already present in the indoor space to give mixing or dilution ventilation or is used to displace air in the indoor space to provide displacement or piston-flow ventilation. The above different ventilation patterns can provide different removal mechanisms of indoor PM. Thus, these ventilation patterns give characteristically different $PM_{10}/PM_{2.5}/PM_1$ removal ability and result in different PM suspension profiles. To minimize exposure to indoor PM, studies on investigating the effect of different ventilation patterns on PM_{10} , $PM_{2.5}$, and PM_1 removal are necessary.

Academic studies regarding PM transport in the indoor environment have been mostly carried out by experimental measurement.^{6–10} Generally, these experiments can provide useful knowledge of airflow and PM transport behavior on the sample points for given experimental

IMPLICATIONS

In many large cities in Asia, because of the living habits and cooking style, indoor PM_{10} and $PM_{2.5}$ levels were found to be approximately two to four times higher than those in the homes in Western countries. As a result, there is a high demand in Asia for investigating indoor air cleaning procedures against PM_{10} , $PM_{2.5}$, and PM_1 . This work developed a computational fluid dynamics technique to investigate indoor airflow patterns and $PM_{10}/PM_{2.5}/PM_1$ removal ability in ventilated partitioned buildings. A series of the numerical scenario simulations on the effect of the ventilation pattern on indoor PM transport was performed. The performance of $PM_{10}/PM_{2.5}/PM_1$ removal efficiency for each scenario was focused on, and the possible reasons for the difference between each other were further discussed. This information would help to provide a useful PM control strategy in partitioned buildings.

configurations. However, it is very difficult to simultaneously measure temporal and spatial information on airflow velocity distribution, PM size, and concentration distribution in the entire building for any specific physical configurations. Computational fluid dynamic (CFD) solutions are, thus, more adequate and convenient for analyzing airflow patterns and PM concentrations inside a building, because building configurations can be numerically made and modified as required within a short time.⁵ Most previous CFD work^{5,11,12} on indoor PM transport are mainly based on the Eulerian advection-diffusion approach, which takes less computing resources. This approach, neglecting the particulate nature of indoor particles, is only adequate for simulating gaseous pollutants or small, neutrally buoyant particles that exactly follow the fluid flow. Some studies^{13,14} have improved this approach by considering the gravity settling in the Eulerian calculation. However, these studies can still give partial particle characteristics. Recently, because of the extraordinary development of the computational facility, more and more CFD research^{15–19} has used the Lagrangian particle tracking approach to numerically examine indoor PM transport behavior, because tracking the continuous movement of particles through the Lagrangian scheme offers considerable particulate insight into the complex indoor airflow characteristics of partitioned buildings, such as various length-scale vortex structures and entry momentum jets. For example, Lu and Howarth¹⁶ and Lu et al.¹⁷ developed a pioneer CFD model to predict PM deposition and suspension in a two-zone chamber. Nevertheless, all of the aforementioned Lagrangian CFD works only focused on the transport behavior of single-size PM, which cannot be used to study removal behavior of size-dependent PM, such as PM₁₀, PM_{2.5}, and PM₁.

Because of the lack of academic works in using the CFD technique in modeling size-dependent PM removal behavior in a partitioned indoor environment in East Asia, the main objective of this study was to investigate indoor airflow patterns and PM₁₀/PM_{2.5}/PM₁ removal ability in ventilated partitioned buildings. A series of the numerical scenario simulations on the effect of a ventilation pattern on indoor PM transport are performed. The performance of PM₁₀/PM_{2.5}/PM₁ removal efficiency for each scenario is studied.

EXPERIMENTAL WORK

Indoor Size-Dependent PM Transport Model

The numerical methodology for simulating the transport patterns of size-dependent PMs in partitioned environment consists of two parts, namely the Eulerian indoor airflow model and the Lagrangian particle trajectory-tracking model. The airflow model, conducting the large eddy simulation (LES) of the Eulerian turbulent flows indoors, is solved first to obtain the velocity and pressure distributions. The result of the velocity distribution is then used in the Lagrangian particle-tracking model to calculate the velocities and trajectories of individual particles.

Eulerian Indoor Airflow Model

LES has recently received more and more attention and has been successfully applied to several natural ventilation problems.²⁰ A fully developed turbulent flow contains eddies of

many length scales. In the LES procedure, small eddies are filtered out, and large eddies are solved numerically by computing the filtered equations. The influence of small eddies that are filtered out cannot be neglected and leads to the subgrid-scale Reynolds stress.²¹ In the present study, the Smagorinsky subgrid-scale model²² is adopted in the LES procedure. The filtered continuity equation and momentum equation in the LES are listed below:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

and

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where the bar “—” represents spatial filtering, $\bar{u}_i$ is the component of filtered instantaneous fluid velocity in the x_i direction, $\bar{p}$ is fluid pressure, ρ is fluid density, ν is fluid kinematic viscosity, and $\tau_{ij} [= -2(C_s \Delta)^2 (\bar{S}_{ij} \bar{S}_{ij})^{1/2}]$ represents the Smagorinsky subgrid-scale Reynolds stresses.²² In τ_{ij} , $\bar{S}_{ij}$ is fluid strain rate, and $\Delta = (\Delta x_i \Delta x_j \Delta x_k)^{1/3}$ is filtered grid width in three dimensions. C_s , a Smagorinsky constant and usually between 0.1 and 0.2,²³ is 0.15 in the present study. The other numerical details can be found in Chang et al.²⁴ It should be noted that because the LES produces time-dependent solutions, the time-averaged velocities ($\bar{u}_i$) can be obtained by statistical analysis of the instantaneous velocities $\bar{u}_i$ according to $\bar{u}_i = (\bar{u}_i) + \bar{u}_i'$ where $\bar{u}_i'$ denotes the turbulent components of the filtered velocities. In addition, the LES is primarily valid for turbulent core flows (i.e., the flow in the regions somewhat far from walls).²¹ To deal with boundary layer flows in partitioned environment, the wall function model near the solid boundary²⁵ and the nonslip boundary on the wall are adopted.

Lagrangian Particle Tracking Model

For the purpose of investigating the transport behaviors of PM₁₀/PM_{2.5}/PM₁, the PM size that the authors focused on is particle aerodynamic diameter <10 μm . Under such a particle size range, time series of instantaneous particle positions can be obtained by numerical integration of the following three-dimensional differential equations, which include the gravitational force, F_G , the drag force, F_D , the Saffman lift force, F_S , and the Brownian motion force, F_B .²⁶

$$\begin{aligned} \frac{1}{6} \pi \rho_p d_p^3 \frac{du_i^p}{dt} &= F_G + F_D + F_S + F_B \\ &= \frac{1}{6} \pi d_p^3 (\rho_p - \rho) g_i \delta_{i3} - \frac{1}{6} \pi \rho_p d_p^3 \cdot \frac{1}{\tau} (u_i^p - \bar{u}_i) \\ &\quad - \frac{1}{6} \pi \rho_p d_p^3 \frac{5.188 \nu^{1/2} d_{ij}}{S d_p (d_{ik} d_{kl})^{1/4}} (u_i^p - \bar{u}_i) \\ &\quad + \frac{1}{6} \pi \rho_p d_p^3 G_i \sqrt{\frac{\pi S_0}{\Delta t}} \end{aligned} \quad (3)$$

Figure 1. Schematic of the two-zone building used by Lu et al.¹⁵

and

$$\frac{dx_i}{dt} = u_i^p \quad (4)$$

where $\bar{u}_i$ is filtered fluid velocity, u_i^p is particle velocity, ρ is fluid density, ρ_p is particle density, x_i is coordinate of particles, t is time, d_p is particle diameter, S is the density ratio between particle and adjacent fluid, δ is unit delta function, τ is relaxation time of the particle,²⁷ and d_{ij} is $[(u_{i,j} + u_{j,i})/2]$ is the deformation rate tensor. The Brownian motion force is modeled as Gaussian white noise

random process, where G_i is zero-mean, unit variance independent Gaussian random number, Δt is particle time step, and S_0 is spectral intensity.²⁶ The numerical details of solving eqs 3 and 4 and the assumptions of the numerical simulation can be found in Chang et al.²⁴

Two kinds of particle boundary condition are used in the present study. Trap boundary means that once a particle touches it, the particle is trapped, and particle tracking process would cease. Walls, floors, and ceilings in the building are established as the trap boundary. Outflow boundary is used for all of the building exterior outlets, such as windows and doors. When a particle passes through the outflow boundary, the particle tracking is terminated.

Grid and Particle Sensitivity Analysis and Model Validation

To validate the accuracy of the numerical scenario simulations for different ventilation patterns, the present numerical model is verified by the reliable measured indoor mass concentrations of a three-dimensional full-scale two-zone building in a paper by Lu et al.¹⁵ As shown in Figure 1, the size of the building is $L(x) \times W(y) \times H(z) = 5 \text{ m} \times 3 \text{ m} \times 2.4 \text{ m}$. The building is divided into two zones by a partition located in the middle of the building length.

Figure 2. Grid sensitivity analysis of airflow computation along the central-line of (a) zone I and (b) zone II. H = building height; U_{in} = inlet velocity.

Table 1. Particle parameters for model verification with an air change rate of 12.71 hr⁻¹.

Particle Size dp (μm)	No. of Total Sample Particles = 800		No. of Total Sample Particles = 2400		No. of Total Sample Particles = 6000		No. of Real Particles Carried
	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	
1	118.17	160	39.39	480	15.76	1200	2.60E + 11
2	118.17	160	39.39	480	15.76	1200	3.26E + 10
3	118.17	160	39.39	480	15.76	1200	9.66E + 09
4	118.17	160	39.39	480	15.76	1200	4.08E + 09
5	118.17	160	39.39	480	15.76	1200	2.09E + 09

Notes: No. of real particles carried = the number of real particles released in the full-size experiment; No. of sample particles = the number of particles used for the numerical simulation; Particle mass carried by each sample particle = the ratio of the initial total particle mass released in the experiment to No. of sample particles.

An internal opening is on the center line of the building. All of the walls and openings of the building are 0.15 m thick and have the same temperature as the ambient air. The airflow in the building is isothermal. Outdoor fresh air enters zone I of the building through the inlet opening (1 m $\times$ 0.5 m) at an upper level. The outlet opening (1 m $\times$ 0.5 m) is situated at a low level of zone II. A total of six cases have been conducted in their experiment, representing six ventilation rates with three internal openings. All of the six cases are used to verify the present numerical model, and two of them (cases 4 and 5) are demonstrated.

Case 4 uses an internal opening with a size of 0.3 m $\times$ 0.7 m and a ventilation rate of 12.71 air changes per hour (ACH, hr⁻¹), whereas case 5 has a 0.95 m $\times$ 0.7 m internal opening and 9.22 ACH. The corresponding Reynolds numbers based on the height of the internal opening are 1400 and 1000, respectively. The size of the smoke particles used in the experiments equally ranges from 1 to 5 μm , with a density of 865 kg m⁻³. Particles are initially injected in zone I and uniformly distributed in zone I as the measurement starts.

Grid Convergence Analysis

Because computing resources are limited, the mesh size of the finite volume cells in the present study cannot be set to be zero. Numerical discretization errors are inevitable. It is important, therefore, before the model validation, to understand the magnitude of numerical discretization errors and ensure that a sufficiently fine grid is used to reduce the error to an acceptable value. To demonstrate

the grid convergence in the present study, four grid resolution tests (the numbers of nonuniform finite-volume cells are 10,000, 50,000, 100,000, and 200,000, respectively) are used to simulate the airflow field of the two-zone building in Figure 1 with 9.22 hr⁻¹. Figure 2 displays the dimensionless time-averaged velocities along the vertical centerlines of zone I and zone II. The results show that the solution is convergent when the grid numbers are >100,000. Therefore, the present study selects 100,000 grid cells as the numerical basis of the indoor airflow computation.

Particle Sensitivity Analysis and Model Validation

In the Lagrangian particle tracking process, the particle number or mass concentrations are generally derived from statistical analysis of the trajectories of the particles. The accuracy of using Lagrangian particle tracking method depends on the release of a statistically significant sample of particles. As a consequence, sensitivity analysis on the size of the particle sampling is performed in the next step. Lu et al.¹⁵ only used 800 particles in their simulation. In the present study, under the aforementioned 100,000 grid cells, three particle sample sizes (the numbers of sample particles are 800, 2400, and 6000) are used to simulate the temporal distributions of indoor mass concentration in the two-zone building. The initial positions of particles are uniformly distributed in zone I, with a sum of 800, 2400, and 6000 particle tracks, respectively. The total particle mass injected in zone I is specified according to the experimental data, and the particle

Table 2. Particle parameters for model verification with an air change rate of 9.22 hr⁻¹.

Particle Size dp (μm)	No. of Total Sample Particles = 800		No. of Total Sample Particles = 2400		No. of Total Sample Particles = 6000		No. of Real Particles Carried
	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	Particle Mass Carried by Each Sample Particle (μg)	No. of Sample Particles	
1	147.35	160	49.12	480	19.65	1200	3.25E + 11
2	147.35	160	49.12	480	19.65	1200	4.07E + 10
3	147.35	160	49.12	480	19.65	1200	1.20E + 10
4	147.35	160	49.12	480	19.65	1200	5.08E + 09
5	147.35	160	49.12	480	19.65	1200	2.60E + 09

mass is uniformly carried by each size group (see Tables 1 and 2 for details).

The numerical particle mass concentrations (C) in each zone at each tracking minute can be determined by using the following:

$$C = \frac{M_s}{V} \quad (5)$$

where M_s is the total mass of suspended particles, and V denotes the volume of the zone. Comparisons of the PM mass concentrations in both zones between the numerical simulations and the full-size experiments are shown in Figure 3. The results show that some discrepancies exist for the case releasing 800 particles. Good agreement of the temporal concentration distributions between the simulated and measured data in each zone can be found for the cases releasing 2400 and 6000 sample particles. The relative difference in the simulated results between the two cases is <10%. Thus, the present study chooses to release 2400 sample particles as the numerical basis of the mass concentration computation. In addition to cases 4 and 5 shown above, the other four cases conducted by Lu et al.¹⁵ have been also adopted to verify the present numerical model, which have demonstrated similar results.

Numerical Scenario Simulations

The indoor size-dependent PM transport model has been tested and validated in the previous section. It, thus, is used to conduct further similar numerical scenario simulations. To investigate $PM_{10}/PM_{2.5}/PM_1$ removal behaviors and suspension profiles in a partitioned indoor environment, the same two-zone building used previously is considered again. All of the openings are $0.8 \text{ m} \times 1.0 \text{ m}$ or $1.0 \text{ m} \times 0.8 \text{ m}$. The air change rate is reduced to 5 hr^{-1} , because natural or mechanical ventilation in an indoor environment rarely exceeds 7 hr^{-1} .⁵ The positions of inlet and outlet openings are modified in such a way that three major indoor ventilation patterns (piston displacement, mixing, and cross-flow displacement ventilation) are created. The airflow in the building is assumed 20°C isothermal. It should be noted that according to the building code requirements issued by the Construction and Planning Agency, Taiwan, the size of ventilation openings in a room cannot be <10% of the floor area. For other East Asian countries, Hong Kong and Japan also have the same or similar restriction of the minimum opening size on their own building codes. In the present study, the ratio of the size of the inlet/outlet opening to the floor area in each room is 10.6%, which fits the building code requirements. In addition, the present study uses an air change rate of 5 hr^{-1} , which is common in the Asian monsoon area. It is believed that an adequate inlet/outlet opening size together with a reasonable outdoor-to-indoor air change rate can result in a typical ventilation condition in East Asia.

As shown in Figure 4, piston-like flow, one commonly used in displacement ventilation, represents an unimpeded straightforward airflow pattern between the incoming and outgoing airstreams, which pass through

Figure 3. Comparison of the simulated particle concentrations with measured data: (a) $ACH = 12.71 \text{ hr}^{-1}$ at zone I; (b) $ACH = 12.71 \text{ hr}^{-1}$ at zone II; (c) $ACH = 9.22 \text{ hr}^{-1}$ at zone I; and (d) $ACH = 9.22 \text{ hr}^{-1}$ at zone II.

Figure 4. Schematic of the three ventilation patterns and particle trajectories: (a) piston displacement ventilation, (b) mixing ventilation, and (c) cross-flow displacement ventilation.

the interior opening of the building and replace the particle-laden air that is already present. The spatial concentration of pollutant within the space is, therefore, expected to be nonuniform. Mixing ventilation appears to mix outdoor clean air with indoor polluted air and to dilute indoor pollutants. If mixing is perfect, the pollutant concentration is uniform throughout the space. Cross-flow ventilation occurs where part of the airflow paths between the incoming and outgoing air streams is hindered in such a way that airflow paths are crossed. Indoor pollutant is both replaced and mixed by the incoming outdoor air.

An indoor PM_{10} profile was measured in the Taipei Metropolis in 2005 by using a portable laser dust monitor (Series 1100, Grimm Labortechnik GmbH & Co. KG). The PM_{10} profile follows a lognormal distribution with a geometric mean diameter (GMD) of $1.09 \mu m$ and a geometric standard deviation (GSD) of 1.27. In the profile, the PM_{10} ,

$PM_{2.5}$, and PM_1 mass concentrations are $48.00 \mu g^{-3}$, $24.28 \mu g^{-3}$, and $13.94 \mu g^{-3}$, respectively. This profile is divided into 10 size groups in terms of aerodynamic diameters ranging from 0.5 to $10 \mu m$ (see Table 3). In each size group, the PM concentration is assumed to be a constant.

Numerical scenario simulations of the three ventilation patterns having $5-hr^{-1}$ air change rate with the above PM_{10} profile as the initial condition are carried out. At the beginning of particle release, particles are distributed uniformly in both zone I and zone II. Particles move after clean outdoor air flowing into the building, resulting in redistribution of the PM concentration. The PM concentration is calculated from the simulated results of ensemble-averaged particle trajectories. Three widely used particle size indexes of PM_{10} , $PM_{2.5}$, and PM_1 are determined by numerically integrating the appropriately weighted moment of the 10 respective particle size groups in Table 3.

In the LES approach, the smallest mesh used herein is 0.05 m, which is near the wall region and is only one order higher than the Kolmogorov length scale. After carrying out the LES for several flow-through times to ensure that the final time-averaged results are independent of the initial conditions, the time-averaged velocities and turbulent statistics are collected over 150 sec with a temporal resolution of $\Delta t = 0.003$ sec. For the Lagrangian particle tracking process, the time step that the authors use is one order smaller than the relaxation time of particles to ensure the numerical accuracy. Six-hundred ensembles are undertaken to obtain the ensemble-averaged trajectories for each sample particle at each time step.²⁴

RESULTS AND DISCUSSION

Indoor Airflow Pattern

By means of the LES procedure and turbulent statistics, the instantaneous and time-average airflow velocities of the 100,000 nonuniform grids are determined. The simulated results of the time-average airflow field at the center line plane for the three ventilation patterns are shown in Figure 5. It can be seen from Figure 5 that the location of the inlet and outlet openings has significant impact on indoor airflow pattern and ventilation effectiveness inside of the building. In the case of piston displacement ventilation (Figure 5a), a strong incoming jet from the windward side moves straightforwardly through the interior opening and finally flows toward the leeward side just like a piston flow. Between the incoming jet and the ceiling, two large but weak counterclockwise circulating eddies

Table 3. Particle parameters of the numerical scenario simulations.

Size Range	(1) 0.5–1 μm	(2) 1–2 μm	(3) 2–3 μm	(4) 3–4 μm	(5) 4–5 μm	(6) 5–6 μm	(7) 6–7 μm	(8) 7–8 μm	(9) 8–9 μm	(10) 9–10 μm
Average diameter (μm)	1	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
Particle mass carried by each sample particle (μg)	1.038	0.542	0.489	0.327	0.269	0.255	0.235	0.216	0.175	0.183
No. of sample particles	480	480	480	480	480	480	480	480	480	480
No. of real particles carried	$9.52E + 08$	$1.47E + 08$	$2.87E + 07$	$6.99E + 06$	$2.71E + 06$	$1.41E + 06$	$7.84E + 05$	$4.69E + 05$	$2.61E + 05$	$1.96E + 05$

Notes: PM_1 mass concentration = [total mass of (1)]/zone volume; $PM_{2.5}$ mass concentration = [total mass of (1)+(2)+0.5*(3)]/zone volume; PM_{10} mass concentration = [total mass of (1)+(2)+(3)+...+(10)]/zone volume.

Figure 5. The time-averaged velocity distributions for (a) piston displacement ventilation, (b) mixing ventilation, and (c) cross-flow displacement ventilation.

located in both zones cannot bring too much outdoor air. The airflow velocities in the piston flow are much stronger than those in the areas of circulating eddies. As a result, good outdoor-to-indoor airflow exchange is only observed in the jet area, and the rest of the building space is poorly ventilated.

In Figure 5b, the airflow paths of mixing ventilation can be classified into three patterns. Most inflow turns its direction and flows upward, moves counterclockwise, and

then exits to the outlet in zone I. This phenomenon is referred to as the shortcut effect. Part of the inflow directly flows into zone II and gets trapped inside. Therefore, a weak circulating region is observed in zone II. There is still some airflow in zone II flowing back to zone I through the upper part of the interior opening. In addition, part of airflow in zone I is impeded in front of the interior opening. It is believed that this phenomenon results from the relatively high pressure in zone II, because zone II is single-sidedly ventilated. For this reason, it is found that the velocity magnitude in zone II is much weaker than that in zone I. The airflow patterns in Figure 5b indicate that it is not apt for fresh air to flow into zone II. It is important to note that the indoor partition will destroy the mixing process in zone II. However, this is inevitable for any partitioned indoor environment.

In Figure 5c, for cross-flow displacement ventilation, the inlet flow reaches the partition and then is forced to make a turn. Because of the blockage effect of the indoor partition, part of airflow in zone I flows downward to form a small clockwise vortex in front of the partition, and part of it moves upward to zone II through the partition opening. In zone II, the incoming airflow jet passes through the upper area and then bends downward toward the outlet. Two strong circulating regions can be seen in the upper part of zone I and the lower part of zone II. Because of the geometric arrangement of the inflow, outflow, and interior opening, cross-flow displacement ventilation provides wider ventilated areas than the other two ventilation patterns. Therefore, all of the space in the building receives more sufficient airflow exchange.

Suspended PM₁₀, PM_{2.5}, and PM₁ Mass Concentrations

Figure 6 displays the temporal variations of the mass concentrations of PM₁₀, PM_{2.5}, and PM₁ in each zone of the building for the three ventilation patterns. In the case of cross-flow displacement ventilation, indoor particles are driven through the incoming airflow from the upwind zone toward the downwind zone. Indoor particles inside of zone I can be blown out effectively. Zone II takes migrated particles from zone I together with their original particles, resulting in increasing PM levels in the first few minutes and then decreasing PM concentrations for the rest of the time. All of the PM₁₀, PM_{2.5}, and PM₁ mass concentrations in both zones are substantially reduced because of their large ventilated areas. For piston displacement ventilation, the effective outdoor-to-indoor airflow exchange only occurs in the narrow piston area so that good PM removal can be seen only in this area. The rest of the building space is poorly ventilated, resulting in poor PM removal. Because of the small ventilated areas, all of the PM₁₀, PM_{2.5}, and PM₁ mass concentrations in zone I and zone II are slowly decreased compared with the other two ventilation patterns. For mixing ventilation, because of its shortcut effect caused by the geometric arrangement of the openings, PM₁₀, PM_{2.5}, and PM₁ mass concentrations in zone I can be effectively reduced to ~86%, 79%, and 72%, respectively, of the initial concentrations after minute 30 of the particle tracking time. However, PM levels in zone II are not accessible to be lowered down, because zone II is single-sidedly ventilated with high

Figure 6. The temporal variations of the mass concentrations of (a) PM_{10} , (b) $\text{PM}_{2.5}$, and (c) PM_1 in each zone of the building for the three ventilation patterns.

pressure inside, in which particles are not easily moved in and out.

PM_{10} , $\text{PM}_{2.5}$, and PM_1 Removal Efficiency

Based on the simulated results in Figure 6, PM levels are spatially averaged for the entire building to obtain the building-averaged removal efficiencies of PM_{10} , $\text{PM}_{2.5}$, and PM_1 at minute 30 of the tracking time. The removal efficiencies of PM_{10} , $\text{PM}_{2.5}$, and PM_1 for piston displacement, mixing, and cross-flow displacement ventilations are 62%, 35%, and

31%; 70%, 59%, and 50%; and 85%, 72%, and 64%, respectively. Among the three ventilation patterns, cross-flow displacement ventilation is considered as the most effective way to remove PM_{10} , $\text{PM}_{2.5}$, and PM_1 . The reason is that cross-flow provides a wider range of ventilated area to transport and remove indoor particles than the other ventilation patterns.

The above results also reveal that coarse particles ($>2.5 \mu\text{m}$) are easier to remove from the building than fine particles ($<2.5 \mu\text{m}$). This can be explained because

Figure 7. The cumulative mass fractions of particle deposition, migration and escape in each zone for the three ventilation patterns: (a) piston displacement ventilation at Zone I, (b) piston displacement ventilation at Zone II, (c) mixing ventilation at Zone I, (d) mixing ventilation at Zone II, (e) cross-flow displacement ventilation at Zone I, and (f) cross-flow displacement ventilation at Zone II.

coarse particles can maintain their velocities for longer time duration because of larger inertia and relaxation time. This phenomenon, together with their stronger gravitational settling, causes coarse particles to move easily from one circulation region to another. Contrarily, $PM_{2.5}$ and PM_1 are easily trapped in eddies indoors, because fine particles have smaller inertia and relaxation time. Thus, fine particles are easily influenced by the surrounding complex indoor airflows in a partitioned environment such as different length-scale vortex structures, entry jets, and circulating flows, which can be clearly seen in the present study.

PM Removal Mechanism

Indoor polluted particles are redistributed after clean outdoor air flowing into the building. During the redistribution process, particles would suspend in the air, migrate to

other zones, settle down to floors, inertially impact or intercept on walls or ceilings, or escape out of the building, which can all be thoroughly simulated by the present model. The above particle transport mechanisms are usually classified into four parts, that is, suspension, migration (carried to the neighboring zone by airflow), deposition, and escape.^{24,27} Deposition and escape are regarded as particle removal mechanisms.²⁷ Figure 7 displays the cumulative mass fractions of particle deposition, migration, and escape in each zone for the three ventilation patterns. In Figure 7, a and b, particle migration and escape are almost as large as particle deposition, because the useful outdoor-to-indoor airflow exchange only occurs in the narrow piston area. For mixing ventilation, as the shortcut effect enables particles to be conveniently blown out, the cumulative mass fraction of escaped particles

Figure 8. Particle size distributions at minute 30 of the tracking time for the three ventilation patterns at (a) zone I and (b) zone II.

in zone I is much more than that of deposited and migrated particles (Figure 7c). Because of the poor ventilation in zone II, most of the particles in zone II are removed by deposition (Figure 7d). Particle migration between zone I and zone II is rare. In Figure 7, e and f, cross-flow displacement ventilation provides wider and stronger ventilated areas so that the majority of the particles in zone I can be carried to zone II. Finally, the particles escape from the building through the outlet.

It can be also seen in Figure 7 that escape is the major particle removal mechanism for displacement ventilation. The relative importance between escape and deposition is determined by their ventilation effectiveness. The cumulative mass fraction of escaped particles is approximately eight times that of deposited particles for cross-flow displacement ventilation. On the contrary, particle escape is only 17% larger than particle deposition for piston displacement ventilation. In the case of mixing ventilation, particle deposition is more important than escape.

Particle Size Distribution

The analysis of particle size distribution is one of the key elements to evaluate the hazards on human health.²⁸ Figure 8 compares the initial particle size distribution and the particle size distribution at minute 30 in each zone for the three ventilation patterns. The GMD and the GSD of the particle size profiles for piston displacement, mixing,

and cross-flow displacement ventilations are 1.04 μm and 1.14; 1.01 μm and 1.07; and 1.00 μm and 1.04, respectively, in zone I and 1.05 μm and 1.17; 1.04 μm and 1.16; and 1.01 μm and 1.06, respectively, in zone II. It is demonstrated in Figure 8 that cross-flow displacement ventilation, the most effective way to remove PM, has the lowest values of GMD and GSD, whereas piston displacement ventilation has the highest values of GMD and GSD. Therefore, all of the three ventilation patterns lead to the shift of the particle size distribution toward smaller size and less deviation, and a ventilation pattern with higher PM removal ability would result in a swifter shift.

In addition, it can be inferred from the above results that, because of the shift of the particle size distribution toward a smaller size, PM_{10} is much easier to be removed from the building than finer particles like $\text{PM}_{2.5}$ and PM_1 for the three ventilation patterns. However, getting rid of coarse particles cannot guarantee a healthy indoor environment, because the remaining high levels of indoor PM_1 and $\text{PM}_{2.5}$ would penetrate deep into the respiratory tract and have a negative impact on indoor occupants. One would expect that it is not enough to use the PM_{10} level as the only indoor PM index. Thus, for the purpose of health protection for indoor occupants, indoor $\text{PM}_{2.5}$ and PM_1 levels should be also considered. Finally, it is important to note that, because of the measurement limitation of the portable laser dust monitor used herein, the

present study considers diameters ranging only from 0.5 to 10 μm . In Table 3, there is only one size group for particle diameter $<1 \mu\text{m}$, which limits the investigation of the temporal variation of fine particles. Further study on the transport behavior of fine and ultra fine particles is needed.

CONCLUSIONS

A series of numerical scenario simulations on the effect of a ventilation pattern on indoor PM removal efficiency in a partitioned environment was conducted. Based on the simulated results, the present research has led to the following conclusions. First, the present numerical model provides a convenient and useful tool to investigate indoor airflow patterns and PM_{10} , $\text{PM}_{2.5}$, and PM_1 transport behaviors in a partitioned building. Second, although the ventilation rate of the building is the same, the location of the inlet and outlet openings has a significant impact on ventilation effectiveness and PM removal efficiency inside of the building. Among the three ventilation patterns, cross-flow displacement ventilation provides wider ventilated areas than the other ventilation patterns. It is considered as the most effective way to remove all of the PM_{10} , $\text{PM}_{2.5}$, and PM_1 . Third, for the three ventilation patterns, PM_{10} is much easier to remove than finer particles like $\text{PM}_{2.5}$ and PM_1 . However, getting rid of coarse particles cannot guarantee a healthy indoor environment, because the remaining high levels of PM_1 and $\text{PM}_{2.5}$ would penetrate deep into the respiratory tract and have a negative impact on indoor occupants. For the purpose of health protection for indoor occupants, it is not enough to only use the PM_{10} level as the indoor PM index. Indoor $\text{PM}_{2.5}$ and PM_1 levels should be also considered. Fourth, displacement ventilation would result in more escaped particles and less deposited particles than mixing ventilation. Finally, particle transport is size dependent and is mainly affected by indoor airflow pattern and particle physical properties. A ventilation pattern having a higher particle removal efficiency would result in a swifter shift of the particle size distribution toward smaller size and less deviation.

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