

Multi-zone simulation of outdoor particle penetration and transport in a multi-story building

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Abstract

In areas with poor ambient air quality, indoor particle concentrations can be significantly affected by particulate matter originating outdoors. The indoor environments of multi-zone and multi-story buildings are affected differently by outdoor particles compared with single-family houses, because of the buildings' more complicated airflow characteristics. The objective of this study is to analyze outdoor particle penetration and transport, and their impact on indoor air, in a multi-zone and multi-story building using a CONTAMW simulation. For the airflow and particle transport analysis, the building leakage, penetration coefficients, and deposition rates were determined by on-site experiments. The results of airflow simulations for cold winters show that outdoor air infiltrates through the lower part of building and exfiltrates from the upper part. The results of the particle simulation also indicated that the airflow characteristics, combined with deposition rates, cause the lower floors of a multi-story building to be exposed to higher fine particle concentrations compared with the upper floors of the building. The study demonstrated that the CONTAMW simulation can be useful in analyzing the impact of outdoor particles on indoor environments through the identification of key particle transport parameters and validated airflow simulations.

Keywords

multi-zone simulation, outdoor particles, penetration, deposition, particle transport, multi-story building

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1 Introduction

Rapid development over the last two decades has caused a progressive deterioration in outdoor air quality in many developing countries (Abdul Rahim 2000). In particular, there has been an exponential increase in urbanization and industrialization over the last few decades in several East Asian countries, including China and Korea, leading to increases in air pollutant emissions (Lee et al. 1999). During Asian dust storm episodes, the outdoor PM₁₀ concentrations in Korea can increase more than four-fold compared with the concentrations before the storm episodes (Chun et al. 2001). According to the Seoul Air Quality Information, the

outdoor daily peak in PM₁₀ concentrations in 2015 reached above 700 µg/m³. Especially in cold winters, high daily average PM₁₀ concentrations of above 560 µg/m³ were observed in Seoul; these high concentrations are attributed to the use of combustion devices for heating. Governments and research institutes have made various efforts to reduce the risk of outdoor PM pollution in recent years.

Since many people spend a considerable amount of time indoors, indoor air quality, particularly in relation to particle pollution, has received significant attention from numerous researchers (Ligocki et al. 1993; Pope et al. 1995; Abt et al. 2000; Long et al. 2001; Wallace et al. 2003; Stephens 2015). Indoor particle concentrations are influenced by

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particles originating both indoors and outdoors. In areas with poor ambient air quality, the indoor particle concentration can be significantly affected by particulate matter originating outdoors (Chen and Li 2014). Particles infiltrate from outdoors through gaps in the building envelope, and through window and door frames, even when they are closed (Chao et al. 2003). Therefore, outdoor particles may have a lasting and significant impact on indoor environments.

A number of researchers have investigated the contribution of outdoor particles to indoor air quality, predominantly by measuring ratios of indoor to outdoor particle concentrations. (Alzona et al. 1979; Ligocki et al. 1993; Ozlaynak et al. 1996; Abt et al. 2000; Lee and Chang 2000; Long et al. 2001; Liu et al. 2003; Wallace et al. 2003; Cao et al. 2005; Kuo and Shen 2010; Chatoutsidou et al. 2015). These studies mainly focused on single family houses, and the investigations have suggested a strong relationship between outdoor and indoor particle concentrations. Unlike single family houses where a single zone assumption is usually made, multi-zone and multi-story buildings involve more complicated airflow characteristics, meaning that outdoor particles have a different effect on the indoor air quality. For example, in winter, when the outdoor particle concentration is generally high, outdoor air infiltrates through the building envelope at the lower floors of the building, and exfiltrates from the upper floors owing to the stack effect. Air pollutants can also spread from lower floors to upper floors due to the inter-floor airflow caused by the buoyancy force (Zhou and Deng 2014). This phenomenon results in a distinctive indoor particle concentration distribution within a building. Moreover, deposition loss in multi-zone buildings may lead to different outdoor particle effects on the indoor air depending on the building zone.

A few studies (Rim et al. 2013; Oh et al. 2015) have involved field measurements, and results postulated the relationships between outdoor and indoor particles in multi-zone and multi-story buildings. However, a full understanding of the impact of outdoor particles within the multi-zone and multi-story building is still lacking because of the limited number of air sampling locations. In practice, using a large number of particle sampling devices simultaneously is expensive and time-consuming (Ma et al. 2012). A careful computer simulation study with reliable inputs for key simulation parameters, such as the particle penetration coefficient and deposition rate, may be capable of providing comprehensive insights for understanding particle transport in multi-story buildings. The objective of this study is to analyze outdoor particle penetration and transport in a multi-zone and multi-story building, and their impact on indoor air. To this end, CONTAMW, a multi-zone airflow and contaminant transport analysis program, was used to predict size-resolved particle concentrations in each zone and on

each floor. Two key simulation parameters, the penetration coefficient and the deposition rate of size-resolved particles, were determined by field measurements for the reference building, and used for the simulation.

2 Multi-zone building simulation

2.1 Overview

To investigate the impact of outdoor particle penetration and transport in a multi-zone and multi-story building, the CONTAMW, which is a multi-zone airflow and contaminant transport analysis software package, was used. As particle transport is affected by a building's airflow, both the airflow and particle transport analyses were simultaneously considered in the simulation for a reference building. For the airflow simulation, the leakage data for the building components were measured using the typical blower door pressurization and depressurization method in compliance with ISO 9972 (ISO 2015a). To validate the airflow simulation, the pressure prediction results were compared with the measured pressure distribution in the reference building. For the particle transport analysis, the two key parameters, the penetration coefficients and deposition rates, were determined by field experiments. CONTAMW is capable of considering particle deposition loss in the inbuilt model, but does not provide a model for particle penetration. A modification to consider particle penetration, which is a function of airflow rates and penetration coefficients, was made in the CONTAMW model. A conceptual diagram of the simulation approach is illustrated in Fig. 1.

2.2 Simulation tool

CONTAMW, a multi-zone airflow and contaminant transport analysis software package, was used for this study. The program has been widely used in research focusing on various contaminant transport issues. Recently, several researchers (Lai 2004; Sohn et al. 2007; Demetriou and Khalifa 2009; Liu and Zhai 2009; Lim et al. 2011; Miller 2011; Dols et al. 2016) used CONTAMW to analyze aerosol transport issues, including not only airborne contaminants but also infectious bio-aerosols such as Severe Acute Respiratory Syndrome (SARS) and Influenza A (H1N1). Detailed governing equations for CONTAMW can be found in (Walton 1989) and (Walton and Dols 2005).

For this study, CONTAMW provides the airflow prediction results depending on the zone leakage data, and also the indoor particle transport load in the interzonal airflow. However, particle penetration through a building envelope and deposition indoors could not be directly considered in CONTAMW. To incorporate these two key

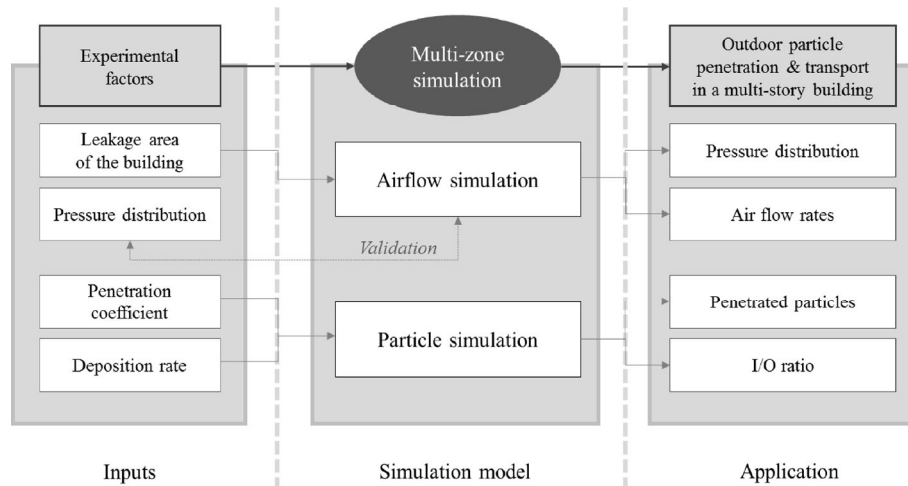


Fig. 1 Conceptual diagram of the simulation approach

parameters when predicting particle concentrations, the application of several input values in CONTAMW was modified.

CONTAMW calculates contaminant concentrations using the following equation:

$$\frac{dm_i^\alpha}{dt} = \sum_j F_{j \rightarrow i} (1 - \eta_j^\alpha) C_j^\alpha + G_i^\alpha + m_i \sum_\beta K^{\alpha, \beta} C_i^\beta - \sum_j F_{i \rightarrow j} C_i^\alpha - R_i^\alpha C_i^\alpha \quad (1)$$

where m_i^α is the mass of contaminant α in control volume i , $F_{j \rightarrow i}$ is the rate of air mass flow from control volume j to control volume i , η_j^α is the filter efficiency in the airflow path, C_j^α is the mass concentration of contaminant α in control volume j , G_i^α is contaminant α generation rate in control volume i , $K^{\alpha, \beta}$ is the kinetic reaction coefficient in control volume i between contaminant α and contaminant β , C_i^β is the mass concentration of contaminant β in control volume i , $F_{i \rightarrow j}$ is the rate of air mass flow from control volume i to control volume j , C_i^α is the mass concentration of contaminant α in control volume i , and R_i^α is removal rate of contaminant α in control volume i .

In contrast to gaseous contaminants, losses from particle-laden flows may be caused by penetration through the building envelope and deposition on surfaces in the indoor environment. In this study, to employ the particle penetration concept, a filter efficiency term η_j^α was used as a substitute for the penetration coefficient in each envelope. In other words, each of the building’s walls was assumed to act as a filter by using a penetration coefficient as the value for the filter efficiency: $(1 - \eta_j^\alpha)$. The removal rate term R_i^α was also employed to model particle deposition indoors. Particle deposition was also represented as a sink element by choosing the deposition rate sink model in CONTAMW. In general,

it is difficult to initiate chemical reactions between particles and other contaminants indoors without the presence of a catalyst, so this study neglected the “chemical reactions” term.

2.3 Building description and simulation conditions

A 5-story office building, located in Seoul, Korea, was chosen as a reference building for this study. The building has multiple zones including office spaces, corridors, bathrooms, an elevator, and stairwell shafts. The typical floor plan and a section of the reference building are shown in Fig. 2. Each office space in the building consists of similar sets of the building envelope, interior finishing materials, and furnishings. A glass curtain wall system is installed over the entire exterior wall of the building. As the reference building was recently built (in 2013), the leakage characteristics for the entire wall are expected to be relatively uniform. The reference building is a relatively small office building with natural ventilation features throughout the office spaces above ground level. Mechanical ventilation systems are only equipped in the basement. The building’s vertical spaces, such as elevators and stairwell shafts, are located in the center and on the west side of this 5-story (with a 2-story basement) building. We assumed that infiltration of airflow and ambient particles can occur in the lower part of the building and be transported through the vertical spaces, especially in winter when the outdoor air quality is usually poor.

The simulation was conducted for a typical winter day between January and February, when the outdoor particle concentrations were notably high and the outdoor temperature was low, resulting in increased airflow between indoors-outdoors as well as inter-zonal airflows. The outdoor temperature was assumed to be -6.7°C , the relative humidity was set at 60%, and the external wind velocity was assumed to be 2 m/s. Measured data for the reference building

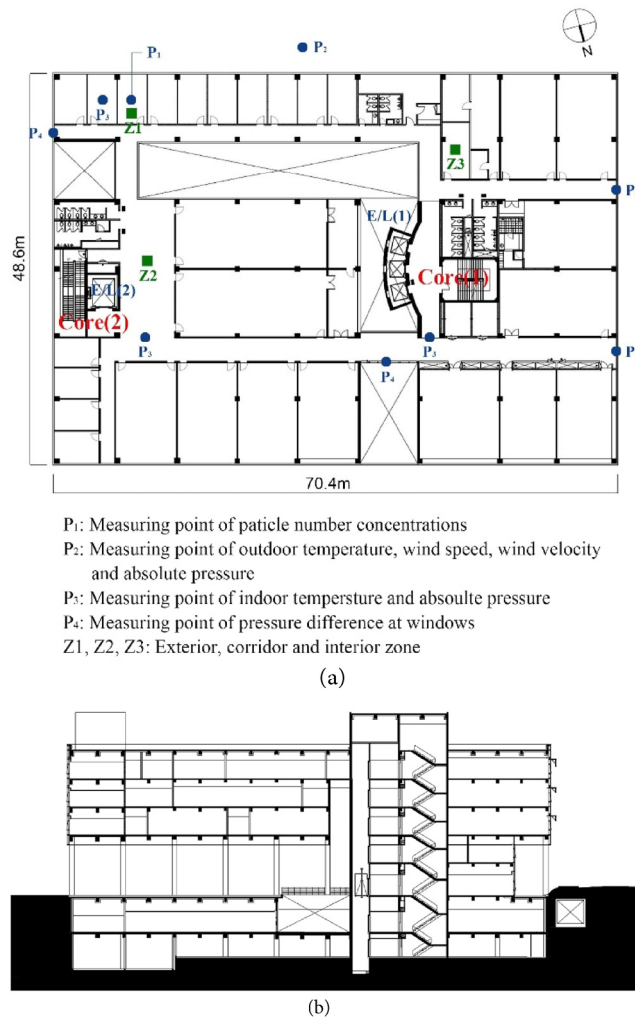


Fig. 2 Floor plan and section of the reference building: (a) typical floor plan; (b) Section

during a cold season were used as input variables, such as temperature and relative humidity, for the indoor environment. The simulation assumed that all openings, including windows and doors, were closed as people usually close the openings during winter.

Particle transport through buildings is a complex matter that depends on the nature of air movements. Particle penetration and transport are also affected by characteristics relating to particle diameter. Therefore, particles, which were defined as having a diameter of less than or equal to 10 μm , were sorted into six groups (0.3 μm , 0.5 μm , 1 μm , 3 μm , 5 μm , and 10 μm) in line with particle sizes based on ISO 14644-1 (ISO 2015b). In CONTAMW, the six different-sized outdoor particles were regarded as different contaminant species, having different input variables for penetration and deposition. Particle sources induced by human activities, office equipment, or other potential internal sources were disregarded in the indoor environment, in order to limit the investigation to the effect of outdoor particles on the indoor environment.

2.4 Acquisition of building leakage data and validation of airflow analysis

To acquire the building leakage area data necessary for the airflow and particle transport simulation, a typical blower door pressurization and depressurization test was utilized. The tested building components included exterior and interior walls, elevator doors, stairwell doors, lobby doors, and interior doors. The blower door equipment used in the test was the Retrotec 3101 blower door system (Retrotec, USA) with one fan. The maximum airflow rate is 4 m^3/s at 50 Pa and the measurement accuracy is $\pm 5\%$ for airflow rate. For validation of the airflow simulation, absolute outdoor minus indoor pressure difference profiles were measured in the reference building, and the pressure distribution predicted by the CONTAMW airflow simulation was compared with the field measurement results.

3 Key parameter identification for particle transport analysis

Two parameters are considered essential particle simulation input values: the penetration coefficient and deposition rate. The penetration coefficient is a dimensionless parameter defined as the fraction of particles that can penetrate indoors (Alzona et al. 1979; Tung et al. 1999; Chao et al. 2003). The deposition rate is the particle loss rate due to deposition, which is generated throughout the process whereby particles are transported and attached to surfaces (Elimelech et al. 1995). In this study, a field test on the reference building was conducted using the natural decay method to identify the particle size-resolved penetration coefficient and deposition rate; the obtained values were used as simulation parameters.

3.1 Natural decay method for estimation of the penetration coefficient and deposition rate

The determination of the penetration coefficient and deposition rate can be conducted using natural decay methods (Ozkaynak et al. 1996; Tung et al. 1999; Chao et al. 2003). The natural decay method is based on an experimental test where the natural decay of particle concentrations should be measured. The penetration coefficient and deposition rate were determined using the following equations. The indoor particle concentration level can be expressed by the following mass balance equation (Chao et al. 2003):

$$\frac{VdC_{in}(t)}{dt} = PQC_{out} - QC_{in}(t) - KC_{in}(t) + E(t) \quad (2)$$

where V is the effective volume of the room, C_{in} is the indoor particle concentration, P is the penetration coefficient, Q is

the air change rate, C_{out} is the outdoor particle concentration, K is the deposition rate on the wall, floor, and other surfaces, and $E(t)$ is the source generation rate inside the control volume.

Assuming that the measured room was unoccupied during the experiments and no specific indoor particle generation sources existed in the room, the term $E(t)$ can be neglected. All the parameters in Eq. (2) are known values obtained from field measurements except for the penetration coefficient P , and the deposition rate K . Assuming that the outdoor particle concentration and the air change rate were constant during the experiments, two terms, $PQC_{out}/(Q+K)$ and $(Q+K)$, can be regarded as constants. As a result, Eq. (3) describes the particle decay profile, and the two key parameters can be estimated by fitting the measured particle concentrations with the following equation.

$$C_{in} = \frac{PQC_{out}}{(Q+K)} + \left(C_{int} - \frac{PQC_{out}}{Q+K} \right) e^{-(Q+K)t} \quad (3)$$

where C_{int} is the initial indoor particle concentration.

3.2 Field measurement procedure

Four repetitions of the field measurements to acquire the key parameters were carried out in a typical room in the reference building in January and February, as shown in Fig. 3. Before the experiment, the test room was vacuumed, and the particle concentration level was increased to a relatively high level by opening windows to allow the inflow of outdoor particles. To achieve well-mixed conditions in the room, mixing fans were operated for an hour. After turning off the fans and closing the windows, the natural decay of the indoor particle number concentration, as well as the outdoor particle concentrations, were monitored by

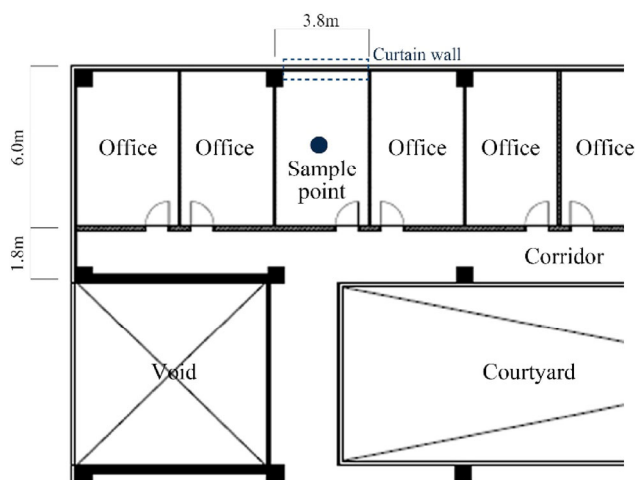


Fig. 3 Test room and sampling point for the key parameter identification

two identical optical particle counters (TSI 9306-v2, TSI, USA). The optical particle counter is capable of counting the 6 sizes of particles (0.3 μm , 0.5 μm , 1.0 μm , 3.0 μm , 5.0 μm and 10 μm) simultaneously at a flow rate of 2.83 L/min with $\pm 5\%$ accuracy. Samples of outdoor PM were taken in the center of the roof, while the indoor PM samples were taken 1 m away from the window and 1.2 m above the floor. Particle number concentrations were recorded every 10 minutes during the experiment periods.

At the same time, the tracer decay method, which uses a CO_2 monitor with a real time data logger (MCH-383SD, Lutron, USA), was used to estimate airflow exchange rates in the test room during the natural decay period. When all openings were closed, CO_2 gas was injected into the test room with a concentration above 1500 ppm. Indoor and outdoor CO_2 concentrations during the test period were recorded by identical CO_2 monitors, and were analyzed to compute the air exchange rates.

3.3 Determination of the penetration coefficient and deposition rate

The estimated penetration coefficient and deposition rates are shown in Fig. 4. The average values of the four repeated measurements are displayed. As shown in Fig. 4 (a), the highest penetration coefficient was 0.85 at 0.3 μm and the lowest penetration coefficient was 0.04 at 10 μm . It was observed that particles with larger diameters ($>1.0 \mu\text{m}$) tended to have lower penetration coefficients. Figure 4 (b) presents the deposition rate of size-resolved particles. Deposition rates ranged from 0.05 h^{-1} to 0.55 h^{-1} , and the highest deposition rate was found to be 0.55 h^{-1} at 10 μm . The coarse particles (3.0 μm , 5.0 μm , 10 μm) generally showed higher deposition rates than the fine particles. These penetration coefficients and deposition rates fall within similar ranges to values suggested by other researchers (Long et al. 2001; Williams et al. 2003; Chao et al. 2003). In their studies, penetration coefficients ranged from 0.72 to 0.79 for fine particles and from 0.58 to 0.48 for coarse particles, while deposition rates ranged from 0.12 h^{-1} to 0.42 h^{-1} for fine particles and from 0.37 h^{-1} to 0.55 h^{-1} for coarse particles.

4 Results

4.1 Airflow simulation results

4.1.1 Pressure distribution profiles

Figure 5 shows the predicted vertical pressure distribution of the reference building, and its validation results. The simulation results for the pressure distribution were compared with the measured pressure difference between the inside

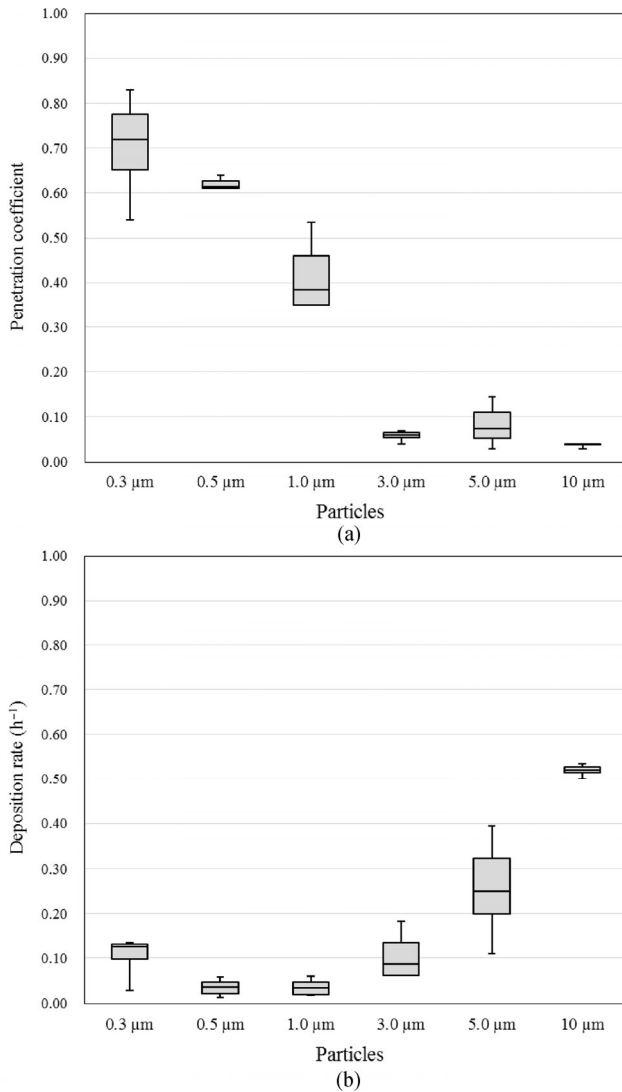


Fig. 4 Size-resolved penetration coefficients and deposition rates of particles, estimated in the test room: (a) penetration coefficients; (b) deposition rates

and outside of the building. Generally, good agreement was found between the simulated and measured values.

The pressure difference between the outside and inside was 10 Pa on the first floor. The pressure difference gradually decreased on the upper floors, as demonstrated by a pressure difference on the top floor of -5 Pa. In the simulated building, the neutral pressure level ($\Delta P = 0$) was approximately located at the 3rd floor. These pressure simulation results indicate that the outdoor air infiltrates into the lower level of building and exfiltrates from the upper level of the building, which is commonly known as the stack effect. Generally, it is known that the pressure difference between indoors and outdoors is ranged from 0 to 5 Pa normally applied to single family houses. The higher pressure difference of 10 Pa predicted on the first floor suggests that particle penetration, which is dependent on the pressure

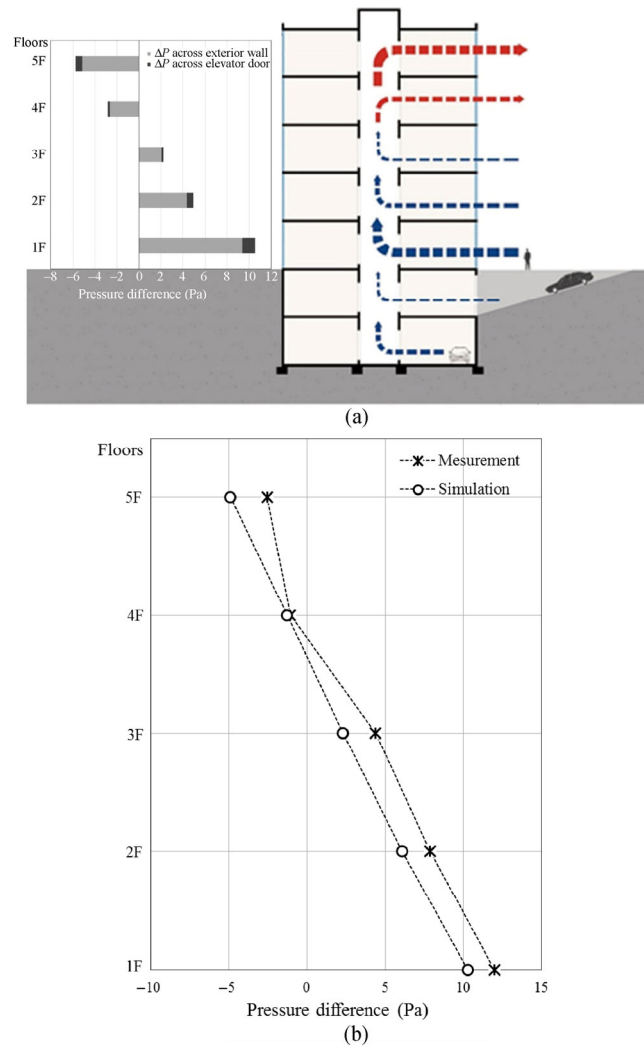


Fig. 5 The predicted vertical pressure distribution of the reference building and its validation: (a) predicted pressure distribution; (b) validation results

difference of the building envelop, would be higher on the lower floors of a multi-story building, especially when the stack effect occurs.

4.1.2 Airflow rates

Figure 6 shows the airflow rate of three representative zones (“exterior,” “corridor,” and “interior”) in the reference building. The three zones were set to examine the differences in airflow and particle transport in the multi-zone building. The exact representative locations can be found in Fig. 2(a). The airflow rate for “exterior (Z1)” indicates air exchange rates with the outdoors, while the airflow rates for “corridor (Z2)” and “interior (Z3)” indicate the airflow rates between adjacent zones. The “+” and “-” sign in Fig. 6 represent the airflow direction, in that “+” indicates that the airflow travels from the outside to the inside and “-” indicates the opposite direction of travel. At the building exterior, the outdoor

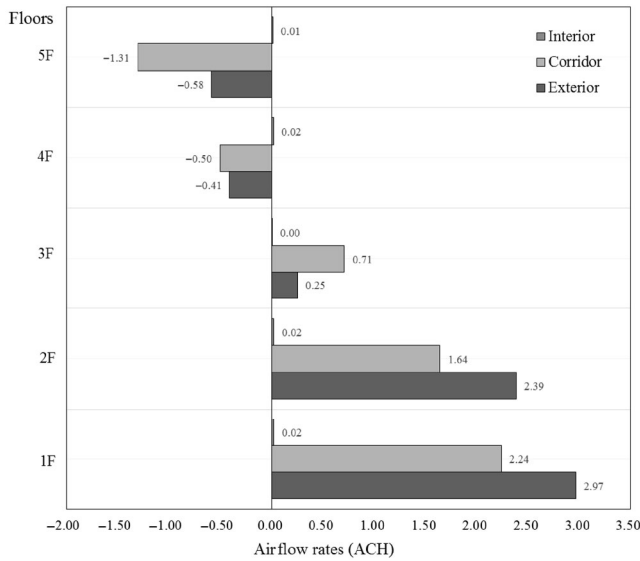


Fig. 6 Airflow rates in the multi-zone and multi-story building

air exchange rates for the lower floors ranged from 2.39 to 2.97 h^{-1} compared with -0.58 to -0.41 h^{-1} for the upper floors. The results clearly suggest that the infiltration of air on each floor is significantly different in terms of the amount of air as well as the airflow direction. Also, they indicate that the outdoor particles' impact on the indoor environment differs significantly from floor to floor.

4.2 Particle simulation results

4.2.1 Amount of particle penetration through the building envelope

Figure 7 illustrates the amount of size-resolved particle penetration (penetration coefficient \times airflow rate) through the building envelope zone of the reference building. The “+” and “-” signs in Fig. 7 represent the direction of particle penetration: “+” indicates particle penetration from the outside to inside, and “-” indicates the opposite direction. The amounts of particle penetration ranged from 0.12 h^{-1} to 2.17 h^{-1} on the lower floors and from -0.49 h^{-1} to -0.06 h^{-1} on the upper floors. The particle transport trends through the building envelope are generally similar to the airflow results. The results show that the outdoor particles penetrate into the lower floors of the building. This particle penetration was prominent for fine particles (0.3 μm , 0.5 μm , 1.0 μm), while the amount of penetration from coarse particles (3 μm , 5 μm , 10 μm) not significant owing to the low penetration coefficients. The result does not indicate that the outdoor particles only affect the lower floors of multi-story buildings, because the outdoor particles that penetrate into the building can be transported through vertical spaces such as elevator shafts and stairwells, resulting in the influence of outdoor particles on the upper floors of the building.

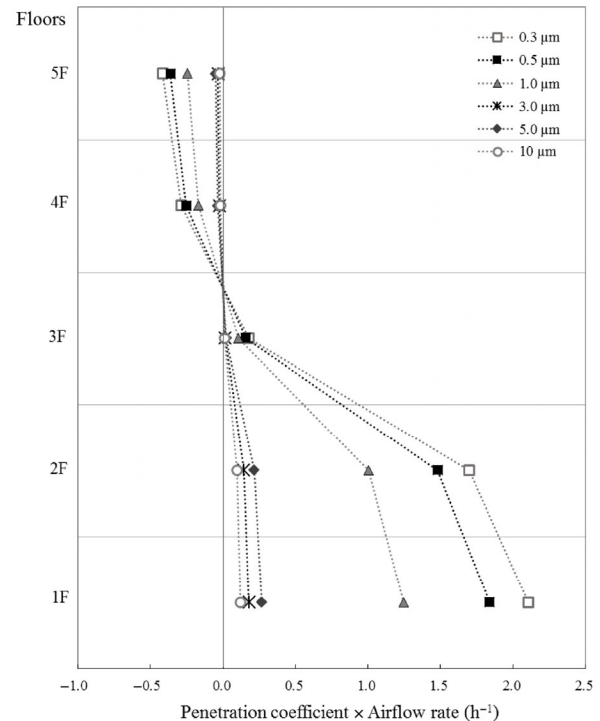


Fig. 7 Amount of particle penetration through the reference building envelope

4.2.2 I/O ratios

Figure 8 shows the size-resolved particle I/O ratio in each zone and for each floor of the reference building. As no indoor particle generation or resuspension was assumed, the simulated I/O ratio indicates the influence of particles originating outdoors on the indoor particle concentrations, considering the particle penetration, deposition, and transport within a building.

The results show that the I/O ratios of coarse particles were generally lower than those of fine particles. This is attributed to the low penetration coefficients and high deposition rates of coarse particles. As indicated above, it was found that the I/O ratios for the lower floors were higher than for the upper floors. For fine particles, the maximum I/O ratio for the lower floors was 0.71, while that for the upper floors was 0.13. These findings were true for both fine and coarse particles. The simulated I/O ratio strongly suggests that the impact of outdoor particles would be significant for the lower floors of a multi-story building. From the results, the upper floors were marginally affected by coarse particles owing to the higher deposition loss rate (0.11 h^{-1} – 0.52 h^{-1}), but significantly affected by the fine outdoor particles. In terms of the zone location, the exterior zone is more affected by outdoor particles than other zones. The average I/O ratio of exterior zone was 0.15, and those of corridor and interior zones were 0.08 and 0.06, respectively. For fine particles, the I/O ratios of the exterior zone ranged from 0.08 to 0.71

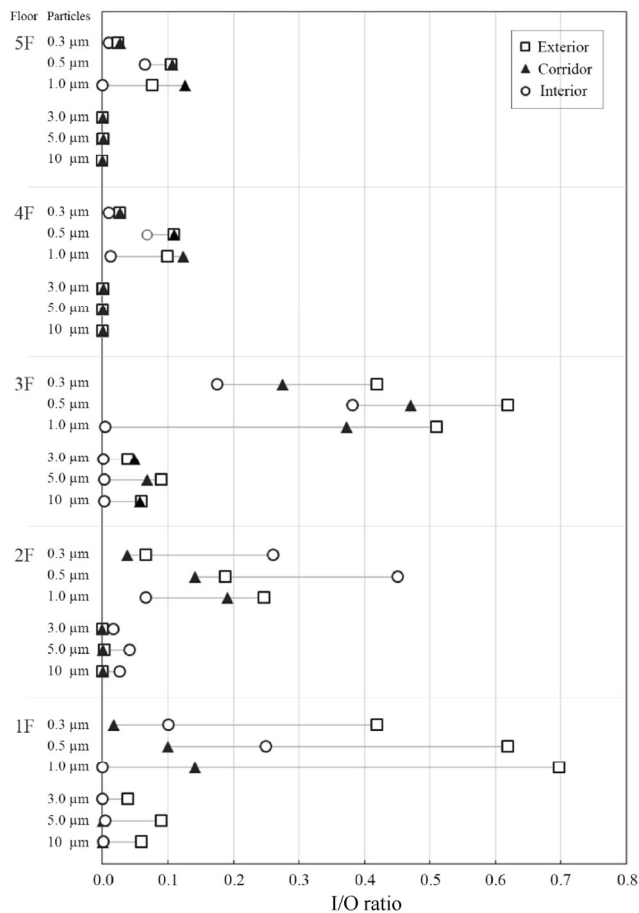


Fig. 8 I/O ratio distribution profiles within the reference building: fine particles (0.3 μm, 0.5 μm, 1.0 μm) and coarse particles (3.0 μm, 5.0 μm, 10.0 μm)

and those of the interior zone ranged from 0 to 0.45. However, there was almost no difference between zones for the coarse particles: for coarse particles, the maximum I/O ratio of the exterior zone was 0.1 and that of the interior zone was approximately 0.

5 Discussion

5.1 Outdoor particle penetration and transport in multi-story buildings

The results from the airflow simulation suggest that the outdoor air infiltrates through the lower floors of the building and exfiltrates from the upper floors. The particle simulation also confirms that the amount of penetrating particles differs from floor to floor, indicating that the impact of external particles on indoor air can differ according to the floor in a multi-story building. South Korea and some Northern Chinese regions have cold winters when the outdoor air quality is very poor owing to industrial and domestic heating. In cold winters, the stack effect occurs frequently, affecting

the building airflow characteristics. The results of this study suggest that the lower part of a multi-story building will experience higher particle concentrations than the higher part of the building. This phenomenon can be explained by the deposition loss of the penetrating particles. According to the results of the predicted I/O ratio distributions within the reference building, the outdoor particle loss increases as the particle flow passes through multiple zones.

In terms of the influence of particle sizes on indoor air, the simulation results suggest that the fine particles (0.3 μm, 0.5 μm, 1.0 μm) showed higher I/O ratios than the coarse particles (3.0 μm, 5.0 μm, 10.0 μm). This result can be confirmed by several previous experimental researches which reported that the I/O ratios for fine particles were higher than those for coarse particles (Thatcher and Layton 1995; Rojas-Bracho et al. 2002; Wang et al. 2006; Colbeck et al. 2010). Our simulation results indicate that the fine ambient particles significantly affect the indoor environment. Fine particles are known to pose more serious health hazards to occupants. This study suggests that appropriate particle control measures should be implemented especially in the lower part of multi-story buildings.

5.2 Impact of fine outdoor particles on indoor air

A potential criticism of this study is that the impact of fine outdoor particles on indoor air could be exaggerated because the simulation results only suggest the particles' I/O ratios without consideration of the actual mass fraction of outdoor particles. A very low mass fraction of fine particles would result in a low impact on the indoor environment despite the higher I/O ratios of fine particles. To examine the actual impact of fine outdoor particles on the indoor environment, an additional analysis was conducted that considered the mass fraction of outdoor particles, using a winter smog episode as an example.

Figure 9 shows the size-resolved particle mass concentrations outdoors and indoors during a winter smog episode. The outdoor mass concentration shows that the amount of fine

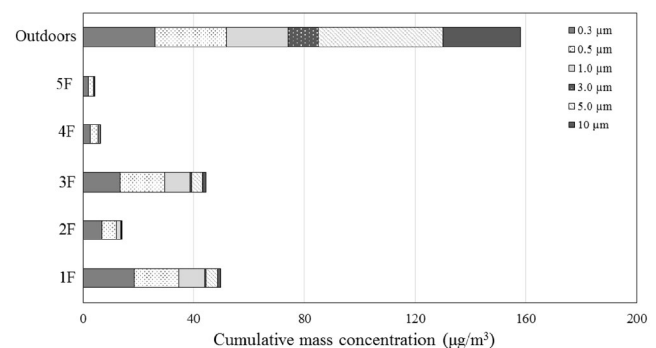


Fig. 9 Size-resolved particle mass concentrations outdoors and indoors

particles is similar to that of coarse particles, and that the indoor fine particle mass concentration is much higher than that for the coarse particles. The analysis confirms the significant impact of fine outdoor particles on indoor environments, especially on the lower floors of a multi-story building. It should be noted that the actual impact of fine particles will vary with the outdoor mass fraction of fine particles.

5.3 Strengths and limitations of this study

This study demonstrates that the CONTAMW simulation can be useful in analyses of the impact of outdoor particles on indoor environments through the identification of key particle transport parameters and a validated airflow simulation. The study also suggests that the outdoor particle impact on the indoor environment can differ from floor to floor, indicating that lower levels of a multi-story building in particular can be exposed to higher fine particle concentrations.

Some limitations of this study should be addressed. The airflow and particle transport simulation was only conducted for the cold winter season. In many Asian cities, the frequency of outdoor particle pollution events has increased in other seasons. The airflow and particle transport characteristics will significantly alter with a change in the outdoor climate conditions. In this study, the airflow simulation was validated and the key particle parameters were determined by field tests. However, a direct validation was not performed for the particle transport simulation owing to the complexity and high cost of multiple point particle measurements. For future studies, a field test measuring particle concentrations at multiple points in a multi-story and multi-zone building is necessary to confirm our conclusions. Also, it should be noted that this simulation has not considered indoor generation and resuspension of particles in the building, as the study aimed at exploring the impact of particle originated outdoors on indoor air. In real indoor environment, the indoor particle concentration is affected not only by outdoor originated particles, but also by indoor originated particles and resuspended particles. A comprehensive analysis considering various scenarios of particle infiltration, indoor-generation, and resuspension would contribute to fully understanding the actual particle distribution in the multi-zone and multi-story building.

6 Conclusion

The objective of this study was to analyze the outdoor particle penetration and transport in a multi-zone and multi-story building, and their impact on indoor air. To this end, a CONTAMW simulation was conducted. The

study demonstrated that the CONTAMW simulation can be used to analyze the impact of outdoor particles on the indoor environment by identifying key particle transport parameters and through a validated airflow simulation. The results of the airflow simulation in a cold winter show that outdoor air infiltrates through the lower part of building and exfiltrates from the upper part. The results of the particle simulation also indicated that the airflow characteristics, combined with the deposition rates, caused the lower floors of the multi-story building to be exposed to higher fine particle concentrations than the upper floors of the building. To confirm this conclusion, a field test that measures particle concentrations at multiple points in a multi-story and multi-zone building will be required.

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