Analysis of $PM_{2.5}$ indoor-outdoor ratio in lobby floor according to configurations of entrance

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ABSTRACT

Outdoor $PM_{2.5}$ has a continuous and significant effect on the indoor environment, and lobby floors, in particular, can be exposed to high concentrations due to entrance doors and greater airflow rates than other floors. In this study, the $PM_{2.5}$ indoor-to-outdoor (I/O) ratio for lobby floors was evaluated according to the operation type and configuration of entrance doors. Airflow analysis was conducted for an office building with multi-zone network simulation, and the I/O ratio was evaluated for different entrance strategies according to the occupant traffic schedule. This study analyzed door configurations with and without vestibules using swinging doors and revolving doors. As airflow analysis results, the neutral pressure level is located at 40% of the total height of the building. The pressure difference across the envelope of the lobby floor was less than the top floor, whereas the airflow was the greatest within the building. As contaminant analysis results, $PM_{2.5}$ I/O ratios reaching a steady state for the single-type (S-S, S-R) was higher than the box and combo-type (B-S, B-R, C-S, C-R) due to vestibule. Entrances consisting of a single door with no vestibule are directly connected to the outdoor environment and can be exposed to $PM_{2.5}$ concentrations equal to or higher than outdoor levels. However, the boxed doorway with a vestibule was exposed to concentrations closer to the outdoors, with a maximum I/O ratio of 1.024 when there was no difference in operating time between the two doors. This indicates that the vestibule strategy is meaningless in a scenario where both doors open and close simultaneously. Therefore, architectural methods to design door configurations and additional measures to control door operations are needed to ensure and manage indoor air quality in lobbies.

KEYWORDS

Entrance Door, $PM_{2.5}$, Multi-zone Network Simulation, Indoor Air Quality

1 INTRODUCTION

In Korea, the number of days exceeding the World Health Organization's daily average criteria of 25 $\mu g/m^3$ is greater than 50% in a year (Lee, 2014). The concentration of indoor $PM_{2.5}$, in the absence of an indoor source, is increased by penetration from the outdoor environment and 30%–75% of indoor $PM_{2.5}$, originating from the outdoor environment (Dockery et al., 1981, Xiong et al., 2004). Outdoor $PM_{2.5}$ has a continuous and significant effect on the indoor environment.

Outdoor $PM_{2.5}$ can be transported indoors by relying on airflow. In high-rise buildings, during winter, indoor-outdoor temperature difference causes to be drawn from the bottom of the building and rise along vertical paths (such as elevator shafts and stairwells) to carry $PM_{2.5}$. Many studies have confirmed the significant impact of $PM_{2.5}$ on indoor environments on the lower floors of a multistory building (Lee et al., 2017, Fu et al., 2022, Park et al., 2022). Lobby floors, in particular, can be exposed to high concentrations due to entrance doors and greater airflow rates than other floors. Therefore, it is necessary to evaluate the impact of entrance doors on indoor $PM_{2.5}$ to implement appropriate particle control measures.

The $PM_{2.5}$ penetration between two zones through doors or cracks has been studied, providing insight into the transport of pollutants (Thatcher et al., 1995, Lv et al., 2018). The investigations

have suggested that architectural characteristics, such as airtightness level, affect the indoor particle concentration (Stephens et al., 2012). However, only a few studies have been conducted in high-rise buildings and multi-zones (Lee et al., 2017). In addition, there is a lack of research focusing on entrance doors as a main pathway for outdoor $PM_{2.5}$.
In this study, the $PM_{2.5}$ I/O ratio for lobby floors was evaluated according to the operation type and configuration of entrance doors. Airflow analysis was conducted for an office building with multi-zone network simulation, and the I/O ratio was evaluated for different entrance strategies according to the occupant traffic schedule. The purpose of this is to provide a basis for designing entrance doors for lobby floors, which are the main penetration pathways for $PM_{2.5}$ in high-rise buildings.

2 APPROACH

2.1 Penetration of $PM_{2.5}$ through entrance doors

The mechanism of indoor $PM_{2.5}$ concentration consists of indoor-outdoor exchange, exchange between indoor spaces, deposition on indoor surfaces, suspension, and generation (Raunemaa et al., 1989, Kulmala et al., 1999). In this study, it was assumed that no resuspension and generation occurred to focus on the penetration process of outdoor $PM_{2.5}$. Therefore, the indoor $PM_{2.5}$ concentrations can be expressed as follows:

$$V\left(\frac{dC_i}{dt}\right) = Q_{io}PC_o - Q_{ij}C_i - KVC_i \tag{1}$$

Where,
V, volume of the room, m^3
C_i, C_o, indoor and outdoor particle concentration, $\#/m^3$
Q_{io}, Q_{ij}, indoor-outdoor and zone i-j exchange rate, m^3/s
P, penetration coefficient
K, particle deposition rate

The three terms on the left-hand side of equation (1) represent indoor-outdoor exchange, exchange between indoor zones, and deposition. The deposition process is affected by the gravity of the particle mass. The indoor concentration is determined by the air exchange rate (Q_{io}, Q_{ii}). Airflow in a building is defined by the following power law:

$$Q = C(\Delta P)^n \tag{2}$$

Where the pressure difference (ΔP) is determined by the geometry of the building and weather conditions, and C and n represent the characteristics of the opening through which the air passes. The airflow through an entrance door depends on its type of operation and configuration. In office buildings, swing, revolving, and sliding doors are typically used, along with vestibules if necessary. For effective lobby floor planning, the variation in the $PM_{2.5}$ I/O ratio with door configuration was analyzed in a simulation case study.

2.2 Simulation conditions

CONTAM, a multizone network simulation software, was used to evaluate indoor $PM_{2.5}$ concentrations under different door conditions. The model building is a 15-story educational facility located in South Korea. Table 1 summarized the building. The building has two main entrances on the first floor, a podium on floors 1st-4th, and a tower on floors 5th-15th. The offices and classrooms are located in the tower section. Assuming an office building with constant occupancy traffic, we derived the expected occupancy load and traffic rate based on the floor area, as shown in Figure 1. The traffic rate can be divided into ranges I and II. Both ranges have the same number of occupants; however, the difference is that range I has a normal distribution over a five-hour range, whereas range II has a normal distribution over a seven-hour range.

Table 1 Summary of model building

Parameter	Content
Location	Incheon, Korea
Floor	15 F
Gross floor area	25,813 m^2
Office floor area	10,534 m^2
Occupant density (IBC, 2012)	9.3 m^2/people

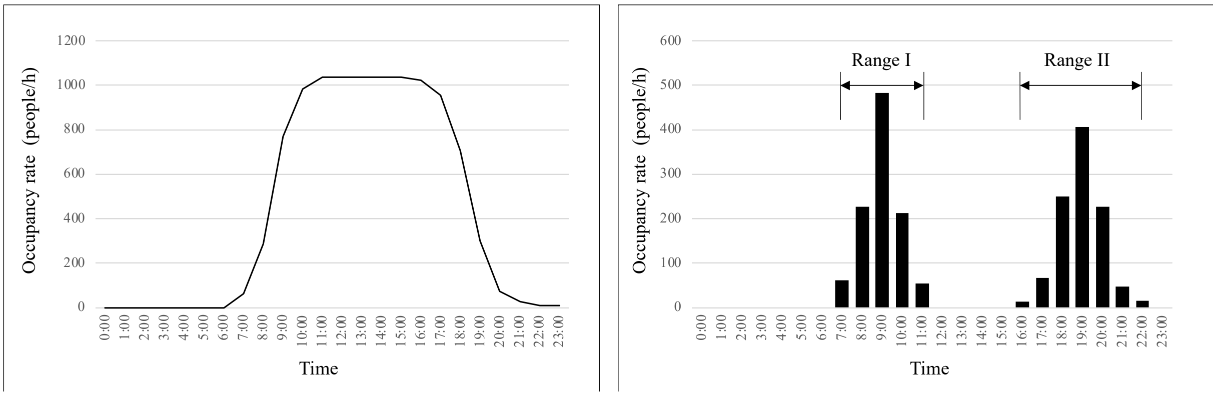


Figure 1 Occupancy schedule (right) and occupancy traffic rates (left) of model building

The input data for the airflow and contaminant analysis of the model building are listed in Table 2. The airflow analysis was performed for the entire building, while the contaminant analysis was focused on the lobby floor. The indoor and outdoor air temperatures and outdoor $PM_{2.5}$ concentrations were kept constant to evaluate the $PM_{2.5}$ I/O ratio for the entrance door conditions. Swing doors and revolving doors were used in this study, whereas sliding doors, which are mostly automatic, were excluded because they require analyzing the opening time. Swing doors and revolving doors, which are the focus of this study, differ in the rate of airflow when the door is operating, i.e., when it is open. Swing doors have an opening size of the door leaf, whereas revolving doors have minimal airflow due to the rotation of the door leaf (Lee et al. 2017). Therefore, while both doors had the same air leakage rate in the closed state, the data when the doors were open were different.

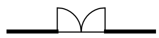
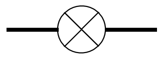
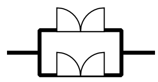
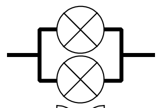
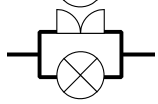
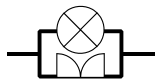
Table 2 Input parameters of model building

Parameter			**Data**	**Unit**	**Reference**
Temperature	Indoor		20	°C	ASHRAE, 2017
	Outdoor		−10.2	°C	ASHRAE, 2017
Air leakage	Envelope		1500	$cm^3/s.m^2$@75Pa	ASHRAE, 2017
	Elevator door		325	cm^2/item@10Pa	Jo et al., 2005
	Entrance door	Stop (close, stationary)	150	cfm@50Pa	Schutrum et al., 1961
		Operating (revolving)	600	cfm@50Pa	Schutrum et al., 1961

	Operating (swing door open)	1.8	m^2/door	Opening area
Contaminants	Particle density	1.27	g/cm^2	Kim et al., 2018
	Particle diameter	0.001-2.5	μm	-
	Outdoor concentration	31.2	$\mu g/m^3$	Lee, 2014

Case I consisted of a single type without a vestibule and a box/combo type with a vestibule. The $PM_{2.5}$ I/O ratio was evaluated for the door operation type and entrance configuration. Case II evaluated the changes in the I/O ratios according to the difference in operation time between the two doors in the box type. The case consisted of a box-type entrance with two swing doors. The main variable in Case II was the time difference between the doors, which can be adjusted using the space between the doors of the vestibule entrance in an actual building. B-0 means that the doors operate simultaneously, B-5 means that the first door operates, and the other door operates 5 s later.

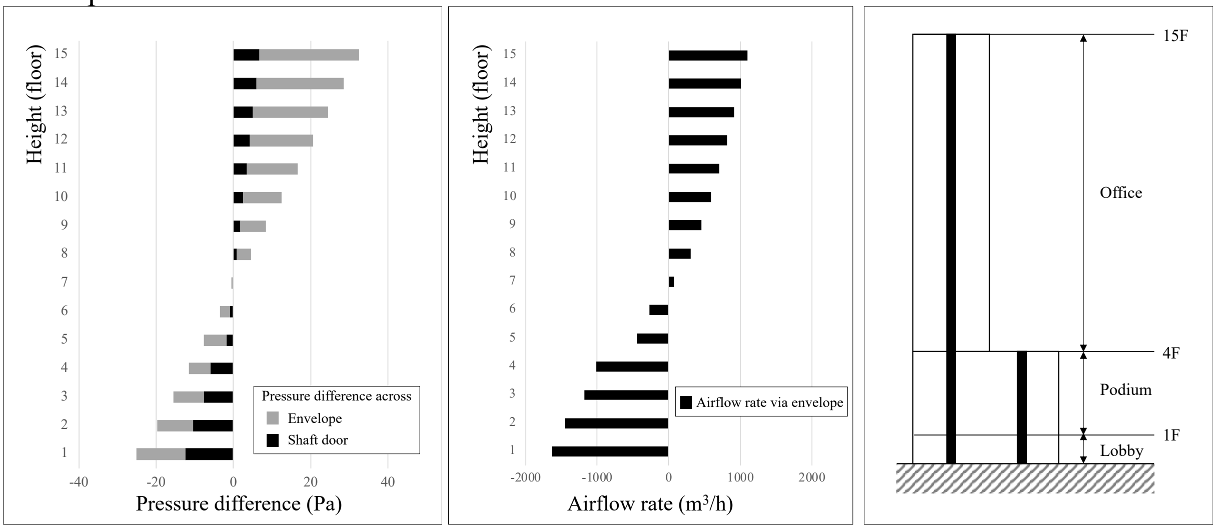
Table 3 Cases for contaminant analysis

Case I	Vestibule type	Operation type	Diagram
S-S	Single	Swing	
S-R	Single	Revolving	
B-S	Box	Swing+ swing	
B-R	Box	Revolving+revolving	
C-S	Box (Combo)	Swing(outside)+revolving(inside)	
C-R	Box (Combo)	Revolving(outside)+swing(inside)	
Case II	**Vestibule type**	**Operation type**	**Time difference of door operation**
B-0	Box	Swing+swing	0 s
B-1	Box	Swing+swing	1 s
B-2	Box	Swing+swing	2 s
B-3	Box	Swing+swing	3 s
B-4	Box	Swing+swing	4 s
B-5	Box	Swing+swing	5 s

3 IMPACT OF ENTRANCE DOOR ON $PM_{2.5}$ I/O RATIO

3.1 Airflow analysis for model building

The airflow analysis was performed using CONTAM, a multi-zone network simulation, to determine the pressure difference and airflow rate in the lobby floor. The model building includes the entrance of B-S with a vestibule on swing doors, with the doors closed and in steady state. Figure 2 shows the pressure profile of the building and the airflow rate in the envelope.



(a) Pressure profile (b) Airflow rate through envelope (c) Elevation plan

Figure 2 Results for airflow analysis of the model building

The neutral pressure level is located at the 7th floor, 40% of the total height of the building. It is located below the center of the building due to the large envelope area of the lower floors (1-4F) and the entrance doors. The envelope pressure difference on the first floor was 12 Pa, which was lower than the top floor (25 Pa). However, the lobby level, the first floor, had a higher airflow rate of 1,634 m^3/h than the top floor (1,102 m^3/h) due to the entrance door and large envelope area. Based on this airflow analysis, the air movement path of the lobby floor for the contaminant analysis was derived.

3.2 $PM_{2.5}$ I/O ratio based on operation type

The simulation was conducted from 12:00 on January 1 to 12:00 on January 3, with 48 h intervals of 1 s. The target period was from January 2 at 0:00 to January 2 at 24:00, with 12 h of indoor concentration stabilization before and after the target period. In all cases, the initial indoor concentration was set to the outdoor concentration, resulting in an initial I/O ratio of 1. The pressure difference between the outside and lobby spaces was set to 12 Pa, which was derived from the airflow analysis. Figure 4 shows the concentration stabilization areas for Case I. The I/O ratio of concentrations reaching a steady state for the single type (S-S, S-R) was 0.518, which was higher than 0.491 for the box and combo types (B-S, B-R, C-S, C-R). This was caused by the decrease in airflow due to the use of the vestibule.

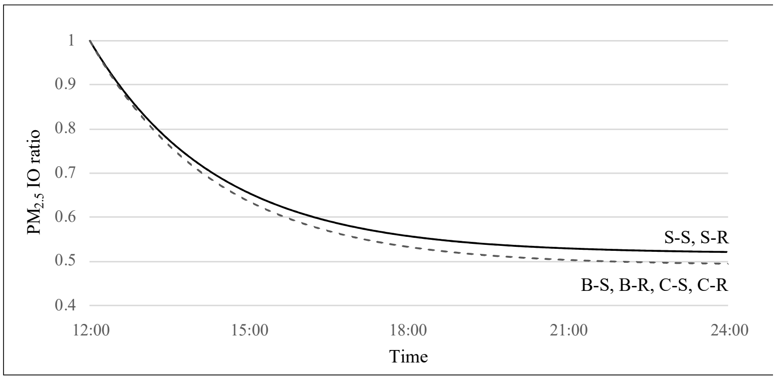


Figure 3 Stabilization of indoor $PM_{2.5}$ concentrations before the target period

Table 4 and Figure 4 show the I/O rate results for the 24 hours. The minimum value of each case is the steady state value, and the results were divided into single-type and box/combo-type. In the box/combo-type, the cases with at least one revolving door, B-R, C-S, and C-R tended to have similar behavior in the entire range.

Table 4 $PM_{2.5}$ I/O ratio of Case I during the target period

Case		**S-S**	**S-R**	**B-S**	**B-R**	**C-S**	**C-R**
$PM_{2.5}$ I/O ratio	Min.	0.518	0.518	0.491	0.491	0.491	0.491
	Avr.	0.768	0.522	0.504	0.492	0.492	0.492
	Max. (Range I)	1.293	0.531	0.551	0.494	0.495	0.495
	Max. (Range II)	1.21	0.53	0.521	0.493	0.494	0.494
Increase rate (%)	Range I	149.6	2.5	12.2	0.6	0.8	0.8
	Range II	106.5	2.1	5.5	0.4	0.6	0.6

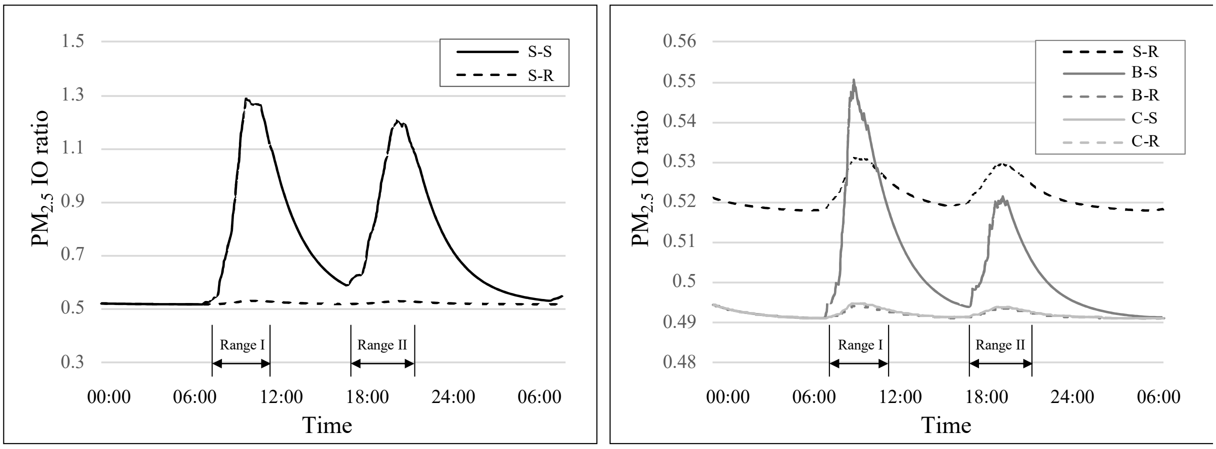


Figure 4 $PM_{2.5}$ I/O ratio of Case I during the target period (Single-type cases (left) and cases without P-S (right))

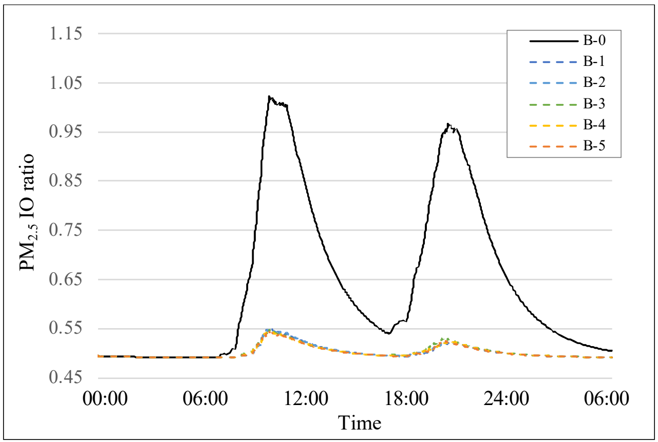
Figure 5 shows the I/O ratio for the results of single-type cases (S-S, S-R) and cases without P-S. In all cases, the I/O ratio increased more rapidly in range I, where the occupant traffic rate was higher. The I/O ratio for S-S was higher than the other cases and increased to 1.29 at the peak of occupant traffic, indicating that the lobby floor can be exposed to higher indoor $PM_{2.5}$ concentrations than outdoor concentrations. Due to the vestibule, the minimum value of S-R is higher compared to the box and combo cases (B-S, B-R, C-S, S-R), which can lead to higher background concentration. Cases except B-S included a revolving door, which had the smallest change in the ratio (within 1%). S-R had a relatively large range of 2.5% because it included a revolving door but was a single type. B-S had the highest percentage increase from normal to peak concentration (12%). Depending on the door operation schedule, there were periods when the I/O rate in B-S was higher than in S-R. The I/O rates of the B-R, C-S, and C-R groups were not significantly different, suggesting that installing at least one revolving door at the entrance door can effectively block $PM_{2.5}$ inflow when occupants enter and exit.

3.3 $PM_{2.5}$ I/O ratio according to operation time difference

The lobby-to-outside I/O ratio was investigated for differences in door operation time. The case study was conducted at a box-type entrance consisting of two swing doors, while the door operation time in an actual building may vary depending on the space between the two doors. Table 5 and Figure 6 present the results of the I/O ratios during the target period.

Table 5 $PM_{2.5}$ I/O ratio of Case II during the target period

Case		B-0	B-1	B-2	B-3	B-4	B-5
$PM_{2.5}$ I/O ratio	Min.	0.491	0.491	0.491	0.491	0.491	0.491
	Avr.	0.663	0.504	0.504	0.505	0.504	0.503
	Max.	1.024	0.551	0.549	0.548	0.545	0.543
Increase rate (%)		108.5	12.2	11.8	11.6	11.0	10.6



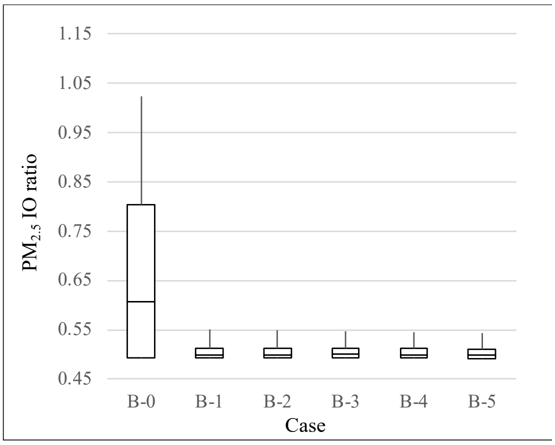


Figure 5 $PM_{2.5}$ I/O ratio of Case II during the target period (Time series data (left) and boxplot (right))

The I/O ratio of B-0 was higher than those of the other cases. The maximum ratio for this case in the high traffic range I was 1.024, showing that it can be exposed to $PM_{2.5}$ concentrations close to the outdoor concentration. B-0 is a scenario in which both doors open and close simultaneously, which is the same as the single-type operation. As the time difference increased from B-1 to B-5, the maximum ratio decreased; however, the difference was insignificant from 10.6% to 12.2%, which can be considered the same level. This means that even if an entrance with a vestibule strategy is applied, it is possible to achieve the same level of results as single-type depending on how the door is operated and controlled.

4 CONCLUSION

In this study, the I/O ratio of the lobby floor to the outdoor $PM_{2.5}$ concentrations according to the operation type and configuration of the entrance was evaluated with a case study. The outdoor $PM_{2.5}$ intake at the lobby space varied owing to different airflow rates, depending on the door operation. This was depicted in this study using swing and revolving doors and analyzed based on the door configuration, with and without a vestibule. An entrance consisting of a single door without a vestibule is directly connected to the outdoor ambient. It can be exposed to $PM_{2.5}$, which is equal to or higher than the outdoor concentration level, depending on the occupancy schedule. Additionally, an entrance with a vestibule can be exposed to high concentrations when no difference exists in the operating times of the two doors. Therefore, in order to ensure and manage indoor air quality at the lobby, architectural methods to design the configuration of the doors and additional measures to control the operation of the doors are required.

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