The Effect of Air Purifier on Smoke Detector Revealed by Fire Dynamics Simulation

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Abstract: In the present study, the relevance of the airflow to the response time of the smoke detector has been investigated regarding the different air purifier locations by Fire Dynamics Simulator (FDS). Particular attention has been devoted to the impact on the smoke detector response with different device types, i.e., top-discharge and front-discharge air purifiers. Additionally, the response delay rate regarding the fire sizes (200 kW and 550 kW) was also evaluated with the top-discharge type purifier. The obscuration plots suggest that the response delay rate generally increases when the air purifier and the smoke detector are in a straight line. The change in the delay rate of the detector was distinct for the top-discharge type device due to the formation of a current barrier by the ceiling jet flow, and a nearby physical barrier (e.g., wall) can further suppress the flow diffusion during a fire event. The delay rate tends to decrease with the increment of the fire intensity.

Keywords: air purifier; smoke detector; indoor airflow; Fire Dynamics Simulator (FDS)

1. Introduction

Rapid global warming is likely to be related to the increase of the periodical appearance of severe dust storms in East Asia, namely, the yellow dust is an atmospheric phenomenon that carries industrial pollutants via strong winds, threatening the environment and human health. The frequent forest fires in North America and Oceania would be an instance of such threats [1,2]. Hence, there has been a growing demand for residential air purifiers due to the recent dust pollutions and airborne contaminants [3].

Air purifiers can effectively trap the dust of the indoor area surrounded by closed and semi-closed spaces. A problem arises, however, when a fire occurs in the (semi)closed spaces where the air purifier is located. High smoke emissions generally result in reduced visibility and thus lower evacuation efficiency. Furthermore, smoke will actively accumulate in the indoor area with the (semi)closed spaces, which in turn prolongs the evacuation process [4]. This increase in evacuation time is a major cause of death for evacuees because of the longer period of smoke and toxic gas inhalation [5,6].

The early signal of an automatic fire detection system can prevent suffocation and enable rapid evacuation. For this reason, much effort has been made to reduce evacuation time to increase the chance of occupants’ survival with the improvement of fire detection performance [7].

The indoor airflow resulting from a fire is often described as a plume form driven by thermal buoyancy moving vertically upward from the fire source, and thus smoke spreads in an upward direction [8]. This is why smoke detectors shall be installed on the ceiling or high on the walls. Generally, fire safety standards of each country regulate the location and number of fire alarm device/systems on the basis of spatial criteria considering certain fire flow characteristics [9].
The temperature and smoke concentration are the major factors that affect the response of smoke detectors. Air purifiers therefore can increase the likelihood of smoke detection failure or delay as they can remove smokes generated by fire. In addition, an indoor HVAC system without a built-in smoke detector in the duct can cause a forced convection with air purifiers, which in turn disturbs the flow of heat and smoke from the fire plume; consequently, the smoke detector may fail to respond [10].

Eventually, the air purification process will increase the Required Safe Egress Time (RSET), which is the time for the safe evacuation of the occupants [11]. As shown in Figure 1, a longer detection time will extend the time frame of RSET.

![Figure 1. Time by item to configure the RSET.](image)

According to the Fire Statistics Yearbook of the Korea Fire Agency released in 2019, 4253 fire accidents were caused by non-operation and failure of automatic fire detection facilities, which account for 10% of all fire accidents [12]. A number of studies have explored some key factors that affect the performance of smoke detectors. Additionally, some authors have revealed alterations of the airflow property regarding different environments or configurations of the air conditioner. Some previous studies on detectors and air purifiers are summarized in Table 1.

| Authors            | Content                                                                 | Reference No. |
|--------------------|-------------------------------------------------------------------------|---------------|
| Park et al. (2002) | Relationship between response characteristics and wind speed of ionized smoke detectors. | [13]          |
| Lee et al. (2016)  | The changes in clean effect regarding the discharge direction of the air purifier. | [14]          |
| Shim et al. (2016) | The correlation between the reaction characteristics of combustibles and fire detectors. | [15]          |
| Choi (2019)        | The real-scale fire experiment on the response characteristics of fire detectors in a ceiling air conditioning environment. | [16]          |
| Kim et al. (2020)  | The effect of increasing the airflow rate of air purifiers on the removal of indoor pollutants. | [17]          |
| Park et al. (2020) | The density change of indoor fine dust regarding the air purifier location and discharge direction. | [18]          |
| Wang et al. (2021) | The relationship between outlet and inlet location and indoor fire.       | [19]          |

Park et al. reported that ionized smoke detectors have an inversely proportional effect to the response characteristics of wind speed changes [13].

Lee et al. revealed that the air purifier with the discharging method to the uppermost outlet would show an excellent cleaning performance in the discharge direction [14].
A study by Shim et al. found that the response characteristic of smoke detectors varies according to the initial combustible types such as oil, wood, rubber, and wet wood. The response characteristics to differential temperature heat detectors, fixed temperature heat detectors, and smoke detectors could be evaluated based on combustible fires [15].

Choi conducted a real-scale fire experiment and carried out fire modeling on the response characteristics of fire detectors in a ceiling air conditioning environment. This study highlights the need for a highly sensitive detector to properly detect a fire when a ceiling-type air conditioner is installed [16].

A previous study by Kim et al. applied a Centrifugal Fan to increase the cleaning capacity of indoor air purifiers. An increase in the airflow rate of the air purifier has confirmed that the air-cleaning effect on the inner pollutant is increased by distributing a faster streamline flow [17].

Park et al. reported the density change of indoor fine dusts regarding the air purifier location and discharge direction [18].

Wang et al. examined the effect of air inlet or outlet location of a fan coil unit (FCU) of an air conditioner on smoke and fire behaviors [19].

The present study aims to explore the link between the responsivity of a smoke detector from automatic fire detection systems and the indoor airflow generated by an air purifier in the presence of home appliances. Therefore, as shown in Figure 2, investigations into some prior research were carried out to establish a simulation model with different types of air purifiers (i.e., top-discharge and front-discharge types) by varying their location, changing the settings of the smoke detector, and altering the configurations of the room where the fire occurred. Further parameters such as fire position and fire size were also considered during the computation.

**Figure 2.** Flowchart of this study design.

### 2. Experimental

#### 2.1. Air Purifiers

Currently, there are two types of air purifiers sold on the market, one that discharges from the front part and the other that discharges from the top. Both types use a motor to suck the indoor pollutant into a low inlet and then emit the clean air filtered by the filter to the outside. At this time, the air discharged through the outlet circulates the indoor air and operates as a circulation-type air purifier that moves particles, such as indoor dust, to the vicinity of the lower inlet [20].

Korea Consumer Agency recommended using 130% of the usable area for the appropriate capacity of the air purifier [21]. The air volume of a commercially available air purifier is set to circulate air 3 to 5 times per hour to maximize the cleaning capacity.
Table 2 shows the conditions for the air volume of the air purifier applied in this study. For the air purifier modeling, two types with different functions of upper discharge—frontal and upward—were selected. Figure 3 shows the types of discharge structure of the two types of air purifiers applied to this study.

Table 2. Test condition of the air purifiers.

| Properties        | Condition   |
|-------------------|-------------|
| Air Volume        | 24.6 m³/min |
| Discharge velocity| 3.41 m/s    |
| Suction velocity  | 0.68 m/s    |

![Figure 3. Types of the air purifiers employed in the simulation. (a) Front-discharge type; (b) top-discharge type.](image)

2.2. Fire Interpretation

2.2.1. Fire Modeling

A fire scenario has been simulated with a reception room using a Fire Dynamics Simulator (FDS) to evaluate the response time of the smoke detector during air purifier operation. The optimal space area of the office facility per person is generally known to be 8.52 m² [22]. Therefore, the office size was set to 81 m², which corresponds to the size for 7 people including a reception room. The area, where the air purifier is located, has been considered as an enclosed space with the windows closed, thereby preventing outdoor air pollutants from entering the room.

Figure 4 shows the detector positions, air purifier locations, and fire source in the fire simulation.

In general, indoor smoke detectors would be installed in the center of the ceiling, but if there is an air conditioner already mounted in that part, the smoke detectors can be placed in alternative positions. Therefore, in this study, the non-centered positions were also included in the simulation, as can be seen in Table 3.

Table 3. Smoke detector analysis position.

| FDS Coordinates | Detector Position 1 (m) | Detector Position 2 (m) | Detector Position 3 (m) |
|-----------------|-------------------------|-------------------------|-------------------------|
| x, y, and z     | 2.5, 4.5, and 2.7       | 4.5, 4.5, and 2.7       | 6.5, 4.5, and 2.7       |
Figure 4. Schematics of the FDS modeling room.

2.2.2. Mesh Resolution

The calculation accuracy strongly depends on the FDS mesh size. The size of the analysis grid can be determined by the characteristic fire diameter using Equation (1) in the fire plume analysis:

\[ D^* = \left( \frac{Q}{\rho_\infty C_p T_\infty \sqrt{g}} \right)^{2/5} \]  

where \( D^* \): characteristic fire diameter, \( Q \): Total heat release rate (kW), \( \rho_\infty \): outside air density (kg/m\(^3\)), \( C_p \): specific heat (kJ/kg·K), \( T_\infty \): outside air temperature (K), \( g \): acceleration of gravity (m/s\(^2\)), and \( \delta_X \): nominal size of a mesh cell.

The \( D^*/\delta_X \) parameter would be only valid if the value is between 4 and 16 [23]. The \( D^* \) applied to this analysis is 0.504 m, and in this paper, \( D^*/\delta_X \) has a value of 10.06, so the mesh size applied to the studies satisfies the convergence condition.

2.2.3. Calculation Conditions

Smoke detectors applied to FDS are classified as the Heskestad model and Cleary model. When a smoke detector operates in a smoke flow area with a lower ceiling jet flow, the Heskestad model has some limitations in terms of accuracy as compared to the Cleary model [24]. In addition, the detector operation requires an obscuration per meter (OPM, %/m) value expressed as ACTIVATION_OBSCURATION. Therefore, the smoke detector set in this study applied the default value of the Cleary Model photoelectric type 1 smoke detector [25,26]. For the OPM value, the actual settings of the smoke detector were applied. Table 4 shows the calculation conditions of FDS, and Table 5 reveals the parameters for the smoke detector.

Table 4. Boundary conditions for fire simulation.

| Properties          | Condition          |
|---------------------|--------------------|
| Room Size           | 9 m × 9 m × 2.8 m  |
| Grid                | 180 × 180 × 56     |
| Heat Release Rate (HRR) | 200 kW            |
| Air Temperature     | 20 °C              |
| Simulation Time     | 150 s              |
Table 5. Smoke detector set value.

| Smoke Detector          | αe  | βe  | αc, L | αc  | OPM (%/m) |
|-------------------------|-----|-----|-------|-----|-----------|
| Cleary Photoelectric P1| 1.8 | -1.0| 1.0   | -0.8| 15.0      |

HRR (Heat Release Rate) applied the fire test result data of the sofa with polyurethane foam padding presented in SFPE (Society of Fire Protection Engineers) “Principles of Smoke Management” [27]. The reaction material is configured as polyurethane, and Table 6 shows the reaction parameters. The surface material of the sofa where the fire occurred is configured as upholstery, and Table 7 shows the surface parameters.

Table 6. Reaction parameters.

| Properties                      | Condition       |
|---------------------------------|-----------------|
| Soot yield                      | 0.10            |
| Reactant of fuel                | C = 6.3, H = 7.1, N = 1.0, O = 2.1 |
| Molecular weight of fuel        | 130.3 g/mol     |
| Stoichiometry coefficient for CO₂| 6.3             |
| Stoichiometry coefficient for H₂O| 3.55            |
| Stoichiometry coefficient for O₂| 7.025           |

Table 7. Surface parameters of sofa.

| Properties                | Condition |
|---------------------------|-----------|
| Specific heat capacity    | 1.0 kJ/kg·K |
| Ignition temperature      | 350 °C    |
| Solid density             | 40.0 kg/m³ |
| Heat of reaction          | 1500 kJ/kg |
| Heat of combustion        | 15,000 kJ/kg |

3. Results and Discussions

3.1. Analysis Results

The standard procedure of a smoke detector installation defines a minimum floor area of 150 m² with a mounting height of 4 m or less from the floor [28]. However, the installation location of the smoke detector is not separately specified. The installation location of the smoke detector applied in this study was divided and configured as follows to reflect the case of the location changes of the smoke detector due to structural obstacles such as a ceiling air conditioning system or a light.

1) Ceiling center (position 2);
2) Two meters left and right from the center of the ceiling (positions 1 and 3).

The response time of the smoke detector during the air purification was analyzed by the response delay rate of the detector regarding the mounted location. The response delay rate (Delay Rate) of the smoke detector is given by Equation (2):

\[
\text{Delay Rate} = \frac{T_x - T_0}{T_0} \times 100\% \quad (2)
\]

where \(T_0\): smoke detector response time without an air purifier, and \(T_x\): smoke detector response time for each air purifier regarding location.
3.1.1. Evaluation of Detector Position 1

Table 8 provides the experimental data on the response time of the smoke detector for each location of the air purifier at detector position 1. The obscuration values of the smoke detectors regarding the different locations are presented in Figure 5.

- The Front-discharge Type device can facilitate smoke spreading in location A where the air purifier is in line with the flame. The response rate (−3.4% in delay rate) of the detector at location A was the fastest with the front-discharge type air purifier. On the other hand, the delay rate of the detector response was measured to be 1.3–54.7% in other locations.
- The response delay characteristic of the Top-discharge Type device was 10.6–54.7%.

Table 8. Detection time of the smoke detector at position 1 regarding the air purifier locations.

| Air Purifier Location | A Time (s) | Delay Rate (%) | B Time (s) | Delay Rate (%) | C Time (s) | Delay Rate (%) |
|-----------------------|------------|----------------|------------|----------------|------------|----------------|
| No air purifier       | 23.6       |                |            |                |            |                |
| Front-discharge type  | 22.8       | −3.4           | 36.5       | 54.7           | 23.9       | 1.3            |
| Top-discharge type    | 26.1       | 10.6           | 34.1       | 44.5           | 29.4       | 24.6           |

Figure 5. Obscuration for smoke detector at position 1 regarding the air purifier location at (a) Air purifier location A, (b) Air purifier location B, (c) Air purifier location C.
3.1.2. Evaluation of Detector Position 2

Table 9 shows the response time for each location of the air purifier at detector position 2. The obscuration values of the smoke detector are shown in Figure 6.

- The Front-discharge Type showed in the response rate of the detectors being between −12.2% and −6.5%. This is a faster response as compared to the smoker detectors without any air purifiers.
- The Top-discharge Type resulted in a response delay characteristic from 57.7% to 94.6%.

Table 9. Detection time of the smoke detector at position 2 regarding the air purifier locations.

| Air Purifier Location | A                  | B                  | C                  |
|-----------------------|--------------------|--------------------|--------------------|
|                       | Time (s)           | Delay Rate (%)     | Time (s)           | Delay Rate (%)     | Time (s)           | Delay Rate (%)     |
| No air purifier        | 29.4 s             |                    |                    |                    |                    |
| Front-discharge type   | 25.8 −12.2         | 27.5 −6.5          | 27.5 −6.5          |                    |                    |
| Top-discharge type     | 49.4 68.0          | 57.2 94.6          | 44.6 57.7          |                    |                    |

Figure 6. Obscuration for smoke detector at position 2 regarding the air purifier location at (a) Air purifier location A, (b) Air purifier location B, (c) Air purifier location C.
3.1.3. Evaluation of Detector Position 3

The response time for each location of the air purifier at detector position 3 is presented in Table 10. Also, Figure 7 displays the obscuration values of the smoke detector 3 for each location.

- The Front-discharge type showed the response rate of the detectors was from $-6.5\%$ to $-3.0\%$ for all locations, which is faster than those without any air purifiers installed.
- The Top-discharge type resulted in the response time of the detectors being very slowly, such as 64.9–121.4%. Among them, the detector at location B revealed the slowest response time.

Table 10. Detection time of the smoke detector at position 3 regarding the air purifier locations.

| Air Purifier Location | A               | B               | C               |
|-----------------------|-----------------|-----------------|-----------------|
|                       | Delay Rate (%)  | Delay Rate (%)  | Delay Rate (%)  |
| No Air Purifier       | 33.6 s          |                 |                 |
| Front-discharge type  | 32.1 $-4.5$     | 31.4 $-6.5$     | 32.6 $-3.0$     |
| Top-discharge type    | 64.5 92.0       | 74.4 121.4      | 55.4 64.9       |

Figure 7. Obscuration for smoke detector at position 3 regarding the air purifier locations at (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.
The findings deduced from the obscuration plots indicate that the response delay rate generally increases when the air purifier and the detector are in a straight line. Especially, the increment was distinct for the top-discharge type device. The change in the response delay rate regarding the location of smoke detectors was also significant for the top-discharge type device. On the other hand, the discrepancy in the delay rate between the purifiers was minimum when the smoke detector was located close to the fire source with the air purifier location B. Because of the physical distance, the air current changes resulting from the different device types can have less influence on the smoke detector performance. There has been a minimum discrepancy in the response time between the air purification and the non-installed conditions as for the front-discharge type device. In contrast, a notable response delay could be found for the top-discharge type purifier. This may be explained by the different discharge directions. The top-discharge type purifier could possibly generate a current barrier that suppress the diffusion of the smoke and heat from the fire source.

3.1.4. Smoke Detection Rate

The smoke density distribution is adopted to correctly understand the characteristic of the smoke detection. The ceiling surface is divided into a uniform grid of 1 m × 1 m, and a smoke detector is mounted in the center of the grid. The total number of smoke detectors is considered in calculating the detection rate. The detection rate (Detection Rate) of the smoke detector in the simulation is given by Equation (3):

\[
\text{Detection Rate} = 1 - \left( \frac{A_0 - A_x}{A_0} \right) \times 100\%
\]

(3)

where \( A_0 \) is the total number of smoke detectors installed on the ceiling \( (A_0 = 81) \), while \( A_x \) is the number of activated smoke detectors. Figure 8 shows the detection rate of the smoke detectors for each type with 10 s intervals.

![Figure 8. Smoke detector detection rate regarding air purifier type. (a) Front-discharge type; (b) top-discharge type.](image)

The time to reach 100% detection can be listed as follows:

- No air purifier: 60 s
- Front-discharge type:
  1. At location A: 50 s;
  2. At location B: 70 s;
  3. At location C: 80 s.
- Top-discharge type:
  1. At location A: 90 s;
The results of the average detection rate on the different device configurations are compared in Figure 9:

![Figure 9. The average value of smoke detector detection rate regarding air purifier type.](image)

It takes 60 s, 80 s, and 100 s to reach the detection rate of 100% for the non-installed condition, the front-discharge device, and the top-discharge device, respectively.

### 3.2. Discussions

#### 3.2.1. Airflow Analysis

The airflow from the air purifier is the crucial factor that determines the smoke movement in the room during the fire event. Hence, the analysis of the airflow distribution is the key to correctly evaluating the reaction time of the smoke detector. The airflow of the front-discharge device is horizontal, and collided with the wall, showing the characteristics of an upward and downward dispersed flow. On the other side, the top-discharge type air purifier produces an ascending airflow in the vertical direction, which spreads along the ceiling. When the ascending flow collides with the jet flow developed from the fire, it results in a vertical descending airflow. Figure 10 displays the vector distribution of the flows near the fire for the front-discharge and top-discharge air purifiers.

![Figure 10. The vector distribution of airflow by air purifier discharge type. (a) Front-discharge type airflow; (b) top-discharge type Airflow.](image)

Figure 11 shows the distribution of ceiling smoke by location of the air purifier type based on the time the smoke detector of position 2 detected fire in the air purifier non-installation condition. The smoke spreads evenly, forming a radial shape along with the ceiling due to heat buoyancy when no air purifier is installed. As shown in Figure 11, it is obvious that the air purifier alters the smoke dispersal pattern.
- The Front-discharge type
  - Location A: the smoke pattern showed a similar tendency to the non-installation condition.
  - Location B, location C: the diffusion of smoke towards the left wall was delayed, compared to the air purifier non-installation condition.
- Top-discharge type
  - All locations: the diffusion of smoke was suppressed by the discharged airflow of the air purifier.

![Figure 11](image1.png)

**Figure 11.** The ceiling jet of obscuration according to the different types of air purifier discharge (29.4 s). (a) No air purifier, (b) front-discharge Type, and (c) top-discharge type.

Compared with the smoke dispersion by the top-discharge device, the smoke tends to propagate less with the front-discharge device, as can be seen in Figure 11c.
3.2.2. Temperature Distribution

The information on the temperature distribution of the ceiling can be used to investigate the effect of the airflow. The thermal flow phenomenon caused by the fire was confirmed by comparing the temperature distribution of the ceiling overtime at (20, 40, and 60) seconds (s). In the case where the air purifier was not installed, the temperature distribution of the ceiling area was uniformly spread in a radial shape by the fire plume. Figure 12 shows the ceiling temperature distribution of the air purifier at non-installation state.

![Figure 12. Temperature distribution of ceiling area—no air purifier.](image)

Figure 12. Temperature distribution of ceiling area—no air purifier.

Figure 13 shows the distribution of ceiling temperature by location of the front-discharge type. The initial pattern of the temperature distribution is determined by the airflow discharged from the air purifier.

![Figure 13. Cont.](image)
Figure 13. Temperature distribution of ceiling area—front-discharge type. (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.

The Front-discharge type was initially affected by the airflow discharged from the air purifier. However, as time passed, the temperature spread to the entire ceiling by airflow movement, compared to the case of non-installation of the air purifier.

By contrast, the top-discharge type showed a phenomenon in which the heat spread was suppressed at the boundary surface by influencing the ceiling jet the collision airflow from the ceiling surface. Figure 14 shows the distribution of ceiling temperature by location of the top-discharge type.

Figure 14. Cont.
The pattern of the heat spreading with the front-discharge type air purifier at location A appears to be similar to that of the no air purifier condition (Figures 11a and 12). On the other hand, the initial and middle stage patterns (20 s, 40 s) of the temperature distribution at location B and C differ from location A. This dissimilarity could be explained by the different surroundings that lead to distinct air flows. The wall behind the sofa can serve as a physical barrier that blocks the air/heat flow, which in turn decreases the impact from the air purifier at location A. The top-discharge type air purifier displays entirely a different pattern compared with the no air purifier and front-discharge type conditions. As for the front-discharge type device, the cold air discharged from the air purifier has less influence on the ceiling; therefore this configuration can maintain the heat diffusion. By contrast, in top-discharge type, the cold air discharged from the air purifier moves directly toward the ceiling. This structure possibly forms a flow barrier that can hinder the diffusion of the heat and air, as can be seen in Figure 14. The origin of the barrier seems to be the location where the flow of cold air migrates toward the ceiling.

3.2.3. Discussion According to the Change of Fire Position

Further analyses are conducted to understand the influence on the detection rate regarding fire locations. Modeling has been applied to the top-discharge type device only, which exhibits a high response delay. The response delay rate of the smoke detector has been calculated by varying the position of the fire source from ⑤ to ⑧ (Figure 15). In this simulation, the smoke detector was analyzed by limiting it to one place in the center of the ceiling.

Figure 16 compares the response time of the smoke detectors regarding the fire positions at different air purifier locations.

The results confirmed that the response delay rate increased from a minimum of 6.2% to a maximum of 111.2%, compared to the non-installed condition of the air purifier. The response time of the smoke detector decreases as the distance between the flame and the air purifier narrows. On the other hand, there is little change in the response delay if no air purifier is installed.

- Location A: since the flame and air purifier are placed in a straight line, the response time is shortened as the distance to the air purifier gets shorter, showing a response delay rate of 6.2%, which is the minimum value at position ⑤.
- Location B: airflow spreads radially from the center of the room without resistance from the wall. Therefore, the response delay rate was higher than in the case of locations A and C, and the response delay rate was 111.2%, which is the maximum value at position ⑧.
- Location C: the distance from the flame is the longest, and thus the reduction in the response delay rate regarding the fire position is small.

Figure 14. Temperature distribution of the ceiling area—top-discharge type. (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.
Figure 15. Modeling on the dissimilar locations of the fire source (top-discharge type only).

Figure 16. Detection time according to fire position (top-discharge type only). (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.

Figure 16. Cont.
3.2.4. Discussion According to the Change of Fire Size

Fire size is also a major factor that affects the delay rate of detector response. A larger fire can lead to a higher diffusion rate of the smoke because of the heat buoyancy. In this simulation, the response delay rate of the smoke detector regarding the fire size has been evaluated by increasing the fire from 200 kW to 550 kW for the room with the top-discharge type device. The smoke detector is analyzed by fixing it to a single place, e.g., the center of the ceiling.

Figure 17 shows the change in response time of the smoke detector regarding the increment of the fire size. It has been found that the response time of the smoke detector was reduced as the fire size increased, but the extended response time resulting from the use of an air purifier did not change.

- At location A: the average response delay rate was 47.3%.
- At location B: the average response delay rate was 89.9%, and the maximum value of 123.6% response delay rate at 250 kW was checked.
- At location C: the average response delay rate was 39.4%, and the minimum value of 23.6% response delay rate at 500 kW was checked.

As a result of the calculation, the average response delay rate of each location was location B > location A > location C. Therefore, it was confirmed that the response time was extended in the corresponding order.

Figure 16. Detection time according to fire position (top-discharge type only). (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.

Figure 17. Cont.
The results obtained from the simulation indicate that the airflow from the top-discharge location B > location A > location C. Therefore, it was confirmed that the response time was extended in the corresponding order.

As a result of the calculation, the average response delay rate of each location was location B > location A > location C. Therefore, it was confirmed that the response time was extended in the corresponding order.

4. Conclusions

In this study, simulations were performed to examine the effect of the air purifiers on the response time of smoke detectors with two types of devices (i.e., top-discharge type and front-discharge type) at three different locations. The results were analyzed according to the installation position of the smoke detector. The relevance of the airflow to the response time of the smoke detector was clearly identified.

The air purifier generates indoor airflow regardless of the device types, thereby affecting the response time of the smoke detector. As for the front-discharge type device, the response delay rate was calculated to be between −12.2% and 54.7%. The response delay rate of the top-discharge type device was evaluated to be between 10.6% and 121.4%. The results obtained from the simulation indicate that the airflow from the top-discharge air purifier can collide with the ceiling jet flow, suppressing the spread of smoke. As a consequence, this gives rise to the response delay of the smoke detector. As for the front-discharge type air purifier, the computation has shown that the discharge airflow has a significant influence on the thermal diffusion during the early stage of fire (20 s, 40 s). Afterward, the air purifier accelerates the thermal diffusion in the room. On the other hand, the top-discharge type device tends to form a flow barrier that can hinder the diffusion of the heat. The core of the barrier for the flow appears to be the location

![Figure 17. Detection time according to fire size (top-discharge type only). (a) Air purifier location A, (b) air purifier location B, and (c) air purifier location C.](image-url)
where the flow of cold air migrates toward the ceiling. The performance difference in the smoke detector is attributed to the dissimilar configuration of the purifier inlet and outlet, which in turn strongly affects the heat/air flow. The information obtained from the temperature distribution suggests that a barrier may be formed at an area where the cold air generated from the purifier moves towards the ceiling. The results from the smoke density distribution signify that it will take a longer time for the top-discharge type device to reach the detection rate of 100% with a minimum of 20 s and a maximum 40 s, as compared with the front-discharge type device. Additionally, the results of the computation suggest that the response delay rate becomes the highest when the smoke detector and the air purifier are aligned in a straight line due to the airflow. Hence, it is necessary to avoid being in a straight line to minimize the impact on the response delay rate of the smoke detector.

Taken together, to enhance the reliability of the smoke detector, the optimal placement would be considered on the basis of the indoor air home appliance performance, the area of use, the installed location, and the number/position of the mounted smoke detectors. Especially, the structure and configuration of the purifier outlet and inlet are likely to be the key factors that determine the air flow and heat dynamics during a fire event. A current barrier can be easily formed when the airflow collides with the jet flow on the ceiling, and a physical barrier close to the jet flow (i.e., wall) could further suppress the air flow diffusion. This could result in a notable delay of the smoke detector response and must be considered in designing an indoor space to increase the survival rate of occupants. The present study will provide key guidance for the appropriate configuration of indoor smoke detectors.

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