

CFD simulation analysis on integrated operation of range-hood and make-up air supply for cooking-generated particulate matter

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Abstract. One of the most important problems of cooking-generated particulate matter (PM) is that it rapidly disperses when the range hood is in operation during cooking. To improve the performance of the range hood and prevent the dispersion of PM, a supply of make-up air equivalent to the airflow rate of the range hood should be provided. In this regard, we place an auxiliary supply system as a make-up supply to solve such problems. The objective of this study is to evaluate the performance of the make-up air supply system and the range hood. To evaluate this system, several case studies were performed involving CFD simulations. The auxiliary supply system is optimized through three types of variables (size of diffuser, distance from the source, and flow angle). An increase in the length of the diffuser causes PM dispersion to decrease. The installation of the diffuser at a certain distance from the emission source is effective in preventing dispersion of cooking-generated PM. In the building analyzed in this study, supplying the make-up air at an angle of 10° was observed to be most effective.

1 Introduction

In recent years, as indoor particulate matter (PM) has received increasing attention, there have been several studies involving PM measurements in households. Congrong He et al. analyzed the source of indoor PM in 15 houses located in Brisbane, Australia, and observed that an occurrence of large amount of PM during cooking. In particular, PM concentrations were observed to be up to 30 and 90 times higher than background levels during frying and grilling, respectively.[1] J. Kearney et al. investigated the indoor and outdoor effects of ultrafine particles proved that indoor-generated particles constitute a large portion and cooking makes up for the greatest percentage.[2] Hence, it is necessary to pay attention to indoor activities that affect the indoor PM, particularly with regard to cooking.

Ventilation is necessary to remove the cooking-generated PM. The main ventilation methods used for apartment houses are mechanical ventilation and natural ventilation. According to Tian et al., mechanical ventilation is more effective than natural ventilation at removing cooking-generated PM.[3] In South Korea, most apartment houses are equipped with ventilation devices. However, the operating rate of the ventilation systems is extremely low among occupants.[4]

One of the most important problems raised in previous studies is that cooking-generated PM rapidly disperses even when the range hood is in operation during cooking.

This suggests that the range hood fails to exhibit sufficient performance when it is in operation. The range hood performance is low because the required make-up air is not supplied when the range hood is in operation. To solve this problem, a ventilation system that combines the range hood with other ventilation systems is necessary.

Therefore, this study aims to propose integrated operation strategies to optimize ventilation effects during cooking. To this end, we evaluated the operation strategies of the auxiliary supply system and the range hood during cooking. The computation fluid dynamics (CFD) simulation analysis method was applied to perform various case studies.

2 Method

In South Korea, residential buildings are equipped with ventilation systems and local exhaust systems. The local exhaust system is generally installed in the kitchen and toilet and is designed to rapidly discharge contaminants in a space that have the largest potential contaminant sources (usually moisture and odor). However, the operation of the range hood involves large amounts of PM exhaust from the kitchen. If the range hood is operated separately, there is insufficient air supply and efficiency reduces. Therefore, for performance improvement, make-up air supply equivalent to the airflow rate of the range hood should be provided.

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To achieve this, an integrated operation of range hood and make-up air supply is required. Utilizing the auxiliary supply system, it can supply make-up air to the range hood. The auxiliary supply system (AS) is installed behind the cooktop and supplies air with a thin and long line diffuser. Through this airflow, an effect similar to that of an air curtain can be achieved. When air is supplied at a high speed from the line diffuser, it demonstrates a behavior characteristic similar to a jet stream.[5] This can block the flow of PM that disperses quickly through the ceiling.

2.1. Building description

The building used for the experiments is the Air Quality Management Laboratory (AQM Lab) of Haatz Inc. located in Pyeongtaek, Gyeonggi-do. This experimental house was constructed based on the same floor plan as a typical Korean apartment. The floor area is 92.6 m², making it a medium-size domestic apartment. The wall height is 2.3 m, which is equal to the height of a standard apartment house. CO₂ was measured in only the living room and kitchen to validate the CFD model. The area of the kitchen and living room is 47 m². The target space was thoroughly sealed by taping it. Figure 1 shows the floor plan of the experimental house, the location of the ventilation diffuser, and measurement points.

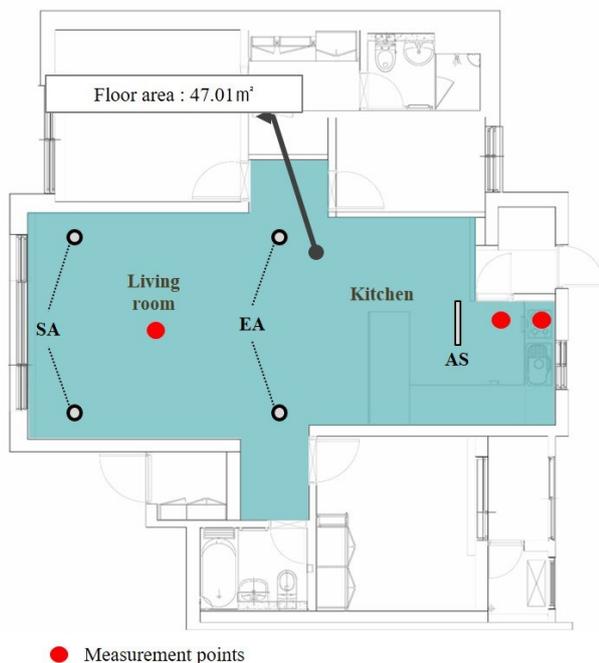


Fig. 1. Floor plan of the experimental house.

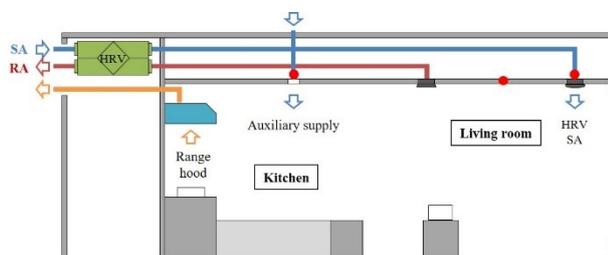


Fig. 2. Schematic of ventilation systems of target building.

2.2 Computational fluid dynamics model

The governing equations for fluid dynamics can be calculated in different forms, including the Navier–Stokes equations, energy equation, and equation of state. Over the past few decades, CFD has played an important role in building design and HVAC systems.[6] Currently, CFD techniques are being widely used in researching indoor air quality.[7]

To analyze the CFD simulation, appropriate turbulence model selection, detailed modeling, and accurate boundary conditions should be established. The CFD simulation items used in this study are summarized in Table 1.

Table 1. Details of CFD simulation.

Component	Contents	
Mesh	Type	Polyhedral mesh
	Cells	580,347
	Prism layer	Thickness: 20 mm
Turbulence specification	Turbulence model	Standard k-ε turbulence model
	Multi-phase model	Eulerian-Eulerian model
	Convection Scheme	2nd-order upwind scheme
	Time	Steady state/Unsteady state
Boundary Condition	Turbulence intensity	0.105
	Turbulence viscosity ratio	10
	Temperature	Measurement data
	Velocity	Measurement data

2.3 Case study

In this study, a case study was conducted via CFD simulation. Simulations were done to optimize the AS during cooking. This assumes a cooking condition and performs a steady-state simulation analysis. For ventilation, the AS and the range hood are simultaneously operated. Case a analyzes the performance of PM dispersion prevention depending on the size of the supply diffuser. The diffuser lengths are 1.5 m, 1.2 m, 0.9 m, and 0.6 m. Based on the PM analysis according to the diffuser length (Case a), an analysis about the position and the flow angle of a diffuser was conducted using 1.2-m-long line diffuser of Case a. Case b evaluates the performance of prevention of cooking-generated PM dispersion when the distance from the emission source (cooktop) changes. Lastly, Case c analyzes the performance when the flow angle is changed from 10° to 30° based on Case b. A total of 12 cases are included. The airflow rate of the range hood and ventilation system is 150 CMH (m³/h). The detailed information of each case for CFD analysis is described in Table 2.

Table 2. Detailed description of case study.

Case	Position of diffuser (from the source)	Size of diffuser	Flow angle
a	1	0.0216 (1.5*0.0072)	Normal
	2	0.0216 (1.2*0.009)	
	3	0.0216 (0.9*0.012)	
	4	0.0216 (0.6*0.018)	
b	1	0.0216(1.2*0.009)	Normal
	2		
	3		
	4		
c	1-1	1.0 m	10°
	1-2		20°
	1-3		30°
	2-1	1.5 m	10°
	2-2		20°
	2-3		30°
	3-1	2.0 m	10°
	3-2		20°
	3-3		30°
	4-1	2.5 m	10°
	4-2		20°
	4-3		30°

3 Validation of CFD model

Accurate and detailed modeling is required for reliable CFD simulation analysis. In this study, the geometries of the kitchen and the living room were modeled in detail to simulate the same situations as the experiment conditions. In addition, a human-body model was created to apply the influence of an occupant during cooking. Prior to the simulation analysis, a grid sensitivity analysis and validation were carried out via the tracer gas method (carbon dioxide).

3.1. Grid sensitivity analysis

The CFD simulation is highly dependent on the size and shape of a grid. Therefore, selecting appropriate mesh properties not affected by the shape and size of the grid is critical. In this study, three grid sizes were applied to perform grid sensitivity analysis. The grid sizes for analysis are shown in Table 3. In the analysis, the normalized concentration and temperature of the kitchen were compared. The results of the grid sensitivity analysis demonstrated that the medium-size grid has an error of less than 5% compared to the fine grid. Therefore, in this

study, the simulation analysis was performed by applying the medium-size grid (Fig. 3). The number of grids (cells) was approximately 580,000 polyhedral cells. There are many complex shapes in the kitchen; and a polyhedral mesh model was selected because it is flexible and can imitate various shapes.

Table 3. Grid sensitivity analysis.

	Coarse grid	Medium grid	Fine grid
Minimum size	0.2	0.1	0.1
Target size	20	10	8
Cells	393,515	583,371	1,109,294

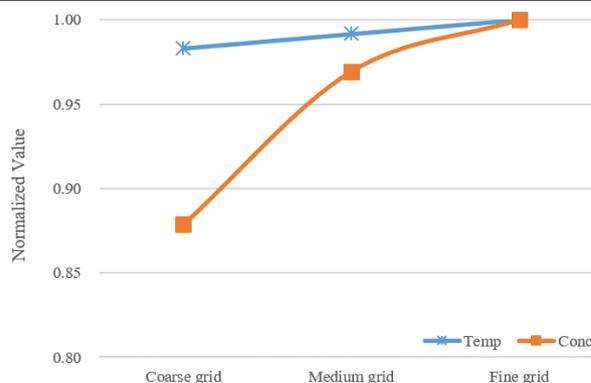


Fig. 3. Results of grid sensitivity analysis.

3.2 Validation of CFD simulation model

Figures 4 and 5 are graphs that compare the result of the CFD simulation analysis and measurement data for validating the simulation model. The simulation was validated using the room temperature and concentration data. Measurements were performed at 10 s intervals, and data were selected when the temperature and concentration distributions reached a steady state. The concentration distribution was measured for the living room, kitchen, and corridor between the living room and the kitchen. To analyze the contaminant concentration, carbon dioxide was applied as a tracer gas.

A comparison between the CFD simulation and the measurement data reveals that the temperature exhibits behaviour characteristics that are very similar to the measurement data. The temperature is underestimated in some regions of the ceiling in the kitchen; however, approximate results can be observed at other points. The average concentrations were utilized for comparison. The concentration data demonstrate that the concentration distribution is also very similar to that of the measurement value. Therefore, these results indicate that there is no difficulty in performing the case study using this simulation model.

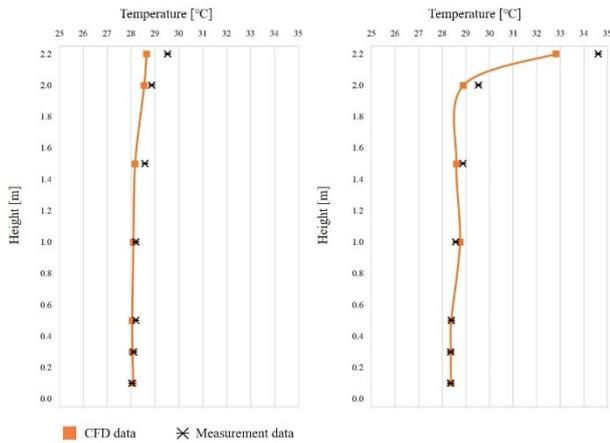


Fig. 4. Temperature distribution of CFD and measurement data.

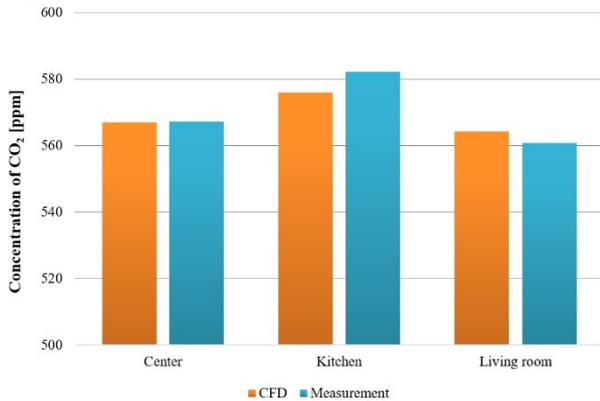


Fig. 5. Comparison of CFD and measurement data (Tracer gas).

4 Results and discussion

4.1. Case a: Size of diffuser

The sizes of the diffusers for the case study analysis had a constant area, but the lengths were different. The area was the same, and therefore, the velocity magnitude of the inlet boundary remained the same even though the length of each diffuser was different. The diffuser was located 1.5 m away from the PM source; the flow angle was a boundary normal.

Figures 6 and 7 show the distributions of PM_{2.5} for each case. The PM_{2.5} concentration for Case a-1 is relatively low compared to that for other cases. In particular, the PM_{2.5} concentration dispersed into the living room is low. The concentration distribution of the vertical section reveals that PM dispersing to the ceiling is blocked by the airflow, and thus, the concentration is considerably lower in the ceiling than in the living room.

Case a-2 shows a concentration distribution similar to that of Case a-1. However, some of the PM disperses towards the end of the living room. The vertical concentration distribution is also almost similar to that of Case a-1. However, the concentration at the bottom is lower than that in Case a-2.

Cases a-3 and a-4 show that their short diffuser lengths make it difficult to prevent the dispersion of the PM. In particular, in Case a-4, the concentration of PM is higher than 80 $\mu\text{g}/\text{m}^3$ in some areas of the ceiling in the living room.

The longer the diffuser length, the more effective it is to prevent the dispersion of cooking-generated PM. However, if the length of the diffuser is long, it may cause inconvenience to the occupants. In this study, a case study on the distance and angle was conducted based on the results of Case a-2 (length of diffuser: 1.2 m).

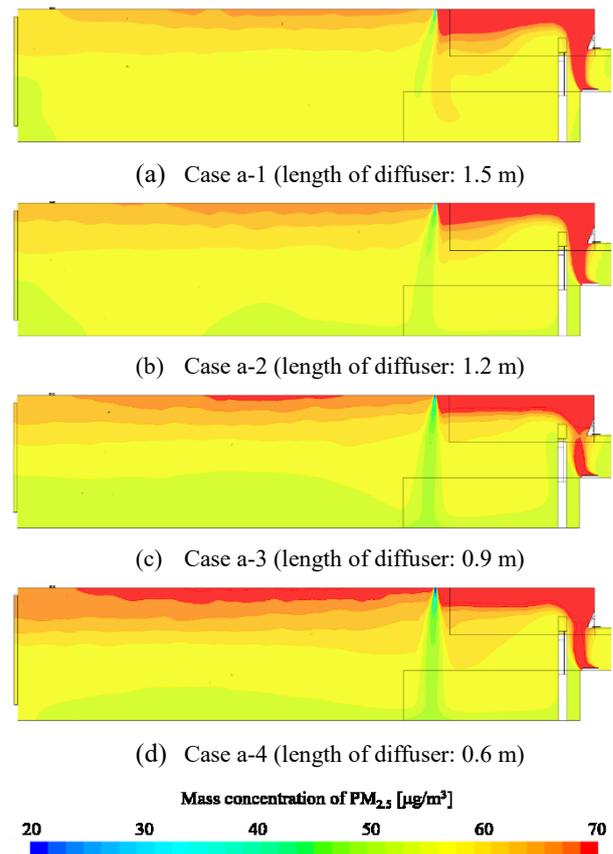


Fig. 6. PM_{2.5} distribution of vertical section (Case a)

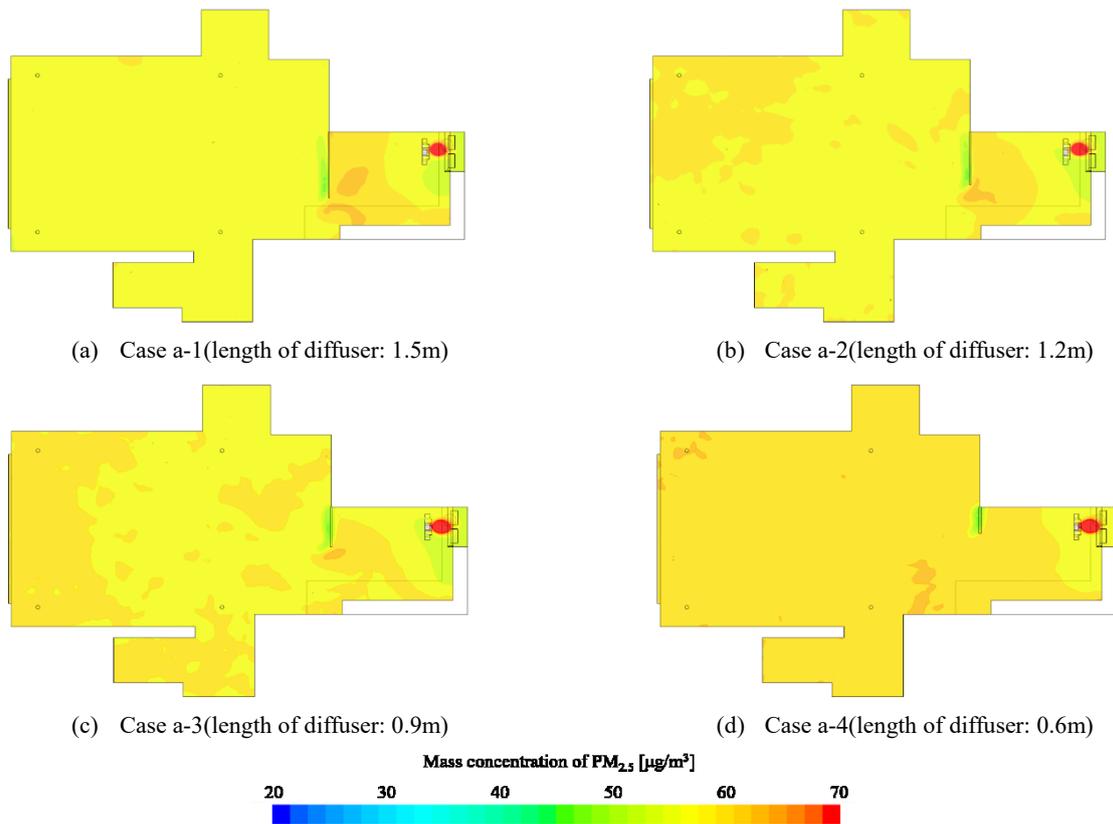


Fig. 7. $PM_{2.5}$ distribution of 1.5m height (Case a)

4.2. Case b: distance from the emission source

In Case b, the $PM_{2.5}$ concentration was evaluated according to the distance from the emission source. A diffuser size of 1.2 m was applied to the SA diffuser. The

distances were 1.0 m, 1.5 m, 2.0 m, and 2.5 m from the source. The closer the distance to the emission source, the faster is the rate of dispersion from the source. Therefore, as the PM is closer to the emission source, the flow angle should be changed, or the boundary velocity increased in order to prevent its dispersion.

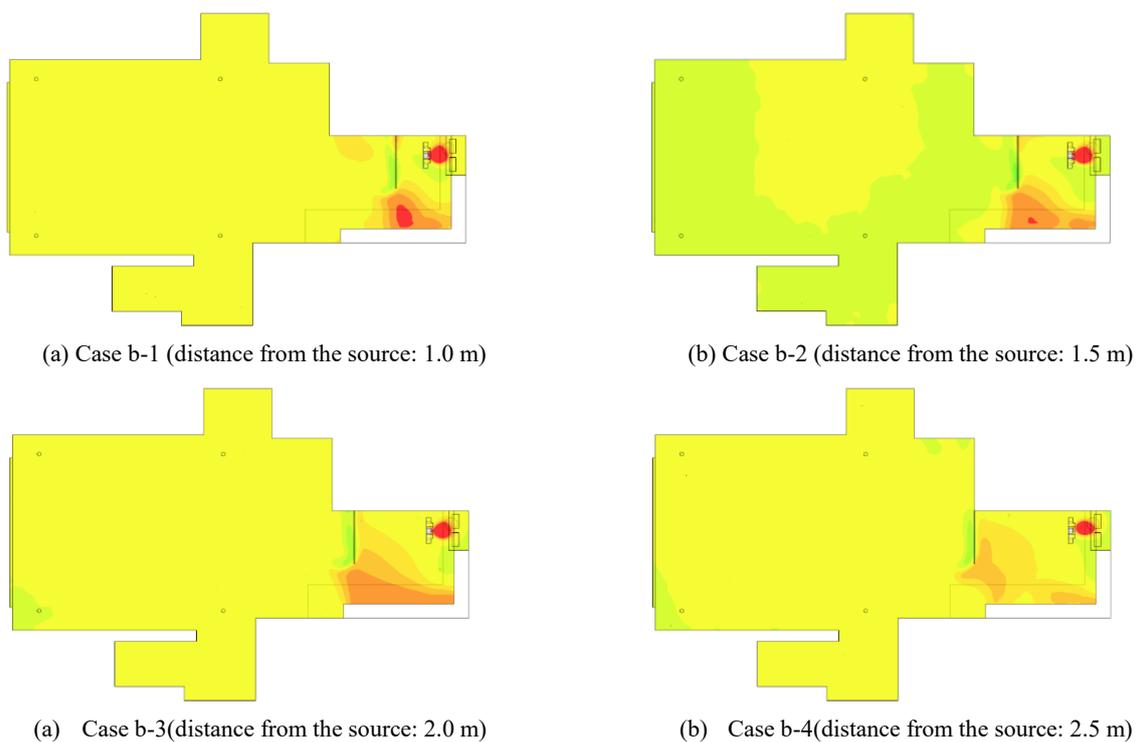


Fig. 8. $PM_{2.5}$ distribution of 1.5m height (Case b)

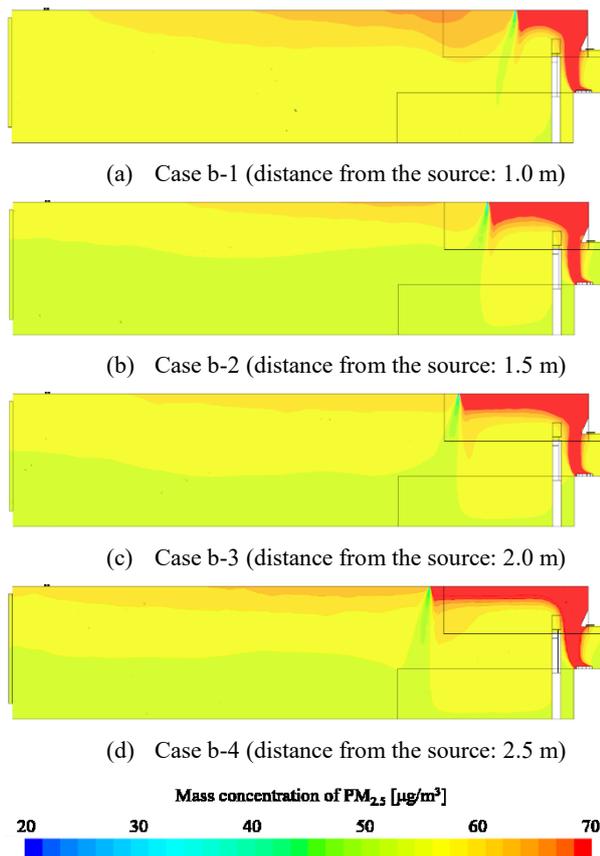


Fig. 9. PM_{2.5} distribution of vertical section (Case b)

Figures 8 shows the distributions of PM_{2.5} for each case. Case b-1 is relatively high in concentration compared to the other cases. Since the distance is shorter, and the dispersion rate is faster, and it is difficult to prevent dispersion; thus, the concentration is high.

Case b-2 shows the lowest concentration distribution. In fact, the dispersion speed on the ceiling is almost 0.3–0.4 m/s, which is relatively low, in comparison to 1.5 m. Therefore, the influence of the dispersion rate decreases after a distance of 1.5 m from the emission source.

Cases b-3 and b-4 show relatively higher PM_{2.5} concentrations than that in Case b-2. Between the kitchen and the diffuser of the AS, there is a space for the PM to stay in. The greater the distance from the

source, the wider is the space. As this space becomes wider, the PM is more likely to disperse to the living room.

4.3. Case c: flow angle

Figure 10 shows the velocity distributions of each case. If the diffuser is installed near the emission source, a wind directly blows towards the occupant cooking food, who can feel comfort. If the diffuser is installed at a distance of 1.0 m and 1.5 m, the wind will blow directly to the occupant when the flow angle exceeds 20°. Therefore, its application seems to be difficult in this case. If the distance is more than 2.0 m from the emission source, a strong wind does not blow directly to the occupant even though the angle can reach up to 30°.

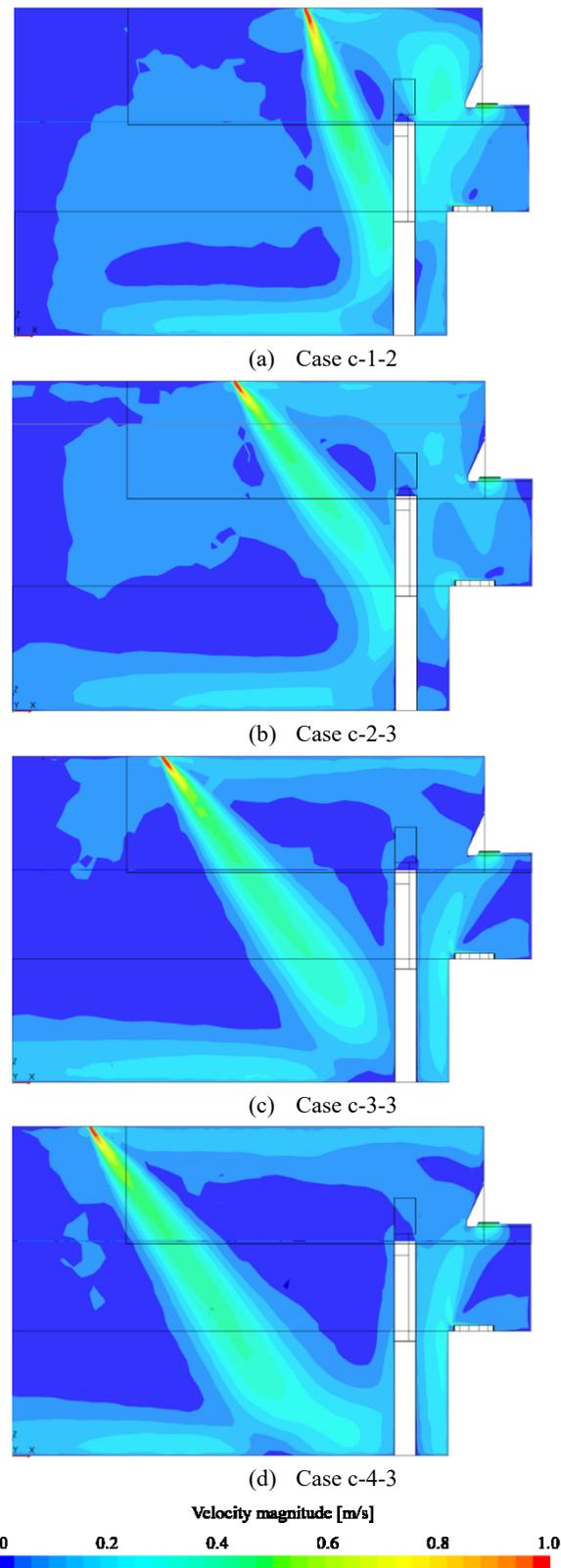


Fig. 9. Velocity distribution in the kitchen

Figure 11 shows the mean concentrations of the PM dispersed into the living room according to the flow angle based on the distance from the emission source. First, when the distance is 1.0 m from the emission source, the amount of PM dispersed into the living room decreases as the angle increases. However, if the flow angle is more than 20°, the application is difficult due to the strong wind.

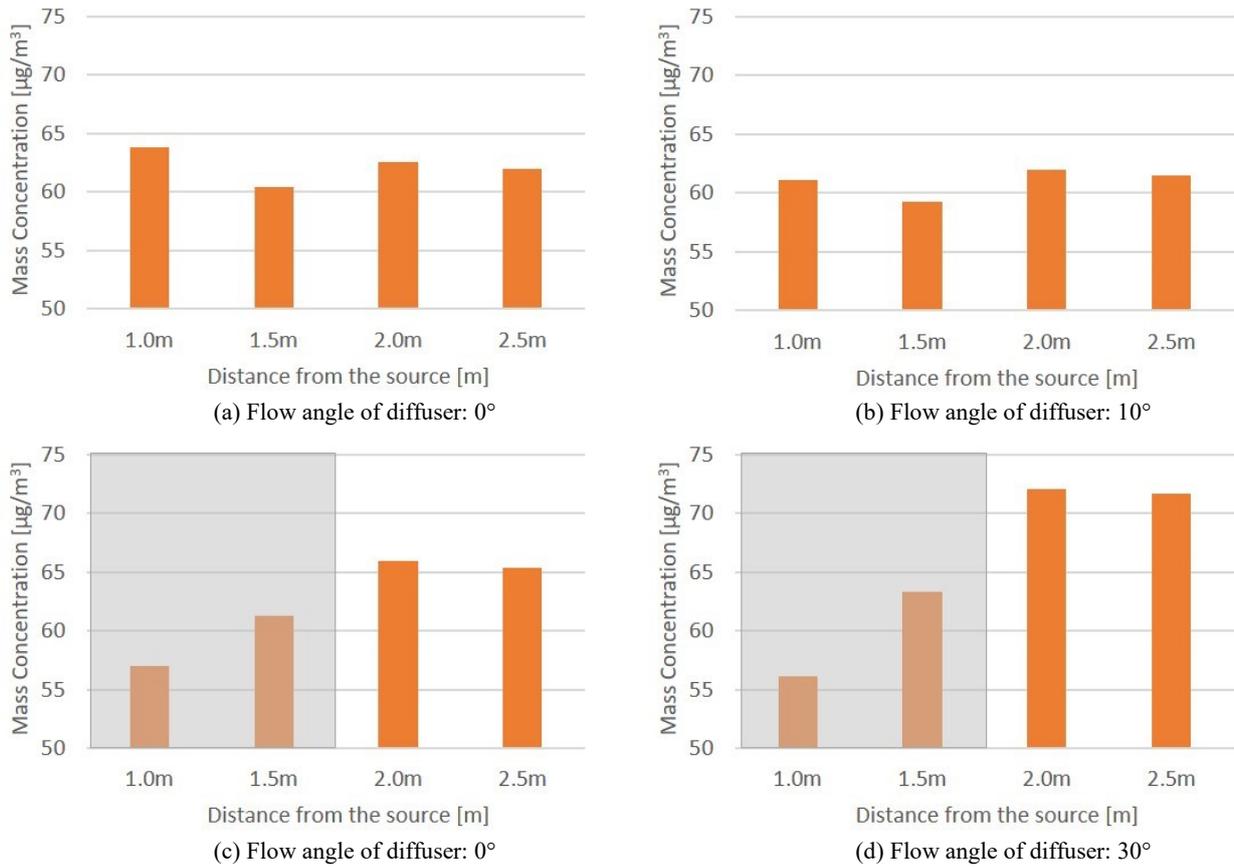


Fig. 11. PM2.5 concentration of living room by flow angle

Therefore, in this case, it is appropriate to supply the make-up air at an angle of 10° .

First, if the distance is 1.5 m from the emission source, the amount of the PM dispersed into the living room decreases for a flow angle of 10° , and the dispersed PM increases as the angle increases. Even in this case, if the flow angle is more than 20° , the wind makes it difficult to perform the application; thus, it is appropriate to supply the make-up air at an angle of 10° .

Even if the distance is 2.0 m or 2.5 m from the emission source, the amount of PM dispersed into the living room decreases until the flow angle reaches 10° ; however, the dispersed PM concentration increases with an increase in the angle. In both cases, as the angle increases, the amount of PM dispersed into the living room also increases considerably. When the flow angle is 10° , the dispersed PM concentration is low in all cases. Therefore, if the flow angle is set at 10° in this building, it will be most effective in reducing the dispersed PM.

4.4. Discussion

The operation strategy used to integrate the range hood with the AS during cooking was analyzed by applying three variables. The experimental house has a 0.6-m-long diffuser, placed 2.0 m away from the source, and the SA flows in the normal direction. The relative analysis of each variable was carried out based on this scenario. The length of diffuser was analyzed for lengths of 0.6, 0.9, 1.2, and 1.5 m. When the length of the diffuser increases, an

additional 3.4% dispersion reduction effect is observed. However, if the length of the diffuser is increased to 1.5 m, the wind may blow directly into the cabinet, which may disperse the PM. Therefore, it is appropriate to set the length of diffuser to 1.2 m in the target building. In this case, the dispersion reduction effect of 2.8% compared to that of the base model can be obtained. The analytical results showed that the flow angle was 10° and the distance from the source was 1.5 m. If the flow angle is adjusted to 10° in the base model, a dispersion reduction effect of 8.02% can be obtained. Further, installing the diffuser 1.5 m away from the source improves 9.95%. In addition, if the flow angle is further adjusted to 10° , a total improvement of 13.4% can be achieved.

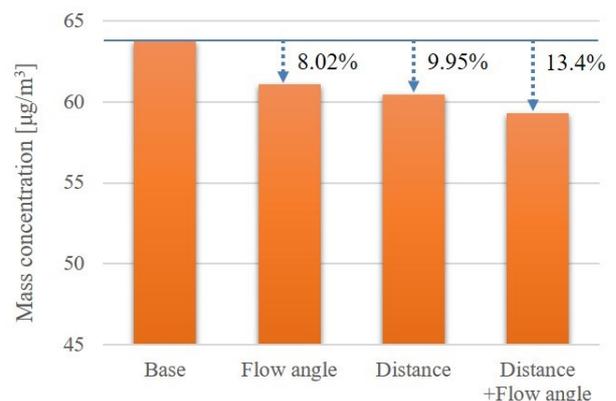


Fig. 12. Performance of each variable during cooking

5 Conclusion

This study proposes strategies to optimize the effects of ventilation during cooking. To this end, it evaluated the operation strategies of the AS and the range hood during cooking. Several variables were set to optimize the effectiveness of each strategy. The CFD simulation analysis method was used to perform case studies for each strategy. The conclusions obtained from this chapter are as follows.

The integration of the AS and the range hood was observed to be effective in preventing the dispersion of PM during cooking. To maximize the effect, several application methods for the AS (size of diffuser, distance from the source, flow angle) were selected, and its performance was evaluated. First, we observed that as the length of the diffuser increases, PM dispersion decreases. As most cooking-generated PM disperse through the ceiling, the area that can be blocked increases as the diffuser length increases. Installing the diffuser at a certain distance from the emission source is effective in preventing cooking-generated PM dispersion. If the distance from the source is too close or too far away, preventing dispersion is difficult. In the experimental house analyzed in this study, PM dispersion was most effectively prevented when the position of the diffuser was 1.5 m away from the emission source. Finally, the flow angle needs to be adjusted. When the flow angle is in the normal direction, the jet axis of the AS is bent in the direction of the living room toward the cooking-generated PM that is being dispersed at a high speed. This can lead to PM dispersion into the living room. Therefore, supplying the make-up air at a certain angle is appropriate. In the building analyzed in this study, it was most effective to supply the make-up air at an angle of 10°. If all systems are optimized, a total reduction of 13.4% can be achieved.

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