Effect of Vent Area Ratio on Vent Flow Characteristics and Temperature Distribution in a Compartment Fire with Two Ceiling Vents

Yu Mi Park\textsuperscript{1}, Chi Young Lee\textsuperscript{1,2}\textsuperscript{†}

\textsuperscript{1}Division of Architectural and Fire Protection Engineering, Pukyong National University, 45 Yongso-ro Nam-gu, Busan 48513, Republic of Korea
\textsuperscript{2}Department of Fire Protection Engineering, Pukyong National University, 45 Yongso-ro Nam-gu, Busan 48513, Republic of Korea

(Received January 14, 2023; Revised January 20, 2023; Accepted February 20, 2023)

Abstract: In this study, the effect of the vent area ratio on vent flow characteristics and temperature distribution in a compartment during a fire in the compartment with two ceiling vents was examined. The area ratio ($A_1/A_2$) between ceiling vent 1 (CV1), with a duct height of 0.19 m, and ceiling vent 2 (CV2), with a duct height of 0.05 m, was varied from 0.052 to 0.542, 1, 5.587, and 19.36, and numerical simulation was performed under these conditions. As the $A_1/A_2$ ratio increased, the flow pattern changed from unidirectional inflow to bidirectional flow for CV1 and from bidirectional flow to unidirectional inflow for CV2. When the $A_1/A_2$ ratio was 0.542, the outflow and inflow mass flow rates for CV1 and CV2 were found to be nearly equal. The outflow and inflow mass flow rates at CV1 were higher than those at CV2 when the $A_1/A_2$ ratio was low, while the outflow and inflow mass flow rates at CV2 were higher than those at CV1 when the $A_1/A_2$ ratio was high. Furthermore, it was observed that the temperature was lower and the temperature difference between the higher and lower regions in the upper part of the measurement position decreased near the lower part of the vent with a larger area compared to the vent with a smaller area. This was probably because the mixing effect increased near the vent with a larger area due to the occurrence of the active bidirectional flow pattern. When the flow pattern at CV1 was bidirectional, the previous correlation for predicting mass flow rate was examined. It was found that the previous correlation underestimated the mass flow rate of the numerical simulation conducted in this study.

Keywords: Compartment fire; Two ceiling vents; Vent flow pattern; Temperature distribution; Numerical simulation

1. Introduction

To minimize human casualties and property damage during a compartment fire, it is essential to quickly discharge smoke outside. Natural smoke ventilation systems can be employed to achieve this, as they have lower construction and maintenance costs compared to mechanical smoke ventilation systems\cite{1}. Natural smoke ventilation systems can be suitable for spaces such as atriums, ships, and theaters\cite{2-5}, and the research conducted under the presence of horizontal vent in the ceiling of compartment can be applied to the design of natural smoke ventilation systems.

Some studies were conducted in the presence of horizontal vent in the ceiling. Park and Lee\cite{4}, based on the work of Park et al.\cite{5}, examined the effects of heat release rate and fire source position on temperature distribution in the compartment and vent flow characteristics. Numerical simulations were performed using the fire dynamics simulator (FDS), and the results were compared with the results of Park et al.\cite{5} to analyze the effects of the location of the fire source on the temperature inside the compartment, the velocity of the vent flow, and its mass flow rate. Park et al.\cite{6} investigated fire phenomena of a full-scale object and a scaled model with horizontal vent in the ceiling of a compartment to check the accuracy of the scaling law for the fire phenomena (e.g., outflow mass flow rate, temperature, and velocity) of the corresponding geometry. Zhang et al.\cite{7} conducted research to predict the temperature during a fire in a compartment with a ceiling vent. They proposed a correlation through theoretical analysis and experiments and reported that the average temperature rise is proportional to the 2/3 power of the heat release rate. Li et al.\cite{8} examined the gas temperature rise and average gas temperature rise rate based on ceiling vent area and
fire size in a compartment with a ceiling vent and analyzed the effect of the ceiling vent area on fire development process. However, these previous studies were conducted under condition where only one ceiling vent was installed. To enhance design flexibility and performance when using ceiling vents for natural smoke ventilation systems, research involving two or more horizontal vents is necessary.

Some studies have been conducted on the behavior of fluids that pass through two horizontal vents. Epstein[9] performed an experiment on the exchange flow caused by the density difference between saltwater and freshwater under the condition of two horizontal vents installed. Based on the experimental results, three combinations of horizontal vent flow patterns were reported, as shown in Figure 1. They represented a case in which the first and second horizontal vents have the flow patterns of unidirectional outflow and unidirectional inflow (Figure 1(a)), a case with bidirectional flow and unidirectional inflow (Figure 1(b)), and a case with bidirectional flow and bidirectional flow (Figure 1(c)). In addition, volumetric flow rate prediction correlations were proposed for certain conditions. In the presence of horizontal vents, it is known that the behavior of fluids that pass through the vents is determined by the density difference and pressure difference through the vents[10,11]. However, in the study conducted by Epstein[9], the flow through horizontal vents was determined only by the density difference under non-fire condition. Recently, Park and Lee[12] investigated the effects of the duct heights of horizontal vents and the position of the fire source on the flow patterns and mass flow rates of the vents as well as temperature distribution in a compartment during a fire in the compartment with two ceiling vents through numerical simulations. In the study of Park and Lee[12], however, the two vents had the same size (5% of the floor area), and research was not conducted on the cases where they had different areas.

![Figure 1. Vent flow pattern reported in a study by Epstein[9].](image)

In this study, the effect of vent area ratio on vent flow characteristics and temperature distribution was examined for a compartment fire with two ceiling vents using numerical simulation. Based on a previous study[12] conducted under the condition of equal vent areas, this study involved varying the areas of the ceiling vents. The mass flow rate of the vent flow, its patterns, and temperature distribution measured below the vents were reported for five vent area ratios, and the relationship between vent flow characteristics and temperature distribution was analyzed. Furthermore, based on the mass flow rate measurement results from the numerical simulation, the flow rate prediction correlation in the previous study[9] was evaluated.
2. Numerical Simulation Methods and Conditions

2.1 Numerical simulation methods

In this study, a scaled model was developed to facilitate experimentation for validating numerical simulation results. Specifically, the research was based on the numerical simulation geometry and conditions used in the previous study[12]. Figure 2 presents a schematic of the numerical simulation employed in this study. The compartment measured 1.36 m in width, 1.5 m in depth, and 1.1 m in height, and it featured two ceiling vents. In accordance with the previous study[12], two vents with different heights were set. As depicted in Figure 2, the height of Ceiling Vent 1 (CV1) is higher than that of Ceiling Vent 2 (CV2), and each ceiling vent is designed as a square. Furthermore, numerical simulations were conducted while varying the areas of the ceiling vents, with further details described in Section 2.2.

In this study, a total of 40 temperature measurement points were set to assess the temperature distribution inside the compartment, as illustrated in Figure 3. These points were placed in the height direction at two positions, labeled as TC1 and TC2. At TC1 and TC2, 20 measurement points were set at 50-mm intervals from the compartment floor. TC1 and TC2 were positioned 340 mm away from the center of the compartment floor and corresponded to the centers of CV1 and CV2, respectively. Moreover, as shown in Figure 3, the outflow and inflow mass flow rates passing through the two ceiling vents were measured.

![Figure 2. Schematic of numerical simulation.](image)

![Figure 3. Positions of temperature and mass flow rate measurements.](image)
The fire source was located at the center of the compartment floor, and the fuel used was methanol. To set the heat release rate, a heat release rate measurement experiment was performed under conditions similar to those of the compartment of this study. Based on the experimental results, a heat release rate of 3.01 kW was applied. Additionally, during the setting of the fire source, the t-squared fire model[13] shown in Eq. (1) was used. An ultrafast fire growth rate and a fire growth factor of 0.1876 kW/s² were applied.

\[
\dot{Q} = at^2
\]

where \( \dot{Q} \) denotes the heat release rate, \( a \) denotes the fire growth factor, and \( t \) denotes time.

In this study, numerical simulation was performed using FDS (Ver. 6.6.0), and \( D^*/\delta x \) (plume resolution index)[14] was considered to set the grid size. Here, \( D^* \) denotes the characteristic fire diameter and \( \delta x \) denotes the grid size. For \( D^*/\delta x \), the National Institute of Standards and Technology (NIST)/the Nuclear Regulatory Commission (NRC)[14] proposed a range of 5-11. Based on this, the grid size was set to 0.01, 0.02, and 0.05 m, and preliminary numerical simulation was performed to examine the numerical simulation results with respect to the grid size. It was found that there was no significant difference between the results of conditions with grid sizes of 0.01 and 0.02 m. However, the results of the condition with a grid size of 0.05 m were significantly different from those of the other conditions. Based on these results of the preliminary numerical simulation, the conservative condition of a 0.01-m grid size was applied to minimize the impact of the grid size on the numerical simulation results. In this study, \( D^*/\delta x \) was 9.4 and the total number of grid cells in numerical simulation was 3,645,600. The numerical simulation time was set to 600 s.

2.2. Numerical simulation conditions

The schematics and detailed conditions of the two ceiling vents examined in this study are presented in Figure 4 and Table 1, respectively. In this study, abbreviations were used to describe the conditions and results of the numerical simulations. In Figure 4 and Table 1, CV1 and CV2 represent ceiling vent 1 and 2, respectively. Furthermore, A and L denote the area and height of each ceiling vent, respectively, while S denotes the length of one side of the ceiling vent. Subscripts 1 and 2 indicate ceiling vent 1 and 2, respectively. For example, CV1_A0.5&CV2_A9.5 refers to the condition where CV1’s area is 0.5% of the compartment floor area (A0.5) and CV2’s area is 9.5% of the compartment floor area (A9.5).

![Schematics of two ceiling vents (side-view)](image-url)
Table 1. Summary of Numerical Simulation Conditions for Two Ceiling Vents

<table>
<thead>
<tr>
<th>Cases</th>
<th>CV1</th>
<th>CV2</th>
<th>A1/A2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1 (m²)</td>
<td>S1 (m)</td>
<td>L1 (m)</td>
</tr>
<tr>
<td>CV1_A0.5&amp;CV2_A9.5</td>
<td>0.5% of Floor Area</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV1_A3.5&amp;CV2_A6.5</td>
<td>3.5% of Floor Area</td>
<td>0.268</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>(0.0718)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV1_A5.0&amp;CV2_A5.0[12]</td>
<td>5.0% of Floor Area</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1024)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV1_A8.5&amp;CV2_A1.5</td>
<td>8.5% of Floor Area</td>
<td>0.416</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1731)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV1_A9.5&amp;CV2_A0.5</td>
<td>9.5% of Floor Area</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1936)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this study, the combined area of the two ceiling vents was set to 10% of the compartment floor area based on the safety guidelines and technical standards for stage facilities in theaters[15], which stipulate that the minimum area of natural smoke vent in a theater must be at least 10% of the stage area. Furthermore, the ratio of each ceiling vent's area to the compartment floor area was used to express the areas of the ceiling vents. As depicted in Figure 4 and Table 1, CV1’s area was set to 0.5 (0.01 m²), 3.5 (0.0718 m²), 5.0 (0.1024 m²), 8.5 (0.1731 m²), and 9.5 (0.1936 m²) % of the compartment floor area, while the corresponding area of CV2 was set to 9.5 (0.1936 m²), 6.5 (0.1325 m²), 5.0 (0.1024 m²), 1.5 (0.0310 m²), and 0.5 (0.01 m²) % of the compartment floor area, respectively. In these cases, A1/A2 ratios were 0.052, 0.542, 1, 5.587, and 19.36. For all cases, the heights of CV1 and CV2 were fixed at 0.19 and 0.05 m, respectively. Additionally, in this study, the numerical simulation results of the previous study[12] were used as the data for the CV1_A5.0&CV2_A5.0 condition (or the A1/A2=1 condition) in Figure 4 and Table 1.

3. Results and Discussion

3.1 Mass flow rate and pattern of vent flow

Figure 5 shows the mass flow rates of the vents measured under the five vent area conditions, as well as the flow patterns determined based on them. For the mass flow rate data, the time-averaged mass flow rate data in the duration of 500-600 s are shown, and the error bars indicate the standard deviations of the corresponding mass flow rate data over time.

For the flow pattern passing through CV1, inflow (unidirectional flow) from the outside of the compartment to its inside was observed under the condition with the smallest CV1 area (Figure 5(a)). Under other conditions, bidirectional flow involving both outflow and inflow through the vent was observed. Similarly, for the flow pattern passing through CV2, inflow was observed under the condition with the smallest CV2 area (Figure 5(e)), and bidirectional flow was mostly observed when the area was large. Hence, for CV1 and CV2, unidirectional inflow...
occurred when the area was small, and bidirectional flow occurred when the area was large. As $A_1/A_2$ ratio increased, the flow pattern changed from unidirectional inflow to bidirectional flow for CV1 and from bidirectional flow to unidirectional inflow for CV2.

**Figure 5.** Mass flow rate and pattern of vent flow.
Based on the results in Figure 5, the vent flow patterns observed under the conditions of the numerical simulation in this study are summarized in Figure 6. Under the numerical simulation conditions, three combinations of vent flow patterns were observed. They represented a case in which unidirectional inflow occurs at CV1 and bidirectional flow at CV2 (Figure 6(a)), a case in which bidirectional flow occurs at CV1 and CV2 (Figure 6(b)), and a case in which bidirectional flow occurs at CV1 and unidirectional inflow at CV2 (Figure 6(c)). As shown in Figure 6, bidirectional flow or unidirectional inflow occurs at each vent under the conditions of the numerical simulation, and unidirectional outflow from the inside of the compartment to its outside is not observed. A combination of outflow at CV1 and inflow at CV2 (Figure 1(a)) was observed in the previous study[9], but no such combination was observed in this study.

Figure 6. Summary of the vent flow pattern observed in this study.
Based on the outflow and inflow mass flow rate measurement results for the vents shown in Figure 5, the effect of the area ratio ($A_1/A_2$) between CV1 and CV2 on the outflow and inflow mass flow rates of the vents is illustrated in Figure 7. Figures 7(a) and 7(b) display the results for CV1 and CV2, respectively. Overall, the outflow and inflow mass flow rates through CV1 increased as the $A_1/A_2$ ratio increased (i.e., as the area of CV1 increased) (Figure 7(a)), and those through CV2 increased as the $A_1/A_2$ ratio decreased (i.e., as the area of CV2 increased) (Figure 7(b)). This implies that as the area of each vent increased, an increasing tendency of the outflow and inflow mass flow rates was observed. Meanwhile, when the $A_1/A_2$ ratio was 0.542, the outflow and inflow mass flow rates were found to be almost identical for both CV1 and CV2. For CV1 (Figure 7(a)), the inflow mass flow rate was higher than the outflow mass flow rate when the $A_1/A_2$ ratio was lower than 0.542, but the outflow mass flow rate was higher than the inflow mass flow rate when $A_1/A_2$ ratio was higher than 0.542. Conversely, in the case of CV2 (Figure 7(b)), the outflow mass flow rate was higher than the inflow mass flow rate when the $A_1/A_2$ ratio was lower than 0.542, but the inflow mass flow rate was higher than the outflow mass flow rate when the $A_1/A_2$ ratio was higher than 0.542. Figures 7(c) and 7(d) show the effect of the $A_1/A_2$ ratio on the outflow and inflow mass flow rates of the vents, respectively. The outflow and inflow mass flow rates at CV1 were higher than those

![Figure 7](image_url). Effect of area ratio between CV1 and CV2 on mass flow rate of vent flow (Note that the numerical simulation data of $A_1/A_2=1$ condition corresponded to the results reported in a study by Park and Lee[12]).
at CV2 when the $A_1/A_2$ ratio was high, whereas the outflow and inflow mass flow rates at CV2 were higher than those at CV1 when the $A_1/A_2$ ratio was low. Meanwhile, in the results of the previous study [12] when $A_1/A_2$ ratio was 1 (the areas of CV1 and CV2 were identical), the outflow mass flow rate of CV1 was higher than that of CV2 (Figure 7(c)), and the inflow mass flow rate of CV1 was lower than that of CV2 (Figure 7(d)). Although CV1 and CV2 had the same area, their mass flow rates were not the same, indicating that the duct height of the ceiling vents affects the outflow and inflow mass flow rates [12].

3.2 Temperature distribution

In this study, the relationship between the temperature distribution measured from the temperature measurement points set below the centers of CV1 and CV2 and the vent flow characteristics was analyzed. As shown in Figure 3, TC1 and TC2 were set below the centers of CV1 and CV2, respectively, and the temperature distribution in the height direction was measured.

Figure 8 displays the temperature distribution results in the height direction measured at TC1, which was set below the center of CV1. Overall, as $A_1/A_2$ ratio decreased, the temperature measured near the lower part of CV1 (i.e., at measurement points of 950 and 1,000 mm) increased, and the temperature difference between the high and low regions in the upper part of the measurement position (i.e., from the middle of the compartment height (550 mm) to the compartment ceiling) increased. For example, the temperature near the lower part of CV1 was high, and the temperature difference depending on the height in the upper part of the measurement position was large when the area of CV1 was small and that of CV2 was large (e.g., CV1_A0.5&CV2_A9.5) compared to when the area of CV1 was large and that of CV2 was small (e.g., CV1_A9.5&CV2_A0.5). It is believed that this temperature distribution tendency is related to the mass flow rate and pattern of the flow passing through CV1.

![Figure 8. Temperature distribution measured in TC1 below CV1.](image)

As shown in Figures 5 and 7, when $A_1/A_2$ ratio was low (i.e., the area of CV1 was small and that of CV2 was large), unidirectional inflow occurred at CV1, and the inflow mass flow rate was low. This implies that the mass flow rate of the cold fresh air introduced into the compartment is low. In this case, active mixing in the upper part of the compartment is difficult. However, when $A_1/A_2$ ratio was high (i.e., the area of CV1 was large and that of CV2 was small), bidirectional flow occurred at CV1, and the outflow and inflow mass flow rates were relatively high. This implies that the outflow of hot gas in the compartment and inflow of cold fresh air from outside the compartment actively occur through CV1, which can cause active mixing in the upper part of the compartment. Hence, when $A_1/A_2$ ratio is high, active bidirectional flow occurs through CV1. This appears to increase the mixing effect in the upper part of the compartment, thereby reducing the temperature near the lower part of CV1 and
decreasing the temperature difference depending on the height in the upper part of the measurement position.

Figure 9 shows the temperature distribution results in the height direction measured at TC2, which was set below the center of CV2. When the area of CV2 was small (the \( A_1/A_2 \) ratio was high), the temperature measured near the lower part of CV2 increased, and the temperature difference between the high and low regions in the upper part of the measurement position increased compared to when it was large (the \( A_1/A_2 \) ratio was low). This is potentially due to the fact that active mixing is difficult when the area of CV2 is small compared to when it is large, as unidirectional inflow occurs and the inflow mass flow rate is low when the area is small, whereas bidirectional flow occurs and the outflow and inflow mass flow rates increase when it is large, as shown in Figures 5 and 7.

![Figure 9. Temperature distribution measured in TC2 below CV2.](image)

3.3 Comparison with previous correlation

The mass flow rate passing through ceiling vents is an important factor in predicting fire phenomena in a compartment. In this study, the previous prediction correlation\[9\] was examined based on the mass flow rate results from Figures 5 and 7. As previously mentioned, Epstein\[9\] conducted research on the exchange flow due to the density difference between saltwater and freshwater in a compartment with two horizontal vents and reported that three combinations of flow patterns were observed, as shown in Figure 1. Epstein\[9\] reported that unidirectional outflow and bidirectional flow occurred at ceiling vent 1 and proposed a correlation to predict the flow rate of the vent flow for those cases. In this study, unlike the results of Epstein\[9\], unidirectional inflow and bidirectional flow are observed at CV1, as summarized in Figure 6. Therefore, for bidirectional flow observed in Epstein's study\[9\] and this study, the prediction correlation proposed by Epstein\[9\] was examined based on the numerical simulation results of this study. The correlation to predict the exchange volumetric flow rate of the vent flow (\( Q \)) proposed by Epstein\[9\] is shown in Eq. (2).

\[
Q = \frac{0.055 \left[ 1 + 400 \left( \frac{L_1}{D_1} \right)^3 \right]^{1/6}}{\left[ 1 + 0.00527 \left( \frac{1 + 400 \left( \frac{L_1}{D_1} \right)^3 \right)^{1/2} \left( \frac{L_1}{D_1} \right)^6 + 117 \left( \frac{L_1}{D_1} \right)^{3/4} \right]^{1/3}} (2)
\]

where \( g \) denotes the gravitational acceleration, \( D_1 \) and \( L_1 \) denote the equivalent diameter and height of CV1, respectively. The equivalent diameter corresponds to the diameter of a circle that has the same area as CV1. Additionally, \( \Delta \rho \) and \( \bar{\rho} \) denote the density difference and average density, which were calculated using Eqs. (3) and (4), respectively.
\[ \Delta \rho = \rho_H - \rho_L \]  
\[ \bar{\rho} = (\rho_H + \rho_L)/2 \]  

where \( \rho_H \) and \( \rho_L \) denote the air density outside the compartment and hot gas density inside the compartment, respectively. The mass flow rates were calculated using the exchange volumetric flow rate and average density obtained from Eqs. (2) and (4), respectively, which were compared with the numerical simulation data.

Figure 10 shows the results of comparing the mass flow rate between the present numerical simulation and previous correlation\[9\] when the flow pattern of CV1 is bidirectional flow. For both the present numerical simulation and previous correlation\[9\], overall, the mass flow rate showed a tendency to increase as \( A_1/A_2 \) ratio increased. However, the previous correlation\[9\] underestimated the mass flow rate of the present numerical simulation. This appears to be because the previous correlation\[9\] was proposed for the case in which the exchange of flow occurs due to the only density difference with no pressure difference through the vent, which differs from the fire situation.

![Comparison of mass flow rate of vent flow through CV1 between present numerical simulation and previous correlation](image)

Based on the numerical simulation results of this study, it was confirmed that the ceiling vent areas, vent flow patterns, mass flow rate, and compartment temperature distribution are closely related in the event of a fire in a compartment with two horizontal vents. Further research on various fire source conditions (e.g., high heat release rate and fire source position) and vent conditions (e.g., quantity, arrangement, and duct height) is deemed necessary in the future. Additionally, it is essential to develop correlations for predicting fire phenomena in a compartment.

4. Conclusions

In this study, the effect of the vent area ratio on vent flow characteristics and temperature distribution for a compartment fire with two ceiling vents was investigated using numerical simulation. A fire source with a heat release rate of 3.01 kW was located at the center of the compartment floor, and vent flow characteristics and temperature distribution were examined when the area ratio \( (A_1/A_2) \) between ceiling vent 1 (CV1) and ceiling vent 2 (CV2) varied from 0.052 to 0.542, 1, 5.587, and 19.36. The main results of this study are summarized as follows:

1. As \( A_1/A_2 \) ratio increased, the flow pattern changed from unidirectional inflow to bidirectional flow for CV1 and from bidirectional flow to unidirectional inflow for CV2. In this study, three combinations of vent flow...
patterns were observed: a case where unidirectional inflow occurs at CV1 and bidirectional flow occurs at CV2, a case where bidirectional flow occurs at CV1 and CV2, and a case where bidirectional flow occurs at CV1 and unidirectional inflow at CV2.

(2) When $A_1/A_2$ ratio was 0.542, the outflow and inflow mass flow rates were found to be almost identical for CV1 and CV2. For CV1, the inflow mass flow rate was higher than the outflow mass flow rate when $A_1/A_2$ ratio was lower than 0.542, but the outflow mass flow rate was higher than the inflow mass flow rate when $A_1/A_2$ ratio was higher than 0.542. In the case of CV2, the opposite tendency was observed. Meanwhile, the outflow and inflow mass flow rates at CV1 were higher than those at CV2 when $A_1/A_2$ ratio was high, while the outflow and inflow mass flow rates at CV2 were higher than those at CV1 when the $A_1/A_2$ ratio was low.

(3) The temperature was low, and the temperature difference between high and low regions in the upper part of the measurement position decreased near the lower part of the ceiling vent with a larger area compared to the ceiling vent with a smaller area. This appears to be because the mixing effect in the upper part of the compartment near the ceiling vent increased due to the occurrence of the active bidirectional flow pattern with high outflow and inflow mass flow rates at the vent.

(4) When the flow pattern of CV1 was bidirectional flow, the mass flow rate showed a tendency to increase as $A_1/A_2$ ratio increased for the present numerical simulation and correlation proposed by Epstein[9]. However, Epstein's[9] correlation underestimated the mass flow rate of the numerical simulation in this study.

**Author Contributions**

Conceptualization, Y.M. and C.Y.; methodology, Y.M.; software, Y.M.; formal analysis, Y.M.; investigation, Y.M.; writing—original draft preparation, Y.M. and C.Y.; writing—review and editing, C.Y.; visualization, Y.M.; supervision, C.Y. All authors have read and agreed to the published version of the manuscript.

**Conflicts of Interest**

The authors declare no conflict of interest.

**Acknowledgments**

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2019R1F1A1062867). This paper was supported by the "National Fire Agency" R&D program [grant number 20016433].

**References**