Effects of Duct Height and Fire Location on Fire Phenomena of Enclosure with Two Horizontal Vents Installed on Ceiling

Yu Mi Park¹, Chi Young Lee¹,²†

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

(Received December 10, 2022; Revised January 3, 2023; Accepted January 4, 2023)

Abstract: The effects of duct height (DH) and fire location (FL) in an enclosure on the mass flow rate and flow pattern of horizontal vent (HV) flow and temperature distribution in the enclosure were investigated through numerical simulations under the condition that two HVs were installed on the ceiling of the enclosure. To evaluate the effect of DH, DHs of HV1 were set to 0.19 m (HV1_DH0.19) and 0.05 m (HV1_DH0.05) under the condition that DH of HV2 was 0.05 m (HV2_DH0.05). The effect of FL was evaluated in three cases where the fire sources were located in the center of the floor (FLC), below HV1 (FL1), and below HV2 (FL2). With respect to the DH effect, the total mass flow rate of the vent flow was slightly higher and temperature was slightly lower in the case of HV1_DH0.19 than that in the case of HV1_DH0.05. However, considering the error bars, the effect of DH in this numerical simulation condition was considered to be insignificant. Furthermore, bidirectional flow patterns appeared in HV1 and HV2 in both DH conditions. Meanwhile, with respect to the FL effect, a bidirectional flow dominated by the mass flow rate of outflow occurred in the HV where the fire source was located, and a unidirectional inflow dominated by the mass flow rate of inflow occurred in the HV where the fire source was not located. The total mass flow rates of FL1 and FL2 conditions were similar, which were higher than those of FLC condition. The temperature was higher in FLC than those in FL1 and FL2. This was due to the small mass flow rate through the HV in the FLC. Meanwhile, an increasing trend of the temperature with the rising measurement height from the floor was observed at most of the temperature measurement points. However, when the fire source was located below HV1 and HV2, as the height from the floor increased, the temperature decreased and the overall temperature was low at the temperature measurement points below the vent where the fire source was not located. This trend was attributed to the occurrence of a strong unidirectional inflow wherein a large volume of low-temperature air flowed into the enclosure from the HV where the fire source was not located.

Keywords: Two horizontal vents; Horizontal vent flow behavior; Enclosure temperature distribution; Duct height; Fire location

1. Introduction

The fire phenomena in an enclosure are closely associated with the vent condition of the enclosure. The behavior of fluid passing through the vent is one of the most important research topics for predicting the fire phenomena in an enclosure. A horizontal vent can be installed at locations such as the ceiling of the enclosure, and the study of the enclosure fire phenomena in these circumstances can be utilized in underground structures, nuclear power plants, theaters, ships, and other applications[1-3].

Some studies have been conducted on the behavior of fluid passing through a horizontal vent. The flow patterns through the horizontal vent can be classified into bidirectional flow, in which outflow and inflow through the horizontal vent occur simultaneously, and unidirectional flow, in which only outflow or inflow occurs[4]. This flow pattern can be determined by the density difference and pressure difference between the upper and lower parts of the horizontal vent[5-8]. In a previous study[5], the effect of a density difference on the characteristics of horizontal vent flow were examined using fluids with different densities (e.g., water and brine). In other studies[6-8], horizontal vent flow was analyzed by conducting a study on the conditions in which both pressure and density differences existed. Most of the aforementioned studies were conducted in a single horizontal vent condition. Meanwhile, Epstein[5] conducted experiments on the characteristics of horizontal vent flow based on density difference using water and brine in the
presence of two horizontal vents as well as in the case of a single horizontal vent. The experimental result revealed that a total of three combinations of horizontal vent flow patterns were observed in horizontal vents 1 and 2: unidirectional outflow and unidirectional inflow, bidirectional flow and unidirectional inflow, and bidirectional flow and bidirectional flow. However, given that these studies have not been conducted in a fire situation, their direct application to a fire situation should be investigated. Furthermore, additional research should be conducted in a situation where two horizontal vents are installed because it is a highly limited condition.

In some studies, horizontal vent flow behavior and fire phenomena were investigated in the event of a fire in an enclosure where only a horizontal vent was installed on the ceiling with no vertical vent. Park et al. [3] conducted numerical simulations to examine changes in the temperature of the enclosure, the velocity of the flow passing through the vent, and its mass flow rate with respect to the vent area and heat release rate (HRR) in the event of a fire in an enclosure where the horizontal vent was located in the center of the ceiling and the fire source was located in the center of the floor. Park and Lee [9] examined the effect of the horizontal vent area and fire location on the fire phenomena of the stage of a theater using its reduced-scale model. The numerical simulation was performed in the case where the horizontal vent was located at the center of the ceiling of the enclosure and the fire source was located on the side of the bottom of the enclosure. The effect of the location of the fire source on the fire phenomena was analyzed through a comparison between the results obtained by Park and Lee [9] and the numerical simulation results obtained by Park et al. [3]. Furthermore, according to the horizontal vent area and fire location in case of a stage fire in a real-scale theater, the mass flow rate of horizontal vent flow was evaluated using the mass flow rate result of vent flow obtained from numerical simulation of the reduced-scale model and the scaling law. Park et al. [10] investigated the scaling law for fire phenomena by performing numerical simulations for enclosure fires in which a horizontal vent existed. The accuracy of the scaling law for the mass flow rate and velocity distribution of the horizontal vent flow and the temperature distribution in the enclosure was checked based on the results of the reduced-scale model and full-scale numerical simulation. Yuan et al. [11] proposed a mathematical model for temperature prediction for a fire in an enclosure under conditions where no horizontal vent existed and where a horizontal vent existed. They performed a comparison between the verification test results and prediction model and reported that the proposed prediction model accurately predicted the temperature distribution over time. Li et al. [12] conducted an experiment to determine the effect of fire size and horizontal vent area on the gas temperature rise of an enclosure fire in which a horizontal vent was installed. They reported that the fire size had a significant effect on the average gas temperature rise when compared to the horizontal vent area. However, in these studies [3, 9-12], a single horizontal vent was used in a fire situation and the research under the condition of two horizontal vents is insufficient. When there are two horizontal vents, the vent flow behavior and fire phenomena can be affected by the condition of the two horizontal vents. Hence, given that one of the horizontal vent conditions corresponds to the duct height of the horizontal vent, this condition should be examined. Furthermore, the relative position between the fire source and horizontal vent is one of the factors that affects the vent flow behavior and fire phenomena [9, 13, 14] in the event of a fire in an enclosure with a single horizontal vent. Thus, the effect of the fire location on the fire phenomena of an enclosure with two horizontal vents should be examined.

In this study, the effects of the duct height of the horizontal vent and the fire location in the enclosure on the enclosure fire phenomena were investigated by performing numerical simulations under the condition of two horizontal vents installed on the ceiling of the enclosure. According to the duct height and fire location under the condition of the same horizontal vent area, the mass flow rate and flow pattern of the horizontal vent flow and the temperature distribution in the enclosure were examined.

2. Details of Numerical Simulation

Figure 1 shows schematic diagrams of the enclosure and two horizontal vents for numerical simulation constructed in this study. In this study, a reduced-scale model was used for experiments to verify the accuracy of numerical simulation results. The size of the enclosure was set to 1.5 m in depth, 1.36 m in width, and 1.1 m in height. Two horizontal
vents were installed on the ceiling of the enclosure, and it corresponded to an airtight condition with no vents except for the horizontal vents. In the reduced-scale model, the enclosure was mostly set as an aluminum plate, and a few walls were composed of transparent polycarbonate plates for visualization of the enclosure’s inside. In this study, numerical simulations were performed for two types of enclosures with different duct heights of horizontal vents. **Figure 1(a)** shows the case where the duct heights of horizontal vent 1 and horizontal vent 2 are the same, and **Figure 1(b)** shows the case where the duct height of horizontal vent 1 is higher than that of horizontal vent 2. **Figure 1(c)** shows a detailed schematic of the horizontal vent conditions. When the duct heights of the two horizontal vents were the same, the duct height was set to 0.05 m, and when the duct heights were different, the duct heights of horizontal vent 1 and horizontal vent 2 were set to 0.19 and 0.05 m, respectively. **Figure 1(d)** shows a schematic diagram of the locations of the two horizontal vents. The center of one horizontal vent was set at a distance of 0.75 m in the depth direction and 0.34 m in the width direction. Moreover, two horizontal vents were set as symmetrical with respect to the center line in the width direction. Meanwhile, the sum of the two horizontal vent areas in all conditions was set as 10% of the floor area. Hence, the area of one horizontal vent was 5% of the floor area, and the areas of horizontal vent 1 and horizontal vent 2 were equal and corresponded to $0.1024 \, \text{m}^2$. The shape of the horizontal vent was set as a square, and the length of one side of the horizontal vent was 0.32 m.

![Schematics of enclosure and two horizontal vents](image)

**Figure 1.** Schematics of enclosure and two horizontal vents.
In the enclosure condition where the horizontal vent’s duct height is the same, as shown in Figure 1(a), the fire source was located in the center of the floor. In the enclosure condition where the duct heights of horizontal vent 1 and horizontal vent 2 differ, as shown in Figure 1(b), a numerical simulation was performed by changing the location of the fire source to the center of the floor, below horizontal vent 1, and below horizontal vent 2. When the fire source was located below the horizontal vent, the center of the horizontal vent and center of the fire source were set on a vertical line (i.e., the center of the horizontal vent coincided with the center of the fire source). For the fire source setting, methanol was used as fuel, and the fire growth rate was set to ultrafast. The maximum HRR was set to 3.01 kW, and numerical simulation was performed under the condition that the HRR was kept constant after the maximum HRR was reached. Figure 2 depicts the change in HRR over time.

In this study, abbreviations were used to express numerical simulation conditions and results, that is, HV denotes horizontal vent, HV1 denotes horizontal vent 1, HV2 denotes horizontal vent 2, DH denotes duct height, FL denotes fire location, FLC denotes that the fire location is centered on the floor, FL1 denotes that it is below HV1, and FL2 denotes that it is below HV2. Numerical simulations were performed under a total of four conditions to examine the effects of the DH of the HV and FL in the enclosure on the fire phenomena in the enclosure, and the following nomenclature was used. Case 1 represents the condition wherein the DH of HV1 is 0.05 m, DH of HV2 is 0.05 m, and FL corresponds to FLC. Case 2 represents the condition wherein DH of HV1 is 0.19 m, DH of HV2 is 0.05 m, and FL corresponds to FLC. Case 3 represents the condition wherein the DH of HV1 is 0.19 m, DH of HV2 is 0.05 m, and FL is FL1. Case 4 represents the condition that the DH of HV1 is 0.19 m, DH of HV2 is 0.05 m, and FL is FL2. Table 1 lists the numerical simulation conditions tested in this study.

**Figure 2.** Change in HRR over time.

<table>
<thead>
<tr>
<th>Cases</th>
<th>HV1 Area (m² and %)</th>
<th>DH (m)</th>
<th>HV2 Area (m² and %)</th>
<th>DH (m)</th>
<th>FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.05</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.05</td>
<td>Center of floor (FLC)</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.19</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.05</td>
<td>Below HV1 (FL1)</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.19</td>
<td>0.1024 m² (5% of floor area)</td>
<td>0.05</td>
<td>Below HV2 (FL2)</td>
</tr>
</tbody>
</table>

Table 1. Numerical Simulation Conditions
Figure 3 shows the measurement positions of the temperature and mass flow rate set in this study. The measurement positions for temperature and mass flow rate are the same in all conditions listed in Table 1. Four arrays of temperature measurement points were set and each temperature measurement point array was termed as TC. Thus, TC1, TC2, TC3, and TC4 were set at 645, 340, 375, and 340 mm, respectively, from the center of the floor. Temperature measurement points were set at intervals of 50 mm between the floor and height of 1000 mm from the floor in every TC. Meanwhile, TC2 and TC4 were temperature measurement points set in the vertical direction below centers of HV1 and HV2, respectively. Furthermore, it was set to measure the mass flow rates of the flows passing through HV1 and HV2.

![Figure 3. Schematic of temperature and mass flow rate measurements.](image)

Fire dynamics simulator (FDS, ver. 6.6.0) was used to perform numerical simulation. For grid size setting, a grid sensitivity test was performed considering the range of the plume resolution index ($D^*/\delta x$) (i.e., $5 \sim D^*/\delta x \sim 11$) [15]. In the plume resolution index, $D^*$ denotes the characteristic fire diameter, and $\delta x$ denotes the length of one side of the cube-shaped grid. Preliminary numerical simulation was performed by setting the grid size to 0.01, 0.02, and 0.05 m, and a conservative grid size of 0.01 m ($D^*/\delta x = 9.4$) was applied based on the analysis of the results. The total number of grids generated through this setting was 3645600 and the numerical simulation time was set to 600 s.

3. Results and Discussion

3.1 Mass flow rate of HV flow

Figure 4 shows the effect of DH on the mass flow rate of flow passing through the HV under the conditions of 0.05 m DH of HV2 and FLC. For comparison, the mass flow rates of outflow and inflow passing through each HV and the total mass flow rates of outflow and inflow passing through the two HVs are shown in Figures 4(a), 4(b), and 4(c), respectively, for Case 1 (HV1_DH0.05) and Case 2 (HV1_DH0.19) conditions. Here, the total mass flow rates of outflow and inflow represent the respective sums of the mass flow rates of outflow and inflow passing through each HV.
through HV1 and HV2. All mass flow rate data are shown by averaging the results of the 500–600 s section, and error bars denote the standard deviations in the corresponding time section.

![Graphs showing mass flow rates](image)

**Figure 4.** Effect of DH on mass flow rate of HV flow under conditions of FLC and HV2 DH0.05.

In the case of the mass flow rate of outflow in Figure 4(a), the mass flow rates of outflows passing through HV1 and HV2 were found to be almost the same in Case 1 (condition of the same DH). However, in Case 2 (condition of the different DHs), the mass flow rate of outflow passing through HV1 with a high DH was higher than that passing through HV2 with a low DH. In the case of the mass flow rate of inflow in Figure 4(b), the mass flow rates of inflows passing through HV1 and HV2 were almost the same in Case 1. However, in Case 2, the mass flow rate of inflow passing through HV2 with a low DH was slightly higher than that passing through HV1 with a high DH. In the case of the total mass flow rate in Figure 4(c), the total mass flow rate of Case 2 was slightly higher than that of Case 1, and the mass flow rate of outflow and inflow were the same in each condition. However, overall, the DH seemed to affect the mass flow rate of flow passing through the HV, but it was considered that the effect of DH was not significant in this numerical simulation condition when the error bars were considered.

**Figure 5** shows the effect of FL on the mass flow rate of flow passing through the HV under the condition that the DH of HV1 is 0.19 m and DH of HV2 is 0.05 m. For comparison, the mass flow rates of outflow and inflow passing through HV1 and HV2 and total mass flow rates of outflow and inflow passing through two HVs, under the conditions where the fire sources are located at FL1, FLC, and FL2, are shown in Figures 5(a), 5(b) and 5(c), respectively.
In the case of the mass flow rate of outflow in Figure 5(a), the measured mass flow rate of outflow was predominant at the HV where the fire source was located (HV1 under FL1 condition and HV2 under FL2 condition). In the HV, where no fire source was located (HV2 under FL1 condition and HV1 under FL2 condition), the mass flow rate of outflow was hardly measured. Meanwhile, in the FLC condition, the mass flow rate of outflow passing through HV1 was higher than that passing through HV2. However, the difference in the mass flow rates of outflows through HV1 and HV2 under the FLC condition was small when compared to FL1 and FL2 conditions. In the case of the mass flow rate of inflow in Figure 5(b), the mass flow rates of inflows passing through HV1 and HV2, where the fire source was located, were low in FL1 and FL2 conditions. Furthermore, the mass flow rates of inflows passing through HV2 and HV1, where no fire source was located, were high. In other words, a low mass flow rate of inflow was measured in the HV where the fire source was located, and a high mass flow rate of inflow was measured in the HV where the fire source was not located. In the FLC condition, the mass flow rate of inflow through HV2 appeared to be slightly higher than that through HV1. However, the difference in mass flow rates of inflows between the HVs in the FLC condition was very small when compared to FL1 and FL2 conditions. As shown in Figure 5(c), the total mass flow rates of outflow and inflow were the same in all conditions. In this study, it was confirmed that the relative location between the fire source and HV (i.e., whether the center of the fire source coincides with the center of the HV) had a significant impact on the mass flow rate of the HV flow.

Based on the mass flow rate measurement results in Figures 4 and 5, the patterns of flows through the HVs observed under the numerical simulation conditions are summarized in Figure 6. Generally, a bidirectional flow...
pattern, in which outflow and inflow occurred simultaneously, and a unidirectional flow pattern, in which only inflow occurred, were observed. By evaluating the effect of DH on the vent flow pattern through comparison between Figures 6(a) and 6(b), a bidirectional flow pattern appeared in HV1 and HV2 regardless of DH in this numerical simulation condition. By examining the effect of FL on the vent flow pattern, based on comparison of Figures 6(c) and 6(d), a bidirectional flow pattern was observed in the HV located directly above the fire source. Furthermore, a unidirectional inflow pattern was observed for the other HV (i.e., the HV that was not located above the fire source). When a bidirectional flow pattern appeared in the HV located directly above the fire source, outflow was dominant when compared to inflow based on the mass flow rate measurement results (Figure 5). Furthermore, in the FLC condition (i.e., when there was no fire source below HV1 and HV2), a bidirectional flow pattern appeared in both HVs. Based on these numerical simulation results, it was confirmed that the FL significantly affected the vent flow pattern.

Figure 6. Observed HV flow patterns.

3.2 Temperature distribution of enclosure

To analyze the effect of DH on the temperature distribution in the enclosure, the temperature measurement results for each TC in Case 1 and Case 2 are shown in Figure 7. In every TC, the temperature increased with increasing height because a hot gas was in the upper portion of the enclosure. Meanwhile, the overall temperature in Case 1 (when the DH of HV1 was low) was slightly higher than that in Case 2 (when the DH of HV1 was high). The potential reason for this tendency is that the mass flow rate of flow passing through the HV is lower when the DH of HV1 is low, when compared to when the DH of HV1 is high, as shown in Figure 4. However, it was considered that the effect of DH on the temperature distribution in the enclosure was not significant based on the results of this numerical simulation.
Figures 7, 8, and 9 show the effect of FL on the temperature distribution in the enclosure. The fire source locations of FL1, FLC, and FL2 were compared when the DH of HV1 was 0.19 m and DH of HV2 was 0.05 m. Figure 8 shows the temperature measurement results at the TC set on the center line of the fire source located below HV1 and HV2. As shown in Figure 3, the temperatures were measured at TC2 in case of FL1 and at TC4 in case of FL2. In both cases, a decreasing trend in temperature was observed as the measurement height increased from the floor (i.e., from the fire source). This is due to the fact that the entrainment of the relatively cool surrounding fluid into the fire plume cools the fire plume. Meanwhile, the temperature distributions in the height direction in the two conditions were similar when the error bars of the temperature data were considered.
Figure 8. Variation of temperature in TC installed along the center line of fire source with height under conditions of HV1 DH0.19 & HV2 DH0.05.

Figure 9. Effect of FL on temperature distribution of enclosure measured in TC installed away from the center line of fire source with height under conditions of HV1 DH0.19 & HV2 DH0.05.
In Figure 9, the temperature measurement results in TCs set away from the center line of the fire source (i.e., TCs not set on the center line of the fire source) are shown under the condition that the DH of HV1 is 0.19 m, the DH of HV2 is 0.05 m, and the FLs are FL1, FLC, and FL2. The temperature measurement results of TC1 and TC3 are shown for all FLs in Figures 9(a) and 9(c), respectively. Figure 9(b) shows the temperature measurement results at TC2 for FLC and FL2 (excluding FL1), and Figure 9(d) shows the temperature measurement results at TC4 for FL1 and FLC (excluding FL2). Overall, in every TC, the FLC case showed a higher temperature than the FL1 and FL2 cases. This is potentially due to the fact that the mass flow rate of the flow passing through the HV in the case of FLC is lower than those of FL1 and FL2, as shown in Figure 5. In the case of TC1 and TC3 in Figures 9(a) and 9(c), a trend of increasing temperature was observed in all FL conditions as the measured height from the floor increased. This suggests that a hot gas was in the upper portion of the enclosure. Meanwhile, in the cases of TC2 and TC4 in Figures 9(b) and 9(d), under the FLC condition, temperature increased with increasing measurement height in the enclosure, which was similar trend to the cases of TC1 (Figure 9(a)) and TC3 (Figure 9(c)). Conversely, in FL2 condition of TC2 (Figure 9(b)) and FL1 condition of TC4 (Figure 9(d)), a decreasing tendency of the temperature was observed as the height from the floor increased, and overall, the temperature was low. Meanwhile, Figure 10 shows the visualization results of temperature distribution for Cases 1–4. The same trends as the temperature measurement results in Figure 9 were observed. These temperature trends are considered to be closely related to the flow pattern and mass flow rate through the HV.

![Figure 10](image_url)

Figure 10. Visualization of temperature distribution for Cases 1–4.
As shown in Figure 6(d), the flow passing through HV1 in the FL2 condition is a unidirectional inflow, and as explained in Figure 5, the mass flow rate of inflow is high. Thus, as shown in Figure 9(b), the temperature at TC2, which is set right below HV1 (i.e., similar to the temperature of inflowing air), and a slight increase in temperature is observed as the measurement height decreases (i.e., approaching the bottom). Similarly, in the FL1 condition, a strong unidirectional inflow through HV2 occurs (Figure 6(c)), which indicates that a large amount of low-temperature air is introduced (Figure 5). Hence, the temperature is low near HV2 and slightly increases as it approaches the bottom as shown in Figure 9(d). It was confirmed that in the event of a fire in an enclosure with two HVs, FL affected the vent flow pattern and mass flow rate passing through the vent, which had a great impact on the temperature distribution in the enclosure.

4. Conclusions

In this study, the effects of the duct height (DH) and fire location (FL) in an enclosure on the mass flow rate and flow pattern of the horizontal vent (HV) flow and the temperature distribution in the enclosure were examined through numerical simulations under the condition wherein two HVs are installed on the ceiling of the enclosure. The effects of DH were investigated under the condition that the FL was at the center of the enclosure floor (FLC) when the DHs of horizontal vent 1 (HV1) and horizontal vent 2 (HV2) were equal at 0.05 m (Case 1) and when the DHs of HV1 and HV2 were 0.19 and 0.05 m, respectively (Case 2). To evaluate the effect of FL, numerical simulations were performed under the condition that the DHs of HV1 and HV2 were 0.19 and 0.05 m, respectively, and when the FLs were at the center of the floor (FLC), below HV1 (FL1), and below HV2 (FL2). The findings of this study were summarized as follows:

(1) With respect to the effect of DH on the mass flow rate of flow passing through HV, it was observed that the total mass flow rate in Case 2 was slightly higher than that in Case 1. However, in this numerical simulation condition, the effect of DH on the mass flow rate of vent flow was not significant considering the error bars.

(2) With respect to the effect of FL on the mass flow rate of flow passing through the HV, the mass flow rate of outflow was predominant in the HV where the fire source was located, whereas the mass flow rate of inflow was low. Conversely, in the HV where no fire source was located, the mass flow rate of outflow was barely measured, and the mass flow rate of inflow was predominant. Meanwhile, FL1 and FL2 conditions showed higher total mass flow rates than the FLC condition and the total mass flow rates of the FL1 and FL2 conditions were similar.

(3) By evaluating the effect of DH on the vent flow pattern, the bidirectional flow pattern was observed in both HV1 and HV2 irrespective of DH. Regarding the FL effect, the bidirectional flow pattern, in which outflow was dominant compared to inflow, was observed in the HV located directly above the fire source. The unidirectional inflow pattern was observed in the HV that was not located above the fire source. Meanwhile, the bidirectional flow pattern appeared in both HV1 and HV2 in the FLC condition where there was no fire source below HV1 and HV2.

(4) With respect to the effect of DH on the temperature distribution in the enclosure, the overall temperature in Case 1 was slightly higher than that in Case 2. This is presumably because the mass flow rate of flow passing through the HV is lower when the DH of HV1 is low compared to when the DH is high. However, it was considered that the effect of DH on the temperature distribution in the enclosure was not significant in this numerical simulation condition.

(5) With respect to the effect of FL on the temperature distribution in the enclosure, the temperature in the FLC condition was higher than that in the FL1 and FL2 conditions. This is due to the fact that the mass flow rate of the flow passing through the HV in the FLC condition is smaller than that in the FL1 and FL2 conditions. In most TCs, a trend of increasing temperature with increasing measurement height from
the floor was observed. However, when the fire source was located below HV1 and HV2 (i.e., FL1 and FL2 conditions), the temperature decreased as the height from the floor increased and the overall temperature was low in TC4 and TC2 installed below HV2 and HV1, where no fire source was located. This is considered to be due to the strong unidirectional inflow in which a large volume of low-temperature air flows into the enclosure through the HV where the fire source is not located.

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). Furthermore, this study was supported by the "National Fire Agency" R&D program [grant number 20016433].

References


