1. Introduction

Large-scale experiments on compartment fire phenomena suffer from practical limitations in terms of time, space, and cost; as an alternative, a scaled model experiment can be conducted using the scaling law to understand large-scale fire phenomena. According to the scaling law, a phenomenon that occurs in two systems is similar when the ratios of all physical quantities related to the phenomenon are identical [1]. Figure 1 shows an example of the scaling law. In Figure 1, $l$, $L$, and $S$ denote the length, large-scale prototype, and scaled model, respectively. The ratio of the lengths ($l/L$) between the scaled model and prototype is referred to as the length scale factor ($\lambda$), and it can be used to build a model that reduces a large-scale prototype by $1/n$ to conduct a study on fire phenomena. Table 1 summarizes the scaling law [3,4] commonly used in the field of fire and firefighting. Here, $x$, $T$, $m$, $\dot{Q}$, $V$, and $t$ refer to the geometric position, temperature, mass flow rate, heat release rate, velocity, and time, respectively; the relationship between the prototype and the scaled model for each parameter is expressed using $\lambda$. The scaling law in Table 1 can be used to predict the results of a fire phenomenon in the large-scale prototype based on the results of the fire phenomenon in the scaled model.

In this study, the scaling law for the fire phenomena was examined based on a stage fire in a theater. The theater includes a stage for performances and an auditorium where the audiences are seated for viewing the performances [5]. A fire can occur in the stage area because of the high-temperature lighting and stage devices used for special effects. A fire curtain and horizontal natural opening can be installed in the stage area of the theater as measures to minimize damage caused by a fire in the theater. The fire curtain is usually installed between the stage and the auditorium; although

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Abstract: The scaling law was examined using numerical simulation for fire phenomena in a compartment with a horizontal natural opening in this study. The results of the large-scale conversion of the scaled model numerical simulation results ([Small-scale] condition) from the earlier studies obtained by applying the scaling law were compared to those of the large-scale numerical simulation performed in this study ([Large-scale] condition). The overall trends for the effects of horizontal natural opening area and fire source location on the discharge mass flow rate through the horizontal natural opening, temperature distribution in the compartment, and flow velocity through the horizontal opening were found to be identical under the [Small-scale] and [Large-scale] conditions. A complex bidirectional flow was observed through the horizontal natural opening under the conditions of this study and the accuracy in predicting the average W-velocity value based on the scaling law was low; however, the accuracy in predicting the range of velocity fluctuation was higher than the average value under certain conditions. Based on the standard deviation of the numerical simulation results, the percentages of the data within ±30% of the difference between the [Small-scale] and [Large-scale] conditions relative to the total number of data were 100, 75, and 88% for the discharge mass flow rate, temperature, and flow velocity through the horizontal natural opening, respectively. The accuracy of the scaling law was found to be high for the discharge mass flow rate under the conditions considered in this study.

Keywords: Scaling law, Horizontal natural opening, Compartment fire, Fire phenomena, Numerical simulation
it is stored away, it can be used to separate the stage and the auditorium in the event of a fire to prevent the fire and smoke from entering the auditorium while audience evacuations are underway[6]. In addition, a horizontal natural opening is installed in the ceiling of the stage; this opening allows smoke and heat to be discharged outside the theater in the event of a fire, which can help lower the temperature inside and secure visibility for the occupants. Fire phenomena in a compartment (e.g., a theater stage) and fluid flow through the horizontal natural opening are both affected by the horizontal natural opening and fire source conditions. Therefore, it is necessary to actively conduct relevant studies to apply the horizontal natural opening in various fields.

\[ \lambda = \frac{l_S}{l_L} = \frac{1}{n} \]

**Figure 1.** Example of scaling law.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype (e.g., Large-scale)</th>
<th>Model (e.g., Small-scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric position</td>
<td>( x_L )</td>
<td>( x_S = x_L \left( \frac{l_S}{l_L} \right) )</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T_L )</td>
<td>( T_S = T_L )</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>( m_L )</td>
<td>( m_S = m_L \left( \frac{l_S}{l_L} \right)^{5/2} )</td>
</tr>
<tr>
<td>Heat release rate</td>
<td>( \dot{Q}_L )</td>
<td>( \dot{Q}_S = \dot{Q}_L \left( \frac{l_S}{l_L} \right)^{5/2} )</td>
</tr>
<tr>
<td>Velocity</td>
<td>( V_L )</td>
<td>( V_S = V_L \left( \frac{l_S}{l_L} \right)^{1/2} )</td>
</tr>
<tr>
<td>Time</td>
<td>( t_L )</td>
<td>( t_S = t_L \left( \frac{l_S}{l_L} \right)^{1/2} )</td>
</tr>
</tbody>
</table>

Previous studies on fires in theaters using a scaled model are summarized below. Kim[1] conducted a scaled model experiment and numerical simulation of a theater using the scaling law to understand the smoke behavior considering the fire curtain and natural smoke vent conditions. A comparison of the experimental and numerical simulation results indicated a difference of -16.1 to -7.8% in temperature, and a -5.0 and 9.7% difference in the discharge mass flow rate with and without a fire curtain, respectively. Moreover, the large-scale numerical simulation results indicated that the smoke discharge time from the stage to the auditorium was delayed in the rows at the center of the natural opening compared to the rows at the corners and with a fire curtain installed than that at those without a fire curtain installed. Yeo[4] conducted a scaled model experiment and large-scale numerical simulation to study design factors affecting smoke ventilation performance. The scaling law was applied in the scaled model experiment to compare the results to the large-scale numerical simulation. Inspired by the existing scaled model experiment by Yeo[4], Kim et al.[6] performed a scaled-model numerical simulation to determine the accuracy of the numerical simulation and compared the results; the effect of the fire curtain in the event of a
large-scale theater fire was predicted by applying the scaling law. They found that the fire curtain had a significant effect on the mass flow rate passing through the natural opening and the proscenium opening and the discharge timing of the soot to the auditorium. Baek et al.\[7\] conducted an experiment to examine the effects of a natural opening and fire curtain in case of a stage fire in a theater using a model that scaled the existing theater at a ratio of 1/14. Their results indicated that, when the natural opening was open, the temperature in the stage area was lower without a fire curtain; however, the temperature in the auditorium was lower with a fire curtain installed. Based on the scaled-model experimental equipment of Baek et al.\[7\], Yang et al.\[8\] performed a scaled model numerical simulation and confirmed that the results from the numerical simulation were consistent with those from the existing scaled-model experiment\[7\]. Meanwhile, Park et al.\[9\] performed a numerical simulation on the scaled stage model when the fire source was located in the center of the stage floor. Using the previous study of Park et al.\[9\], Park and Lee\[10\] conducted a numerical study on the effects of the natural smoke vent area and fire source location on the compartment fire phenomena. The discharge mass flow rate through the natural smoke vent in case of a large-scale theater fire was predicted using the numerical simulation results and the scaling law. The prediction results suggested that the discharge mass flow rate was 43.53 times higher when the natural smoke vent area was 10% of the floor area with the fire source located in the center of the floor than when the natural smoke vent area was 1% of the floor area with the fire source located on the side of the floor.

The use of a scaled model for investigating fire phenomena has considerable advantages in terms of time, space, and cost compared to those using a large-scale prototype; however, the validity and accuracy of the scaling law must be reviewed to predict the fire phenomenon in the large-scale prototype accurately through the scaled model. The validity and accuracy of the scaling law were examined in some studies. For example, Ko\[11\] conducted large-scale and small-scale compartment fire numerical simulations for existing experimental studies\[12,13\] to evaluate the effectiveness of the scaling law based on the ventilation parameters applied to compartment fire studies. The results of the analysis confirmed that the flow pattern, ejected flame behavior, and temperature distribution characteristics inside the compartment were similar between the large-scale and small-scale models. Quintiere et al.\[14\] conducted an experiment using a 1/7 scaled model and large-scale prototype for heat and fluid flow through a corridor in the event of a compartment fire and compared the results. However, the accuracy of the scaling law varies with the fire conditions, and the review of the existing studies suggests that there are insufficient quantitative evaluations regarding the accuracy of the scaling law. Therefore, there is an urgent need to continue studies on verifying the accuracy of the scaling law under various fire conditions.

In this study, the scaling law is investigated for fire phenomena in a compartment with a horizontal natural opening installed using the fire dynamics simulator (FDS). The FDS is a widely used program in the field of fire and firefighting, and its accuracy in predicting fire phenomena has been examined in an earlier study\[15\]. In this study, a large-scale compartment is constructed based on a scaled model of a theater stage reported in the previous studies\[9,10\]; then, a numerical simulation is performed. The results from the scaled model numerical simulation performed in the previous studies\[9,10\] are scaled by applying the scaling law and compared to the results of the large-scale numerical simulation performed in this study to identify the effects of the horizontal natural opening area and fire source location on the discharge mass flow rate through the horizontal natural opening, temperature distribution in the compartment, and flow velocity through the horizontal natural opening.

2. Numerical Simulation Method and Conditions

The large-scale compartment subject in this study was established by enlarging the scaled compartment model constructed in the previous studies\[9,10\] 14 times. Figure 2 shows a schematic of the numerical simulation for the large-scale compartment considered in this study. The size of the compartment is 28.56 m (width) × 14.0 m (depth) × 15.4 m (height); a single horizontal natural opening is installed at the center of the compartment ceiling. The areas of the horizontal natural opening are 1 and 10% of the floor area of the compartment, which correspond to 3.8416 (1.96 m × 1.96 m) and 40.96 (6.3 m × 6.3 m) m², respectively.
As shown in Figure 2, the location of the fire source is at the center or on the side of the compartment floor; methanol used in the previous studies\cite{9,10} is applied as a fuel. The heat release rate of the fire source is set to 990 kW for all cases by applying the scaling law to 1.35 kW from the previous scaled model studies\cite{9,10}. The t-square fire model ($\dot{Q} = a t^2$)\cite{16} is applied to the change in heat release rate over time; here, $a$ represents the fire growth factor.

Figure 3 shows the measurement positions for the mass flow rate through the horizontal natural opening and the temperature distribution in the compartment. The mass flow rate passing through the horizontal natural opening installed in the center of the compartment ceiling is set to be measured. The temperature measurement position is referred to as TC (thermocouple tree) for the temperature distribution. TC1, TC2, and TC3 are set at 12.04, 7.14, and 4.76 m from the center of the floor, respectively, and TC4 is set in the vertical direction between the center of the compartment floor and the horizontal natural opening. TC1–TC3 measure the temperature every 2.8 m in the direction of the height from the floor; TC4 measures the temperature at 11.2, 12.6, and 14.0 m in the direction of height from the center of the floor. Thus, there are a total of 18 temperature measurement positions inside the compartment.

A vertical velocity component (W-velocity) of flow through the horizontal natural opening was measured. Figure 4 shows a schematic of the measurement positions for the flow velocity through the horizontal natural opening. Figure 4(a) shows the case where the horizontal natural opening area is 1% of the floor area; Figure 4(b) shows...
the case where the horizontal natural opening area is 10% of the floor area. The velocity was measured at a total of three points at intervals of 0.56 m when the horizontal natural opening area was 1% of the floor area; the positions were named $V_5$-$V_7$. The velocity was measured at a total of 11 points at the same intervals of 0.56 m as in the 1% case when the horizontal natural opening area was 10% of the floor area; the positions were named $V_1$-$V_{11}$.

If the fire source is on the side of the floor, the velocity measurement position closest to the fire source is $V_7$ when the horizontal natural opening area is 1% of the floor area or $V_{11}$ when the horizontal natural opening area is 10% of the floor area.

![Image](image1.png)

(a) Horizontal natural opening area = 1% of the floor area  
(b) Horizontal natural opening area = 10% of the floor area

**Figure 4.** W-velocity measurement position in horizontal natural opening.

FDS (ver. 6.5.3) was used for the numerical simulation. The plume resolution index ($D^*/\delta x$)[17] was considered for setting the grid size. Here, $D^*$ represents the characteristic fire diameter, and $\delta x$ represents the length of one side of the grid. The Nuclear Regulatory Commission proposes an appropriate $D^*/\delta x$ range of 4-16 for the numerical analysis[18,19]. In the previous studies[9,10], $D^*/\delta x$ was set to 6.8 and the grid size to 0.01 m. Considering these conditions, $D^*/\delta x$ was set to 6.8 and the grid size to 0.14 m in this study; the total number of grids was set to 4,076,800. The numerical simulation time was set to 1000 s.

In this study, the numerical simulation for the large-scale compartment fire was performed under four conditions. **Table 2** summarizes the numerical simulation conditions. The horizontal natural opening area was set to 1 and 10% of the floor area, and the locations of the fire source were specified in the center and on the side of the floor. Cases where the horizontal natural opening (HO) area was 1 and 10% of the floor area were named HO_01 and HO_10, respectively. Cases where the fire source (FS) was located in the center and on the side of the stage floor were named FS_CENTER and FS_SIDE, respectively. For example, the case where the horizontal natural opening area is 1% of the floor area, and the fire source is in the center of the stage floor is referred to as HO_01&FS_CENTER.

For a comparison with the numerical simulation results, the results of the large-scale conversion of the scaled model numerical simulation performed in the previous studies[9,10] by applying the scaling law were referred to as the [Small-scale] condition and the results of the large-scale numerical simulation performed in this study were referred to as the [Large-scale] condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Horizontal natural opening area</th>
<th>Fire source location</th>
</tr>
</thead>
<tbody>
<tr>
<td>HO_01&amp;FS_CENTER</td>
<td>1% of the floor area</td>
<td>Center</td>
</tr>
<tr>
<td>HO_10&amp;FS_CENTER</td>
<td>10% of the floor area</td>
<td></td>
</tr>
<tr>
<td>HO_01&amp;FS_SIDE</td>
<td>1% of the floor area</td>
<td>Side</td>
</tr>
<tr>
<td>HO_10&amp;FS_SIDE</td>
<td>10% of the floor area</td>
<td></td>
</tr>
</tbody>
</table>
3. Numerical Simulation Results and Analysis

3.1 Discharge mass flow rate through the horizontal natural opening

Figure 5 shows the effects of the horizontal natural opening area and fire source location on the discharge mass flow rate through the horizontal natural opening. Figure 5(a) illustrates the case where the fire source is located in the center of the floor; Figure 5(b), on the side of the floor. The results of the discharge mass flow rate are expressed by averaging the data over the range 900–1000 s, and the error bars indicate the standard deviation of the data.

As shown in Figure 5, the discharge mass flow rate was greater when the horizontal natural opening area was large (HO_10) than that when it was small (HO_01) given the same fire source location. Additionally, the discharge mass flow rate was greater when the fire source was located in the center of the floor than when it was located on the side of the floor, given the same horizontal natural opening area. This is because the horizontal natural opening exists directly above the fire source when the fire source is in the center of the floor, and this facilitates smoke discharge to outside the compartment. This overall trend was observed under both the [Small-scale] and [Large-scale] conditions.

![Figure 5. Effects of horizontal natural opening area and fire source location on the discharge mass flow rate.](image)

3.2 Temperature distribution inside compartment

Figure 6 shows the effects of the horizontal natural opening area and fire source location on the temperature distribution in the compartment. Figures 6(a) and 6(b) illustrate the case of the fire source in the center of the floor; Figures 6(c) and 6(d), on the side of the floor. The temperature results correspond to the data averaged over the range of 900–1000 s, and the error bars indicate the standard deviation of the data.

The temperature in the compartment decreased with an increase in the horizontal natural opening area when the fire source was at the center of the floor (Figures 6(a) and 6(b)). At TC1–TC3, the temperature increased as the temperature measurement position shifted from the bottom to the top; this is because a high-temperature smoke layer was formed in the upper part of the compartment. At TC4, the temperature decreased as the temperature measurement position shifted from the bottom to the top because of the increased distance from the fire source and cold air introduced from the surrounding to the fire plume. The temperature in the compartment decreased as the horizontal natural opening area increased when the fire source was on the side of the floor (Figures 6(c) and 6(d)); this is similar to the case of the fire source in the center of the floor (Figures 6(a) and 6(b)). However, the effect of the horizontal natural opening area was relatively smaller than when the fire source was in the center of the floor. The overall trends in the temperature distribution measurement results were similar under the [Small-scale]
and [Large-scale] conditions.

The temperature difference at TC1–TC3 in the compartment was found to be insignificant regardless of the fire source location when the horizontal natural opening area was relatively smaller (HO_01). The temperature distribution in the compartment was higher when the fire source was located on the side of the floor than when it was in the center of the floor, especially when the horizontal natural opening area was relatively larger (HO_10); this trend was similarly observed under the [Small-scale] and [Large-scale] conditions. The temperature distribution at TC1–TC3 was found to be lower overall under the [Small-scale] condition than that under the [Large-scale] condition.

3.3 Flow velocity through the horizontal natural opening

The effects of the horizontal natural opening area and the fire source location on the W-velocity of the flow through the horizontal natural opening were examined. Figure 7 shows the flow velocity distribution for the measurement position obtained by averaging the data over the range of 900–1000 s at each fire source location. Figures 7(a) and 7(b) illustrate cases where the fire source was located in the center and on the side of the floor, respectively; the error bars indicate the standard deviation of the corresponding data.
The change in W-velocity with the location is evident when the fire source is in the center of the floor (Figure 7(a)). An outflow mainly occurred near the center ($V_6$) of the horizontal natural opening when the horizontal natural opening was 10% of the floor area, whereas an inflow mainly occurred at the periphery. Thus, the flow through the horizontal natural opening was found to have a bidirectional flow pattern. The change in W-velocity with the location is not as apparent when the fire source is on the side of the floor (Figure 7(b)) as it is when the fire source is in the center of the floor. This overall trend is observed under the [Small-scale] and [Large-scale] conditions. However, the difference in the W-velocity distribution between the [Small-scale] and [Large-scale] conditions was relatively large when the fire source was in the center of the floor, and the horizontal natural opening area was large (i.e., HO_10&FS_CENTER). A very complex bidirectional flow pattern manifests through the horizontal natural opening in the event of a compartment fire with a single horizontal natural opening on the ceiling. Given this complex flow pattern, the prediction of the average W-velocity value by applying the scaling law seems to be limited under certain conditions.

Figure 7. Effects of horizontal natural opening area and fire source location on average W-velocity distribution of flow through horizontal natural opening.

Figure 8. Effects of horizontal natural opening area and fire source location on temporal variation in the W-velocity of the flow through the horizontal natural opening measured at $V_6$. 
Figure 8 shows the W-velocity measured at the center ($V_6$) of the horizontal natural opening over time. Figures 8(a) and 8(b) correspond to the cases where the fire source is in the center and on the side of the floor, respectively. In all cases, the W-velocity fluctuates greatly over time, and the range of the fluctuation is larger with the fire source located in the center than on the side of the floor. Table 3 summarizes the range of fluctuation in the W-velocity over time under each condition. The fluctuation range in the flow velocity is similar under the [Small-scale] and [Large-scale] conditions. That is, the accuracy in predicting the range of the velocity fluctuation is more improved than the accuracy in predicting the average W-velocity value through the scaling law.

Table 3. Fluctuation Range of W-velocity of Flow through Horizontal Natural Opening

<table>
<thead>
<tr>
<th>Condition</th>
<th>[Small-scale] Case</th>
<th>[Large-scale] Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>HO_01&amp;FS_CENTER</td>
<td>-1−3.5 m/s</td>
<td>-1−4 m/s</td>
</tr>
<tr>
<td>HO_10&amp;FS_CENTER</td>
<td>1−5 m/s</td>
<td>-1.5−3 m/s</td>
</tr>
<tr>
<td>HO_01&amp;FS_SIDE</td>
<td>-1−1 m/s</td>
<td>-1−1.5 m/s</td>
</tr>
<tr>
<td>HO_10&amp;FS_SIDE</td>
<td>-1−1 m/s</td>
<td>-1−1.5 m/s</td>
</tr>
</tbody>
</table>

3.4 Accuracy of scaling law

The accuracy of the scaling law was evaluated by quantitatively comparing and analyzing the results of large-scale conversion of the scaled model numerical simulation results from the previous studies[9,10] with the scaling law ([Small-scale] condition) and results of the large-scale numerical simulation ([Large-scale] condition) performed in this study. Figure 9 shows the comparison of the discharge mass flow rate through the horizontal natural opening, temperature distribution in the compartment, and flow velocity through the horizontal natural opening between the [Small-scale] and [Large-scale] conditions. For the flow velocity through the horizontal opening, the results from three points ($V_5$, $V_6$, $V_7$) were used under the condition (HO_01) where the horizontal natural opening area was 1% of the floor area. The results from five points ($V_1$, $V_5$, $V_6$, $V_9$, $V_{11}$) were used under the condition (HO_10) where the horizontal natural opening area was 10% of the floor area.

The numbers of data within ± 10, ± 20, and ± 30% of the difference between the [Small-scale] and [Large-scale] conditions were obtained from among all data to evaluate the accuracy of the scaling law. For the discharge mass flow rate (Figure 9(a)), the total number of data is 4, and there are 1, 3, and 3 data within ± 10, ± 20, and ± 30% of the difference between the [Small-scale] and [Large-scale] conditions, respectively, based on the average value. Based on the standard deviation (i.e., error bars), all data were within ± 10%. For the temperature (Figure 9(b)), the total number of data is 72, and there are 1, 10, and 44 data within ± 10, ± 20, and ± 30% of the difference between the [Small-scale] and [Large-scale] conditions, respectively, based on the average value. Based on the standard deviation, 5, 23, and 54 data were within ± 10, ± 20, and ± 30%, respectively. For the flow velocity (Figure 9(c)), the total number of data for the comparison is 16; there are 0, 4, and 4 data within ± 10, ± 20, and ± 30% of the difference between the [Small-scale] and [Large-scale] conditions, respectively, based on the average value. Based on the standard deviation, 14 out of 16 total data were within ± 10, ± 20, and ± 30%, respectively.

Table 4 summarizes the percentages of the number of data within ± 10, ± 20, and ± 30% of the difference between the [Small-scale] and [Large-scale] conditions for the total number of data. As expected, the percentages were higher based on the standard deviation than those based on the average value. Based on the standard deviation, the percentages of the number of data within ± 30% of the difference between the [Small-scale] and [Large-scale] conditions were approximately 100, 75, and 88% for the discharge mass flow rate through the horizontal natural opening, temperature, and flow velocity through the horizontal natural opening, respectively. The percentages were greater for the discharge mass flow rate, which indicates the high accuracy of the scaling law for the discharge mass flow rate.
Figure 9. Comparison of discharge mass flow rate, temperature, and W-velocity between [Small-scale] and [Large-scale] cases.

Table 4. Percentage (%) of the Number of Data within ±10, ±20, and ±30% of Difference between [Small-scale] and [Large-scale] Cases for the Total Number of Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Within ±10%</th>
<th>Within ±20%</th>
<th>Within ±30%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Considering Average Value</td>
<td>Considering Standard Deviation</td>
<td>Considering Average Value</td>
</tr>
<tr>
<td>Discharge Mass Flow Rate</td>
<td>25%</td>
<td>100%</td>
<td>75%</td>
</tr>
<tr>
<td>Temperature</td>
<td>1%</td>
<td>7%</td>
<td>14%</td>
</tr>
<tr>
<td>W-velocity</td>
<td>0%</td>
<td>88%</td>
<td>25%</td>
</tr>
</tbody>
</table>

4. Conclusions

The scaling law was examined using numerical simulation for fire phenomena in a compartment with a horizontal natural opening. The results of the large-scale conversion of the scaled model numerical simulation results from the previous studies[9,10] obtained by applying the scaling law ([Small-scale] condition) and the results of the large-scale numerical simulation performed in this study ([Large-scale] condition) were compared and analyzed. The main results of this study are summarized below.
(1) The overall trends regarding the effects of the horizontal natural opening area and fire source location on the discharge mass flow rate through the horizontal natural opening, temperature distribution in the compartment, and flow velocity through the horizontal natural opening were the same under the [Small-scale] and [Large-scale] conditions.

(2) A bidirectional flow was observed through the horizontal natural opening under the conditions of this study; further, the flow velocity (W-velocity) passing through the horizontal natural opening was found to fluctuate significantly over time. Given this complex flow pattern, the accuracy in predicting the average W-velocity value through the scaling law was low under certain conditions, but the accuracy in predicting the range of velocity fluctuation was higher than the average value.

(3) Based on the standard deviation in the numerical simulation results, the percentages of data within ± 30% of the difference between the [Small-scale] and [Large-scale] conditions relative to the total number of data were 100, 75, and 88% for the discharge mass flow rate through the horizontal natural opening, temperature, and flow velocity through the horizontal natural opening, respectively.

(4) The accuracy of the scaling law was high for the discharge mass flow rate under the conditions of this study.

This study evaluated the accuracy of the scaling law in the event of a fire with a complex bidirectional flow occurring in a single horizontal natural opening. The accuracy of the scaling law may vary with the situation and conditions of a fire, and therefore, additional research to examine the accuracy of the scaling law under various fire conditions will be required in the future. Such research is expected to contribute to the broader application of the method of using a scaled model in fire-related studies, which will provide several advantages in terms of time, space, and cost.

Author Contributions

Conceptualization, M.Y. and C.Y.; investigation, M.Y. and Y.Y.; writing—original draft preparation, M.Y.; writing—review and editing, Y.Y. and C.Y.; 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.

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References