

Effect of Insect Repellent Bomb on Unwanted Fire

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Abstract: A fire detection and alarm system triggered by any element other than fire, such as smoke or a foreign object, is referred to as an unwanted fire alarm. According to the data from the National Fire Agency, as of 2021, the ratio of the number of unwanted-fire dispatches to the total number of 119 dispatches is 17.2%, and the ratio of the number of malfunctions to the number of dispatches triggered by fire detection and alarm systems has remained above 99% for 10 years, resulting in a loss of firefighting resources. In this study, we conducted unwanted fire alarm experiments using insect repellent bombs and implemented the detector and smoke experiments into a three-dimensional numerical analysis to verify the usefulness of the analysis. The smoke concentration at detector points P1 to P3 reached 15%/m in both experiments and numerical simulations, confirming the similarity. For points P4 to P6, the analysis showed that the time at which the smoke concentration started to increase and the time at which it reached its peak were similar in both experiments and numerical simulations. For P7 to P8, the smoke concentration did not reach 15%/m in both experiments and numerical simulations, indicating that the results were similar. The findings of this study suggest that numerical analysis can be used to implement the flow characteristics of domestic smoke generated by an insect repellent bomb, and this study can be used as basic research for analyzing the flow of smoke in a detector or studying the characteristics of a detector through numerical analysis in the future.

Keywords: Unwanted fire; Smoke detector; Flow behavior; Numerical method

1. Introduction

Unwanted fire alarm implies that the detector detects any element other than fire, such as dust or domestic smoke, as fire and triggers an alarm. Figure 1 and Table 1 present the 119 life safety activities[1] and the fire ratio for fire detection and alarm systems[2] over a 10-year period, respectively, as reported by the National Fire Agency. From 2011 to 2020, malfunctions accounted for more than 99% of dispatches triggered by fire detection and alarm systems, and the number of unwanted-fire dispatches as a percentage of all 119 dispatches increased approximately 16-fold, from 1.1% in 2012 to 17.2% in 2021. These unwanted fire alarms are wasting firefighting resources and causing problems with the reliability of firefighting equipment. Therefore, research on methods to reduce the occurrence of unwanted fire alarms is necessary.

Before conducting the study, we reviewed the related earlier studies. Yu Ho Jeong tested the response performance of a smoke detector under fire and unwanted-fire conditions by applying an algorithm, that discriminates the degree of light scattering according to the particle size, to a conventional photoelectric smoke detector[3]. Son et al. proposed a multi-sensor fire detector to reduce the occurrence of unwanted fire alarms and confirmed that the multi-sensor fire detector can reduce the occurrence of unwanted fire alarms through actual fire tests to verify the temperature response characteristics and smoke and CO response characteristics of the multi-sensor fire detector[4]. Lee et al. conducted dust tests on samples to solve the problems that occur in a detector, such as detector malfunction, and confirmed that when the pollution level inside the smoke detector chamber is increased by dust and wind speed, it affects the smoke density per unit volume inside the chamber, that can cause detector malfunction even at the concentration of unwanted fire[5]. Lee et al. used a smoke detector to analyze the pollution level by representing the dust that can be generated indoors with different colors of fiber dust. Dust experiments and sensitivity tests showed that differences existed in the pollution level and voltage measurement in the photoreceptor in the smoke detector chamber depending on the color of fiber dust[6]. The main focus of earlier studies was to identify the
response characteristics of smoke detectors to unwanted fires, and experiments to identify the cause of unwanted fire alarms were primarily conducted using fire and dust experiments. Therefore, this study collected data such as detector triggering time and smoke concentration through experiments on unwanted fire alarms triggered by domestic smoke, and verified the usefulness of numerical analysis by implementing unwanted fire alarm experiments with a detector and domestic smoke in numerical analysis and comparing the analysis results. When numerical analysis is used to study unwanted fires, phenomena that are difficult to observe experimentally, such as flow, can be easily analyzed, and results can be predicted by adjusting various experimental conditions such as density and temperature. In this study, we used insect repellent bombs to generate domestic smoke. Insect repellent bombs are often used to ward off insects indoors. When they are used, their use should be reported in advance, and the detector should be disconnected or covered. If these procedures are ignored, the detector may erroneously detect a fire. Therefore, insect repellent bombs were used in this experiment, and the flow of domestic smoke generated by the insect repellent bomb and its effect on the detector were analyzed.

![Figure 1. Current status of 119 life safety activities over the past 10 years.](image)

Table 1. Fire Ratio for the Fire Detection and Alarm System over the Past 10 Years

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Dispatches</th>
<th>Number of Malfunctions</th>
<th>Number of Malfunctions</th>
<th>Number of Fires</th>
<th>Rate of Fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>1,034</td>
<td>1,032</td>
<td>99.8</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>2012</td>
<td>1,120</td>
<td>1,115</td>
<td>99.6</td>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>2013</td>
<td>1,454</td>
<td>1,446</td>
<td>99.4</td>
<td>8</td>
<td>0.6</td>
</tr>
<tr>
<td>2014</td>
<td>2,878</td>
<td>2,865</td>
<td>99.5</td>
<td>13</td>
<td>0.5</td>
</tr>
<tr>
<td>2015</td>
<td>4,039</td>
<td>4,023</td>
<td>99.6</td>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>2016</td>
<td>6,823</td>
<td>6,796</td>
<td>99.6</td>
<td>27</td>
<td>0.4</td>
</tr>
<tr>
<td>2017</td>
<td>8,909</td>
<td>8,872</td>
<td>99.6</td>
<td>37</td>
<td>0.4</td>
</tr>
<tr>
<td>2018</td>
<td>17,055</td>
<td>17,004</td>
<td>99.7</td>
<td>51</td>
<td>0.3</td>
</tr>
<tr>
<td>2019</td>
<td>23,973</td>
<td>23,873</td>
<td>99.7</td>
<td>64</td>
<td>0.3</td>
</tr>
<tr>
<td>2020</td>
<td>32,764</td>
<td>32,685</td>
<td>99.8</td>
<td>79</td>
<td>0.2</td>
</tr>
</tbody>
</table>
2. Unwanted Fire Experiment

A schematic and an actual photograph of the laboratory for the unwanted fire alarm experiment are shown in Figures 2(a) and 2(b), respectively. The laboratory comprises two rooms (Room 1 and Room 2) and a corridor. The insect repellent bomb is placed in Room 1 that is 2.5 m wide, 4 m deep, and 2.5 m high. Room 1 has a sink with a weighing scale and an insect repellent bomb on it. Room 2, with the same dimensions as those of Room 1, is located to the left of Room 1. The corridor is 7 m wide, 1.5 m deep, and 2.5 m high, with a window allowing observers in the monitoring room to observe the events occurring in the laboratory and check whether the smoke detector is activated. P1 through P8 denote the locations where analog photoelectric smoke detectors are installed. Using P1 that is installed directly above the insect repellent bomb in Room 1 as a reference point, smoke detectors are installed 1.5 ± 0.2 m apart inside the room and 1.8 ± 0.2 m apart in the corridor. Figure 3 shows a photoelectric smoke detector installed inside the laboratory. The smoke detector, with a diameter of 0.12 m, is triggered when the smoke obscuration is greater than or equal to 15%/m according to the South Korean detector standards, and the change in smoke concentration over time can be measured and stored through the receiver. Figure 4 shows the insect repellent bomb used in the experiment. At the beginning of the experiment, the insect repellent bomb was ignited to produce smoke. To measure the mass reduction of the insect repellent bomb, a weighing scale capable of measuring 0.1 g per second was placed, and the temperature change at the surface during smoke generation was measured to be used as a boundary condition for the numerical analysis.
The unwanted fire alarm experiment was conducted thrice. In each experiment, the temperature was set between 10 and 20 °C and the relative humidity between 40 and 60% according to the appropriate room temperature and humidity values set by the Ministry of Health and Welfare, and the experiment was conducted for 1,800 s. The three unwanted fire alarm experiments were referred to as Case 1, Case 2, and Case 3. During the experiments, the change in smoke concentration of the smoke detector at each location (from P1 to P8) was measured and used as comparison data to investigate the reliability of the numerical analysis.

3. 3D Numerical Analysis

3.1 Computational domain

For the computational domain of the numerical analysis, we implemented a laboratory of the same size as that used in the experiments, as shown in Figure 5(a). Room 1 was configured with a sink, weighing scale, and an insect repellent bomb. The sink was 1.8 m wide, 0.55 m deep, and 0.795 m high, and the weighing scale was 0.26 m wide, 0.3 m deep, and 0.111 m high. Figure 5(b) shows the insect repellent bomb, with a diameter of 0.056 m and a height of 0.113 m. The inlets shown as yellow areas of $0.014 \times 0.004 \text{ m}^2$ are set to produce smoke. Figure 5(c) shows the detector in the computational domain. We obtained the drawings from the smoke detector manufacturer and implemented them in the computational domain through a 3D modeling process. Based on these, we reproduced the phenomenon of smoke passing through the inside of the detector and measured the smoke concentration at the center of the detector. Figure 5(d) shows the locations of the smoke detectors. The smoke detector located directly above the insect repellent bomb was named P1, and detectors were placed at points P1 to P3 in Room 1, P4 to P6 in the corridor, and P7 to P8 in Room 2.
3.2 Governing equations and boundary conditions

The numerical analysis assumed a three-dimensional unsteady-state turbulent flow and used the standard k-ε turbulence model[7]. The governing equations[8] used in the analysis are as follows.

Continuity Equation: \[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \] (1)

Momentum Equation: \[ \frac{\partial}{\partial x_i} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \tau_{ij} \] (2)

Energy Equation: \[ \frac{\partial}{\partial x_i} (\rho T) + \frac{\partial}{\partial x_j} (\rho u_i T) = \frac{\partial}{\partial x_i} \left[ \mu \right] + \frac{\partial}{\partial x_j} \left[ \frac{\mu_f}{\sigma_f} \right] \frac{\partial T}{\partial x_j} \] (3)

Turbulent Kinetic Energy Equation: \[ \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_i} \left[ \mu + \frac{\mu_f}{\sigma_f} \right] \frac{\partial k}{\partial x_j} k + G_k - \rho \varepsilon \] (4)

Dissipation Rate Equation of the Turbulent Kinetic Energy Equation: \[ \frac{\partial}{\partial t} \varepsilon + \nabla \cdot (\rho \varepsilon V) = \nabla \cdot \left[ \left( \mu + \frac{\mu_f}{\sigma_f} \right) \nabla \varepsilon \right] + \frac{1}{T_e} C_{e1} \rho_e - C_{e2} \rho \frac{T_e}{T_0} - \frac{\varepsilon_0}{T_0} + S_\varepsilon \] (5)

Concentration Equation: \[ \frac{\partial}{\partial t} (\rho C) + \frac{\partial}{\partial x_j} (\rho u_j C) = \frac{\partial}{\partial x_j} \left[ \rho D_j + \frac{V_j}{\sigma_j} \right] \frac{\partial C}{\partial x_j} \] (6)

Ideal Gas Equation: \[ \rho = \frac{P}{RT} \] (7)

where \( \tau_{ij} = \left[ \mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_j} \delta_{ij} \), \( \mu_1 = \mu + \frac{k^2}{\varepsilon} \), \( G_k = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \) (8)

\( \rho \) denotes the density, \( u_i \) and \( u_j \) denote the velocity components of each coordinate axis, \( p \) denotes the pressure, \( \mu \) denotes the viscosity modulus, and \( R \) denotes the gas constant. \( \sigma_k \), \( \sigma_\varepsilon \), \( \sigma_f \), and \( C_{e2} \) denote experimental constants with values of 1.0, 1.2, 1.0, and 1.9, respectively. For \( C_{e1} \), \[ \frac{\eta}{5 + \eta} \] is used, up to 0.43.

As boundary conditions for the numerical analysis, the amount of smoke generated and the amount of temperature change at the surface were measured and corrected, as shown in Figure 6, and assigned to the inlet condition such that smoke could be generated and could rise from the smoke outlet of the insect repellent bomb. Figure 6(a) shows the amount of smoke generated. The mass reduction of the insect repellent bomb was measured at intervals of 1 s using the weighing scale. It was then converted into mass flow rate as shown in Figure 6(b). We determined that the amount of mass change measured after 250 s was due to the weighing scale error, and set the smoke release duration to 250 s as a boundary condition input. The mass reduction of the smoke bomb used in the experiment was 45.5 g; the mass was 198.8 g before the experiment and 153.3 g after the experiment. The corrected amount of smoke generation was 45.7 g. Because the error was approximately 0.4% compared to the mass reduction measured in the experiment, the corrected amount of smoke generation was determined to be suitable for use as a boundary condition for the numerical analysis. To implement the temperature of the surface of the insect repellent bomb in the numerical simulation, we measured the temperature change at the surface of the insect repellent bomb, as shown in Figure 6(c), and corrected it, as shown in Figure 6(d). For the wall conditions in the computational domain, we set adhesion and insulation conditions. The initial temperature was set to 26 °C that was the measurement result in the experiment.
3.3 Mesh setup and numerical analysis method

The meshes in the computational domain for numerical analysis were set as presented in Table 2. The default mesh size was set to 0.1 m; the closer the wall, the denser the meshes. The minimum mesh size was 0.002 m, that was 2% of the default size, and the maximum size was 0.1 m, that was 100% of the default size. Because the inlet part of the insect repellent bomb and the smoke detector were smaller than those in the computational domain and were regions where the amount of flow change was large, we assigned 0.002 m and 0.001 m for their mesh sizes, respectively, and used 2,353,642 for the total number of meshes.

<table>
<thead>
<tr>
<th>Room 1, Room 2, Corridor</th>
<th>Base Size (m)</th>
<th>Minimum Size (m)</th>
<th>Maximum Size (m)</th>
<th>Number of Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.002</td>
<td>0.1</td>
<td>1,350,466</td>
</tr>
<tr>
<td>Inlet</td>
<td>0.002</td>
<td>0.0004</td>
<td>0.002</td>
<td>832</td>
</tr>
<tr>
<td>Smoke Detector</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.001</td>
<td>1,002,344</td>
</tr>
</tbody>
</table>

The numerical analysis was performed using STAR-CCM+ version 16.08[8], a commercial computational fluid dynamics (CFD) program. The aforementioned governing equations were calculated by discretization using the finite volume method (FVM). Segregated flow solver was used to solve the mass and momentum equations, and the semi-implicit method for pressure-linked equation (SIMPLE) algorithm was used to accurately predict the velocity
field that satisfies the continuity equation through the continuity and momentum equations [9]. Because the analysis was performed by iteratively calculating with nonlinear equations, the convergence of the calculated values had to be checked. Regarding the convergence of the dependent variables in each mesh through iterative calculations, we determined that the values converged when the residual reached $10^{-3}$ or less.

4. Results

To examine the accuracy of the numerical analysis results, the smoke concentrations at the detector points (P1 to P8) measured in the experiment were compared, as shown in Figure 7. Two types of analog detectors (ASD1 and ASD2) were set up to measure the smoke concentration in the experiment, and the three experimental data (Case 1, Case 2, Case 3) were compared with the numerical analysis data (CFD).

The experimental and numerical analysis results for detector points P1 to P3 located in Room 1 are shown in Figures 7(a), 7(b), and 7(c). In both the experimental and numerical analysis results, the smoke concentration of 15 %/m was reached, and the time to reach it was compared. Cases 1 to 3 showed that the time at which 15 %/m smoke concentration was reached was 28 to 78 s, 130 to 235 s, and 166 to 313 s for detector points P1 to P3, respectively. In the case of CFD, the time at which 15% smoke concentration was reached was 46 s, 103 s, and 193 s for detector points P1 to P3, respectively. For points P1 and P3, the numerical analysis results were within the range of the experimental results. Whereas in the case of point P2, the 15 %/m smoke concentration was reached 27 s faster in the numerical analysis than in the experiment.

![Figure 7. Comparison of smoke concentration in experiments and CFD.](image-url)
The experimental and numerical analysis results for detector points P4 to P6 located in the corridor are shown in Figures 7(d), 7(e), and 7(f). The smoke concentration reached 15 %/m in the experiments but not in the numerical analysis. Therefore, to analyze the trend between the experiments and numerical simulations, we compared the time at which the peak smoke concentration was reached and the time at which the smoke concentration in the detector began to increase between the numerical analysis and experimental results. In Cases 1 to 3, the time at which 15 %/m smoke concentration was reached was 147-852 s, 583-772 s, and 628-1,594 s for detector points P4 to P6, respectively. In the case of CFD, the time at which 15% smoke concentration was reached was 356 s, 633 s, and 900 s for detector points P4 to P6, respectively, that were within the range of the experimental results. The time at which the smoke concentration began to increase was 116-659 s, 428-657 s, and 368-600 s, respectively, in Cases 1 to 3, and 179 s, 256 s, and 378 s, respectively, in the case of CFD. In the case of point P5, the increase began 172 s earlier in the numerical analysis than in the experiment. Whereas in the cases of points P4 and P6, the numerical analysis results were included in the range of the experimental results.

The experimental and numerical analysis results for detector points P7 and P8 located in Room 2 are shown in Figures 7(g) and 7(h). Because the smoke concentration of 15 %/m was not reached in most of the experimental and numerical analysis results, we compared the time at which the smoke concentration began to increase in the detector to analyze the trend between the experimental and numerical analysis results. In Cases 1 and 2, the smoke concentration began to increase between 210 and 832 s at point P7; however, in Case 3, it did not increase. In the case of CFD, the time at which the smoke concentration began to increase was 732 s for P7. In the case of P8, the smoke concentration began to increase at 786 s in Case 1; however, the other experimental and numerical analysis results showed no increase in smoke concentration.
5. Conclusion

In this study, experiments and numerical analysis of unwanted fire alarms triggered by domestic smoke were conducted, and the smoke concentration was compared and analyzed for each detector point to verify whether numerical analysis can be used to implement unwanted fire alarm situations triggered by smoke.

(1) At detector points P1 to P3, a smoke concentration of 15 %/m was reached in both experiments and numerical analysis, and the reaching time was also similar between the experimental and numerical analysis results.
(2) At detector points P4 to P6, the smoke concentration reached 15 %/m in the experiments but not in the numerical analysis. However, the time at which the smoke concentration began to increase was similar between the experimental and numerical analysis results.
(3) At detector points P7 and P8, a smoke concentration of 15 %/m was not reached in most of the experiments and numerical analysis, showing a similarity between the experimental and numerical analysis results.
(4) In the numerical simulation, the wall surface was assumed to be insulated. However, the temperature on the actual wall surface varies depending on the location on the wall surface. In addition, the degree of roughness on the wall surface was set to smooth in the numerical analysis, unlike the actual wall. This explains the difference in results between the experiments and numerical analysis.

Based on the results of this study, we concluded that numerical analysis can be used to implement the flow characteristics of domestic smoke generated by an insect repellent bomb, and this study can be used as basic research for analyzing the flow of smoke in a detector or studying the characteristics of the detector by numerical analysis in the future.

Author Contributions

Writing original draft preparation, S.J. Kim; Data curation, investigation, S.J. Kim; Supervision, Project administration, S.C. Lee; Writing review and editing, S.J. Kim and S.C. Lee; All the authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References