A Comparison on Detected Concentrations of LPG Leakage Distribution through Actual Gas Release, CFD (FLACS) and Calculation of Hazardous Areas

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(Received October 16, 2020; Revised November 20, 2020; Accepted December 3, 2020)

Abstract

Recently, an interest in risk calculation methods has been increasing in Korea due to the establishment of classification code for explosive hazardous area on gas facility (KGS CODE GC101), which is based on the international standard of classification of areas - explosive gas atmospheres (IEC 60079-10-1). However, experiments to check for leaks of combustible or toxic gases are very difficult. These experiments can lead to fire, explosion, and toxic poisoning. Therefore, even if someone tries to provide a laboratory for this experiment, it is difficult to install a gas leakage equipment. In this study we find out differences among actual experiments, CFD by using FLACS and calculation based on classification code for explosive hazardous area on gas facility (KGS CODE GC101) by comparing to each other. We developed KGS HAC (hazardous area classification) program which based on KGS GC101 for convenience and popularization. As a result, actual gas leak, CFD and KGS HAC are showing slightly different results. The results of dispersion of 1.8 to 2.7 m were shown in the actual experiment, and the CFD and KGS HAC showed a linear increase of about 0.4 to 1 m depending on the increase in a flow rate. In the actual experiment, the application of 3/8” tubes and orifice to take into account the momentum drop resulted in an increase in the hazardous distance of about 1.95 m. Comparing three methods was able to identify similarities between real and CFD, and also similarities and limitations of CFD and KGS HAC. We hope these results will provide a good basis for future experiments and risk calculations.

Keywords: LPG, Release, Dispersion, Hazardous area, FLACS

1. Introduction

It is difficult to demonstrate the gas-flow of flammable gases such as LPG (liquefied petroleum gas) in a visualized form due to the invisible and odorless properties of the gas. Even if it is possible to smell any odorant for gas, this is not sufficient to measure an exact amount between explosive limits. Three constituents, known as the fire triangle, are required to ignite a fire: heat, fuel, and an oxidizing agent (usually oxygen)[1]. However, it is not easy to recognize fuel, which is a flammable gas, as it is not seen. Oxygen in air exists all around, and it always occupies one corner of the fire triangle. Heat lasting from earlier use and the enormous number of electrical devices in our world are all potential sources of ignition that are very close to fire. Hence, it is necessary to secure the safety of facilities handling explosive materials and establish infrastructure for the improvement of technology in the relevant fields[2]. Therefore, one of the three conditions of ignition (heat, fuel, oxidizing agent) should be controlled to prevent an explosion. The first and most basic aspect in this control is classifying the spatial zone and clarifying the extent of dimensions in terms of hazardous distance to lower the risk of flammability/explosion from the point of gas release. Next, appropriate or special explosion-proof devices that do not function as igniter can be used in properly classified hazardous zones. Thus, the most important considerations are classifying zones and measuring their distances for safety. More specifically, this study deals with the span of releasing gas in areas. Classification
of hazardous area is a technique for assessing the probability of formation of a flammable atmosphere and its likely duration. It has long been a widely used technique in the chemical industry, as a step towards deciding whether electrical and other equipment need special protective features in order to prevent it causing a fire or explosion[3].

2. Experimental Method

In this study, an actual leakage test, CFD and calculation (KGS HAC) method were used to compare the detectable concentrations of LPG that leaked from LPG cylinder. To compare the values obtained by each method, the same leakage diameter, pressure, temperature and leakage coefficient were adapted to calculate mass flow rate. The mass flow rate was based on actual leakage test. Table 1 shows the common input variables. The same values were used for pressure, temperature and discharge coefficient. The discharge coefficient is the value determined in the form of orifice, and in the actual experiment a well-processed orifice was used, so 0.99 was used.

2.1. Actual leakage experiment

Actual leakage experiment was conducted at Energy Safety Empirical Business Center of Korea Gas Safety Corporation. Figure 1 is the schematic diagram of the actual leakage test. The experiment was designed such that leakage occurs according to the set flow rate [5, 10, 15, 20 LPM] from the gas cylinder.

Figure 2 is the schematic diagram of the arrangement of gas sensors in this experiment. 2 types and about 100 catalytic combustion method gas sensors were arranged in the aluminum frame. Two types of gas sensors were used considering the installation cost and reliability of sensors. The sensor uses a low-cost MQ-2 and a customized KGS-701 sensor. The KGS 701 sensors, which are reliable according to the manufacturing specifications, were installed at the main location points where gas leakage is expected, and the MQ-2 sensors were installed at the periphery. All gas sensors were calibrated in advance using 1 and 2.1% of standard gas, and DAQ was connected so that data could be received in real time. The performance of the sensor is kept constant through sufficient ventilation time for each experimental case.

Figure 3 shows the appearance of the sensors that have been set up, the acquired data and the appearance of the gas sensor. The acquired data represented the contours of the front (XZ), plane (XY), and side (YZ) using an interpolation method and an origin program, through which the diffusion of gas was visualized.

Origin is a data analysis software that allows users to draw contours of gas concentrations by selecting interpolation methods in various ways, such as weighted average. Excel VBA, on the other hand, does
not provide interpolation, so the map was drawn including interpolation function. Where the site of data loss was internal, the Bicubic-interpolation function was used. Where the site of data loss was external, the interpolation function was converted and applied for it to be applicable to extrapolation.

3. CFD and Numerical Calculation Methods

3.1. Computational fluid dynamic (CFD)

For the CFD, FLACS was used to check the dispersion of propane gas. FLACS is a program specialized in gas explosion, dispersion and risk assessment.

The main governing equations for gas leakage analysis of FLACS are expressed as equations (1) to (6). The equations (1) to (6) address conservation of mass, Navier-Stokes momentum, transport equation for enthalpy and fuel mass fraction.

\[
\frac{\partial}{\partial t} (\beta \rho) + \frac{\partial}{\partial x_j} (\beta \rho u_j) = \frac{m}{V} \tag{1}
\]

\[
\frac{\partial}{\partial t} (\beta \rho u_j) + \frac{\partial}{\partial x_j} (\beta \rho u_j u_j) = -\beta_j \frac{\partial}{\partial x_j} (\beta \rho u_j) + \beta_k \frac{\partial}{\partial x_j} F_{u_k} + \beta_k F_{u_k} + \beta_l (\rho - \rho_0) g_i \tag{2}
\]

\[
\frac{\partial}{\partial t} (\beta \rho \beta_k) + \frac{\partial}{\partial x_j} (\beta \rho u_j \beta_k) = \frac{\partial}{\partial x_j} \left( \beta_j \frac{u_{eff}}{\sigma_k} \frac{\partial \beta_k}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \beta_j \frac{Y_{f,eff}}{\sigma_k} \frac{\partial \beta_k}{\partial x_j} \right) + R_{f,eff} \tag{3}
\]

\[
\frac{\partial}{\partial t} (\beta \rho Y_{f,eff}) + \frac{\partial}{\partial x_j} (\beta \rho u_j Y_{f,eff}) = \frac{\partial}{\partial x_j} \left( \beta_j \frac{u_{eff}}{\sigma_k} \frac{\partial Y_{f,eff}}{\partial x_j} \right) + R_{f,eff} \tag{4}
\]

\[
\frac{\partial}{\partial t} (\beta \rho k) + \frac{\partial}{\partial x_j} (\beta \rho u_j k) = \frac{\partial}{\partial x_j} \left( \beta_j \frac{u_{eff}}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \beta_k P_k - C_{\mu \epsilon} \beta_\epsilon \beta_k \rho \frac{\epsilon^2}{K} \tag{5}
\]

\[
\frac{\partial}{\partial t} (\beta \rho \epsilon) + \frac{\partial}{\partial x_j} (\beta \rho u_j \epsilon) = \frac{\partial}{\partial x_j} \left( \beta_j \frac{u_{eff}}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_j} \right) + \beta_k P_k - C_{\mu \epsilon} \beta_\epsilon \beta_k \rho \frac{\epsilon^2}{K} \tag{6}
\]

\( \beta \): Volume porosity [-]

\( \rho \): Density [kg/m³]

\( u \): Velocity [m/s]

\( x \): Concentration of gas [mol/mol]

\( \sigma \): Stress tensor [N/m²]

\( F \): Force [N]

\( h \): Specific enthalpy [J/kg]

\( u_{eff} \): Effective viscosity [Pa S]

\( p \): Absolute pressure [Pa]

\( Q \): Heat [J]

\( V \): Volume [m³]

\( \gamma \): Mass fraction [-]

\( R_{f,eff} \): Reaction rate for fuel [kg/m³s]
105

가스 누출 실험, CFD 및 거리산출 비교를 통한 LP가스 누출 검지농도 분포에 대한 고찰

Table 3. Input Values for KGS HAC 1.16

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<td>1,901,325</td>
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<td>Case 4</td>
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<td>1,901,325</td>
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</tbody>
</table>

Figure 5. Orifice appearances on CFD and Actual experiment equipment (case 5).

Figure 6. Graph for identifying hazardous distance by KGS HAC.

\[
\frac{dG}{dt} = SP\sqrt{\frac{M}{RT}}\left(\frac{2}{\gamma\gamma-1}\right)^{1/2} \left(1 - \frac{P_o}{P}\right)^{\gamma/\gamma-1} \left(\frac{P_o}{P}\right)^{1/\gamma} \left(\frac{P_o}{P}\right)^{1/\gamma}
\]

\[
P_c: \text{Critical pressure of gas [Pa]}
\]
\[
P_o: \text{Ambitne pressure [Pa]}
\]
\[
\gamma: \text{Polytropic coefficient } \gamma = \frac{MC_o}{MC_p - R}
\]
\[
S: \text{Orifice diameter [m²]}
\]
\[
P: \text{Inner pressure [Pa]}
\]
\[
M: \text{Molecular weight [kg/kmol]}
\]
\[
R: \text{Ideal gas coefficient [8314 J/kmolK]}
\]
\[
\frac{dG}{dt}: \text{Mass flux [kg/s]}
\]

Table 3 shows the KGS HAC inputs used to calculate the hazardous distance. The same input value was used for each case and the leakage rate value was similar to the value in CFD. In this table, the inner pressure was set by absolute pressure of cylinder. The KGS HAC uses Pabs to calculate the distance, which is different from CFD. The unit is different from the table above, as the unit entered in KGS HAC was applied.

KGS HAC calculates the hazardous distance using the graph shown in Figure 6. There are 3 characteristics of gas release type on the graph.

The hazardous distance corresponding to the Y-value is read as a combination of release characteristics (X-axis) and graphs. The release characteristics were calculated in consideration of safety factors based
The hazardous distance is determined by the release characteristics (X-axis) and three types of gas. The release characteristics are calculated by considering the mass flow rate, the explosion limit and the safety factor (K). The types of gases mentioned above are jet gas, diffuse gas, and heavy gas. The safety factor (K) and gas type have a great influence on the increase and decrease of hazardous distance. The graph shows that the hazardous distance of the heavy gas is about twice the hazardous distance of the jet gas at the same release characteristic, and that the diffuse gas has an intermediate value. Jet gas is released at high speed without obstacles after leakage, and diffuse gas loses momentum due to obstacles after leakage. The reason for the large hazard range of diffuse gas is that the scouring effect at the boundary surface of the gas column is greater than that of jet gas. The wide hazard range of diffuse gas is due to the greater scattering effect on the gas boundary with loss of momentum than in the case of jet gas.

The safety factor (k) is a value determined in terms of the lower explosion limit, and a value between 0.5 and 1 is used. It is recommended to use 1 for substances the explosive lower limit of which is well known from the test results or literature, 0.8 for substances where the lower explosive limit can be calculated, and 0.5 for other cases.

Figure 7 is an operation that calculates a hazardous distance using KGS HAC. Entering gas type, safety factor, size of leakage hole, pressure, etc. as representative input variables, mass flow rate (W) and characteristic leakage potential are calculated. Hazardous distances can be calculated based on calculated values.

4. Results and Discussion

4.1 Actual leakage experiment

All results of the leakage test are shown as a contour map in Figure 8 according to the position indicated by interpolation method. It shows 20 LPM results at each plane XY, XZ, YZ.

According to the dispersion results, the maximum gas dispersion distance was extracted as shown in Figure 9. In case of 5 LPM, it shows a dispersion distance of about 2.2 m at 32 s. In case of 10 LPM, it shows a dispersion distance of about 1.8 m at 20 s. In case of 15 LPM, it shows a dispersion distance of about 2.6 m at 18 s. In case of 20 LPM, it shows a dispersion distance of about 2.7 m at 14 s. Before conducting the experiment, it was expected that the dispersion distance would appear longer with increase in the amount of gas leaked. However, in the actual experiment, almost all results show dispersion distance of more than 2 m, and the tendency according to the change in leakage flow rate could not be confirmed. These unexpected results are considered due to the effect of dispersing the flow even with a small amount of airflow owing to the very light density of the gas.

Although the experiment was conducted indoors in such a furnace, the diffusion of gas at 15 and 20 LPM tends to rise upward.

4.2. Computational fluid dynamic (CFD)

The contour lines of the CFD results show values of 2.38~0.058%, which is the lower limit of propane and the detectable concentration (1/4 of the lower limit).

Figure 10 presents the picture of a gas plume viewed from the side of a case 1 leak. The maximum leakage distance was 0.357 m after about 3.5 s of leakage. After that, as the leakage stabilized, the distance gradually became shorter, and after about 10 s, it stabilized to about 0.32 m.

Figure 11 shows the picture of a gas plume viewed from the side of a case 2 leakage. The maximum leakage distance was 0.64 m after about 5.75 s of leakage. After that, as the leakage stabilized, the distance gradually became shorter, and after about 13 s, it stabilized to about 0.59 m.

Figure 12 presents the picture of a gas plume viewed from the side of a case 3 leakage. The maximum leakage distance was 0.85 m after about 6.75 s of leakage. After that, as the leakage stabilized, the distance gradually became shorter, and after about 10 s, it stabilized to about 0.82 m.

Figure 13 shows the picture of a gas plume viewed from the side
of a case 4 leak. The maximum leakage distance was 1.03 m after about 8.50 s of leakage. After that, as the leakage stabilized, the distance gradually became shorter, and after about 18 s, it stabilized to about 0.97 m.

In the case of actual experiments, the leakage is carried out in two stages, in which the gas passing through the flow meter passes through the 3/8” tube and passes through the orifice of a set size. This will result in changes in pressure and momentum in the 3/8” tube. In Scenario 5, the first step was to set up the gas released from the flow-meter and the second step was to simulate passing through a 3/8” tube.

As a result, a momentum drop occurred in the gas passing through the orifice. Figure 14 shows gas leakage over time in scenario 5 and gas leans downward as momentum drops. In addition, the dilution rate also decreased as the release rate decreased, spreading to about 1.85
Scenario 5 simulates the most similar form to the actual experiment, confirming that the CFD leakage model is similar to the actual situation, even considering variables such as wind, atmospheric temperature, and pressure in the real world.

4.3. Numerical calculations (KGS HAC)

Hazardous distance was calculated based on the input value in Table 3 (section 4.2) using KGS HAC. It was calculated to be 0.55 m for case 1, 0.78 m for case 2, 0.96 m for case 3, and 1.1 m for case 4. As in the CFD result, the hazardous distance increased as the leakage flow increased and it was also confirmed that the maximum hazardous distance was very similar. For KGS HAC, calculations for scenario 5 were omitted because calculations of effects from pressure and momentum drop were not supported.

5. Conclusion

In this study, we compared and analyzed the actual gas dispersion through empirical experiments as well as gas leakage simulation and calculation in ideal situations. In the case of computational methods, there were slight differences due to the numerical differences between CFD and KGS HAC, but the hazardous distance were similar. On the other hand, the results of the actual leakage experiment were different from those of the computational methods. The first reason for this difference seems to be that the flow changes even by the degree of micro-winds that are not measured through the anemoscope, owing to the very light density of the gas. The first reason seems to be that the gas leaked at 15 LPM and 20 LPM spreads upward. The second reason is assumed to be the momentum drop in 3/8"SUS tube caused by the gas passing between the flowmeter and the orifice. Accordingly, 3/8" tubes and orifice sizes were modeled as real-size, and simulations were carried out. Through the flowmeter (stage1), 3/8" tube (stage 2) and orifice (stage 3) it was confirmed that the flow rate dropped significantly due to the momentum drop. In this case, the spread increases with the attenuation of the dilution effect. As a result, we were able to check the dispersion distance of 2 m in CFD.

Figure 14. Plume contour of case 5 leakage.
Table 4. Results of All Dispersion Tests

| Scenarios | Hazardous distance [m] |
|-----------|------------------------|------------------|
|           | Experiment             | CFD (FLACS)      | KGS HAC |
| 1         | 2.2                    | 0.357            | 0.55    |
| 2         | 1.8                    | 0.64             | 0.78    |
| 3         | 2.6                    | 0.85             | 0.96    |
| 4         | 2.7                    | 1.013            | 1.1     |
| 5         | 2.7                    | 1.95             | -       |

to the actual situation, and it was confirmed that the dispersion increased to 1.95 m maximum.

A summary of the results for each case is as follows.
- In actual leakage, the dispersion of gas can be changed due to micro-wind effects.
- In actual gas leakage situations, it is very difficult to have a consistent tendency due to the changed ambient air temperature, pressure, wind, etc.
- In the case of calculation methods using CFD and KGS HAC, the dispersion distance increased steadily as the flow rate increased, considering the ideal condition.
- As a result of modeling an environment similar to the actual experiment as CFD, the hazardous distance may increase significantly due to a momentum drop in 3/8" tubes and orifices.
- Calculations using KGS HAC cannot take into account a momentum drop. The KGS HAC is likely to require future updates to calculate these situations.

References


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