Korean Chem. Eng. Res., 56(6), 811-818 (2018)
https://doi.org/10.9713/kcer.2018.56.6.811
PISSN 0304-128X, EISSN 2233-9558

Investigation of the LPG Gas Explosion of a Welding And Cutting Torch at a Construction Site

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(Received 9 October 2018; Received in revised form 2 November 2018; accepted 2 November 2018)

Abstract – A fire and explosion accident caused by a liquefied petroleum gas (LPG) welding and cutting torch gas leak occurred 10 m underground at the site of reinforcement work for bridge columns, killing four people and seriously injuring ten. We conducted a comprehensive investigation into the accident to identify the fundamental causes of the explosion by analyzing the structure of the construction site and the properties of propane, which was the main component of LPG welding and cutting work used at the site. The range between the lower and upper explosion limits of leaking LPG for welding and cutting work was examined using Le Chatelier's formula; the behavior of LPG concentration change, which included dispersion and concentration change, was analyzed using the fire dynamic simulator (FDS). We concluded that the primary cause of the accident was combustible LPG that leaked from a welding and cutting torch and formed a explosion range between the lower and upper limits. When the LPG contacted the flame of the welding and cutting torch, LPG explosion occurred. The LPG explosion power calculation was verified by the blast effect computation program developed by the Department of Defense Explosive Safety Board (DDESB). According to the fire simulation results, we concluded that the welding and cutting torch LPG leak caused the gas explosion. This study is useful for safety management to prevent accidents caused by LPG welding and cutting work at construction sites.

Key words: Liquefied petroleum gas (LPG), Trinitrotoluene (TNT), Fire dynamic simulators (FDS), Le Chatelier's formula, Welding and cutting

1. Introduction

In South Korea, there has been no decline in the loss of human life and property damages caused by liquefied petroleum gas (LPG) accidents. LPG is used for welding and cutting at small-scale construction sites. According to the Ministry of Public Safety and Security, a total of 43,413 fires occurred in 2016, and 1,074 fires were caused by welding and cutting, which is an average of about 2.9 such fires per day. An analysis of the fire and explosion accidents related to welding and cutting for the past five years revealed that the ignited objects were flammable gas (35.7%), combustible substance (28.6%), urethane panel (14.3%), urethane foam (7.1%), and other substances (14.3%). Those accidents occurred at plants (21.4%), military facilities (14.3%), roads and pipelines (14.3%), and buildings (14.3%) [1].

Among the many serious disasters caused by welding and cutting, one that recently occurred on the construction site of subway line 4, 638-14, Gumgok-ri, Jinseung-eup, Namyangju, Gyeonggi-do, Korea on June 1, 2016 involved leaking LPG that exploded and caused four deaths and ten injuries. On December August 4, 2014 while workers were working on LPG welding and cutting work, a 10 kg LPG gas cylinder valve burst out at Waste Treatment Plant in Cheongju, which resulted in three injuries. Finally, on December April 30, 2011 LPG welding at Sejin Heavy Industries' shipyard in Ulsan, which resulted in four deaths [2].

It is clear from these cases that inflammable materials are the main cause of explosions during welding and cutting work. In particular, LPG welding and cutting, which is widely carried out on construction sites, continuously causes casualties. In this study, the explosion of leaked LPG during the welding and cutting involved in reinforcing a subway bridge foundation was investigated. Previous studies related to LPG explosion are as follows, LPG as leaked from an LPG tank to a fixed storage container, causing an explosion. So, they investigated the cause through accident investigation [3].

The aim of this study was to investigate the cause of the explosion and the type of explosion of LPG by comparing the explosion data of various combustible materials with the experimental data by estimating the leakage amount of combustible gas (LPG).

2. Accident Analysis

2-1. Accident timeline

The explosion accident occurred at the construction site when LPG leaked into an underground space, which was a subway construction site with the upper side open. Reinforced concrete was being prepared to be constructed, the LPG and oxygen gas tanks were on the ground for cutting rebar, and the gas torch (LPG + oxygen) was

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‡This article is dedicated to Prof. Lae Hyun Kim on the occasion of his retirement from Seoul National University of Science and Technology.

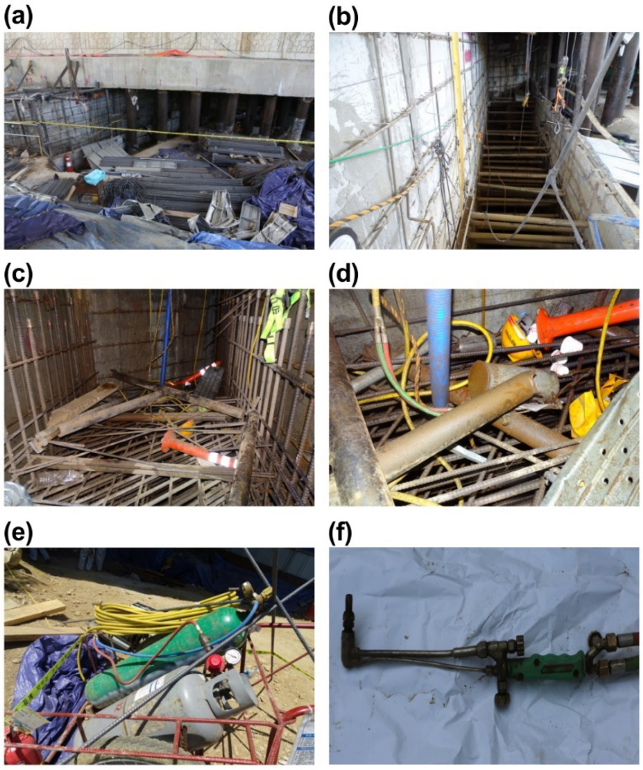

Fig. 1. (a) Complete view of the accident site; (b) Outside the trench; (c) Inside the trench where the ignition occurred; (d) Place where the torch was found inside the trench; (e) Welding and cutting rods, LPG, and oxygen tanks; (f) Welding and cutting torch.

underground. It is speculated that inflammable gas leaked and remained, and when a worker ignited the torch in the vicinity, the explosion occurred. When such an inflammable liquid leaks from the interior of a constructed structure and pools at the bottom of trench, a heavy inflammable vapor layer is formed, which is hazardous [4-9].

The photos in Fig. 1 show the accident site.

Table 1 presents the timeline of events around the LPG leakage accident. This table was prepared from the testimony of site workers and the time record of rescue operation of the firefighters. The exact explosion time could not be determined and site workers stated that the explosion occurred a few minutes after the torch was ignited [10-14].

The LPG explosion caused four deaths and ten injuries. Fig. 2

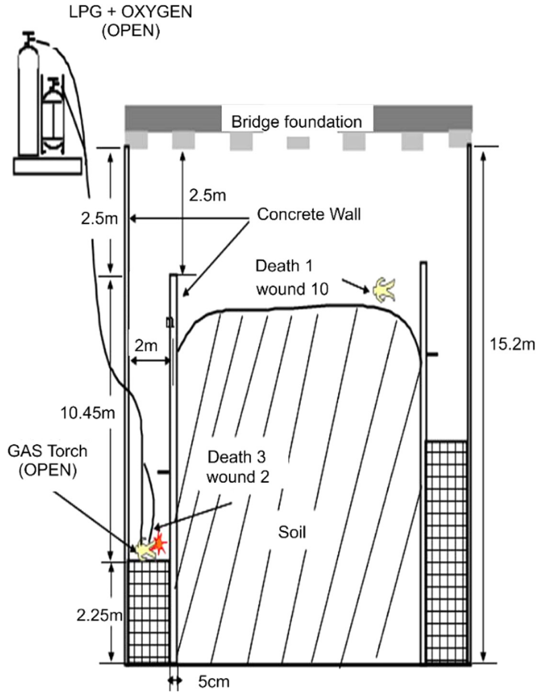

Fig. 2. Schematic diagram of the accident site.

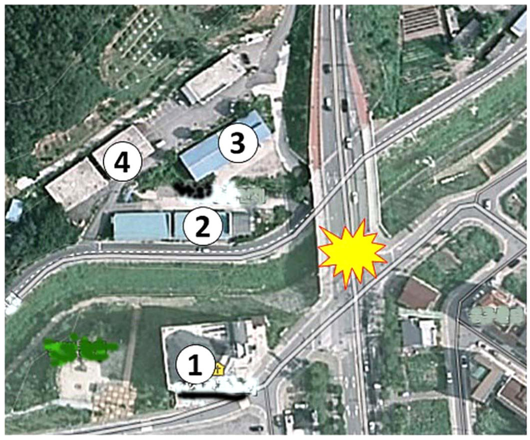

Fig. 3. Locations of four damaged facilities relative to the explosion.

illustrates the positions of those who were killed or injured at the site. In addition, the windows of nearby stores and houses were shattered, and the construction site and adjacent buildings were cracked. Fig. 3

Table 1. Accident timeline

Time	Contents
Around 07:00	17 field staff started their work
Around 07:10	Danger prediction training (Tool Box Meeting) completed
Around 07:10	Preparation for LPG Welding and cutting ① Main valve of the gas tank and the valve of the oxygen tank opened (on the ground surface). ② Torch valve opened in the 5-m underground trench. ③ Torch ignited on the base block (horizontal flame). ④ Optimal flame for welding and cutting formed by controlling the oxygen valve (horizontal flame). ⑤ Torch moved downward for welding and cutting (vertical flame). ⑥ Arrival of torch at the optimal point for welding and cutting results in explosion.
07:10–07:27	Estimated explosion period
Around 07:27	Receipt of 119 Call
Around 07:43	119 Rescue team arrival and start of rescue operation
Around 09:11	Completion of rescue operation

Table 2. Details of facility damage by estimated explosion period (7:10–7:27)

Reference No.	Facility Type	Damage Explanation	Distance from Explosion (m)
1	Church	- Disassembled ceiling - Car damage caused by fallen ceiling	70
2	Warehouse	- Door and window broken - Distortion of frame (beam)	65
3	Warehouse	- Door and window broken - Distortion of frame (beam)	70
4	House	- Door and window broken - Corridor wall cracked	90

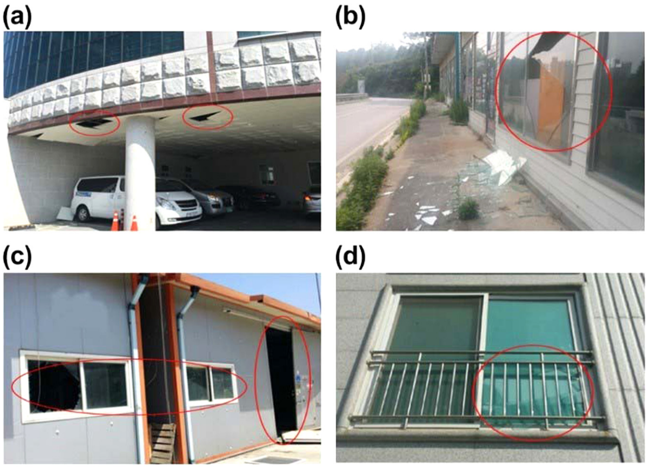

Fig. 4. (a) Damage to Building No. 1, disassembled ceiling; (b) Damage to Building No. 2, broken door and window; (c) Damage to Building No. 3, distortion of frame (beam); (d) Damage to Building No. 4, broken door and window.

shows the locations of damaged facilities, for which civil complaints were filed. Table 2 and Fig. 4 provide details of the damage and photos of each point.

2-2. Accident pre-investigation

The trench where the explosion started was measured to be 10 m wide, 2 m long, and 12 m high. Approximately 13 or 14 holed footboards, each of which was 40 cm wide, were installed inside the trench so that a semi-closed structure was formed to block air flow.

The environmental conditions on the day of the accident were obtained by checking the weather conditions for the period of the accident at the Korea Meteorological Administration. The ambient temperature was 19.8 °C, the humidity was 81%, and the air pressure was 1008 hPa.

The LPG welding and cutting machine used at the site consisted of an LPG tank, oxygen tank, hose, and torch. A certain mixture of two gases was ignited to cut rebar. The gas tank was positioned on the ground, and the torch, connected to a 20-m hose, was found on a 2.25-m base block. Approximately 6.8 kg of LPG remained in the 20-kg tank found at the site.

The structure and size of the trench of leaked LPG gas is shown in Fig. 5.

The field survey revealed that the explosion occurred near the underground trench where the workers ignited the gas torch and moved about. Based on the testimony of workers, it was very likely that the explosion occurred about 5 m underground after the gas torch was ignited. In addition, it seemed that gas leaked from the torch in the trench.

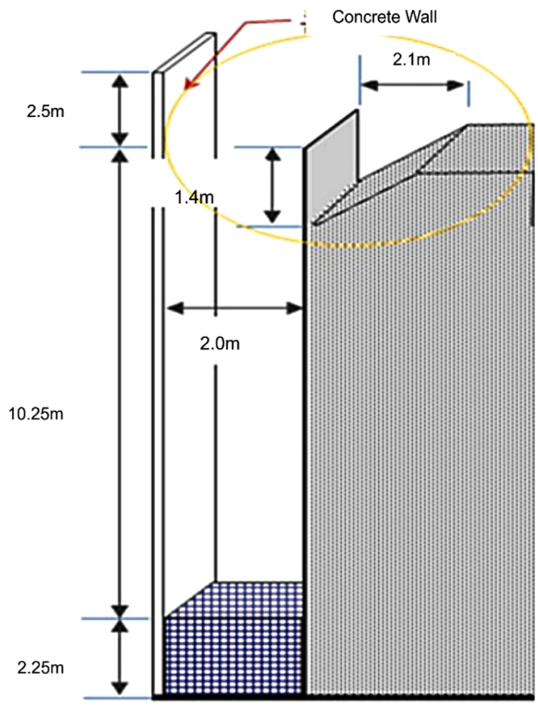

Fig. 5. Space for blocking foreign substances from the outside of the trench.

The main objective of this study was to determine the ignition point of the leaked LPG. Any inflammable gas explodes only within a explosion range. In the case of this accident, the time between LPG leakage and the formation of a explosion range was estimated to be a maximum of 13 hours based on the duty hours of the workers. This estimation was applied to the simulation to determine explosion ranges for each period and trench height.

3. Accident Investigation Procedure

The accident investigation methodology followed in this study is based on the following steps.

1) Accident site visits and observation

2) Verification of LPG gas welding and cutting procedure used

3) Prediction of explosion range in the event of LPG leakage (Le Chatelier's formula)
4) Accident data collection
5) Concentration and time prediction for explosion range using Fire Dynamics Simulator (FDS)
6) Verification of LPG explosion impact using Department of Defense Explosive Safety Board (DDESB)
7) Discussion and results investigation and experimental simulations

The main objectives of a risk assessment study are to identify the potential hazards, assess the risk from the individual scenarios, evaluate the risk control measures to reduce the risk to people, and recommend improved working procedures.

3-1. Prediction of explosion range in the event of LPG leakage (Le Chatelier's formula)

LPG is a highly inflammable, non-toxic, and non-corrosive liquid. It is stored as compressed liquid in a tank and turns into a gas when released into the air. Explosion in air occurs only within a certain mixing proportion range of LPG and air. When the inflammable LPG is either below or above these limits, no explosion occurs. These limits are called explosion limits, the highest and lowest levels where explosion occurs are the upper explosion limit and the lower explosion limit, respectively.

Because the temperature when the accident occurred was 19.8 °C, according to the South Korea meteorological administration, the explosion limits were corrected by using the following formula to consider temperature. As pressure did not have a significant effect on the explosion range, it was excluded from the calculation:

$$LFL_T = LFL_{25°C} - (0.8LFL_{25°C} \times 10^{-3})(T-25) \quad (1)$$

where,

LFL_T : Lower explosion limit at a specific temperature(T)
$LFL_{25°C}$: Lower explosion limit at 25 °C
ΔHc : Disappearance of combustion gas [kcal/mol]
T : Temperature [°C]

$$UFL_T = UFL_{25°C} - (0.8UFL_{25°C} \times 10^{-3})(T-25) \quad (2)$$

where,

UFL_T : Upper explosion limit at a specific temperature (T)
$UFL_{25°C}$: Upper explosion limit at 25 °C

$$LFL_T = 2.074 - (0.8 \times 2.974 \times 10^{-3})(19.8-25) \fallingdotseq 2.08 \quad (3)$$

$$UFL_T = 9.45 - (0.8 \times 9.45 \times 10^{-3})(19.8-25) \fallingdotseq 9.41 \quad (4)$$

Consequently, the explosion range of LPG was calculated to be 2.08-9.41%.

3-2. Accident data collection

In this study, we used FDS to measure the variation of LPG concentration, which leaked into the underground trench over time. The computational fluid dynamics (CFD) software FDS was used to model the whole process of any potential accident based on liquid and gas release accidents [17].

Table 3. Simulation input data conditions

Item		Data
Flammable Gas		LPG
Release rate		0.006 m^3/min (Gas)
Release duration		780 minutes (13 h)
Atmospheric conditions	Temperature	19.8 °C
	Humidity	81%
	Atmospheric pressure	1008 hPa

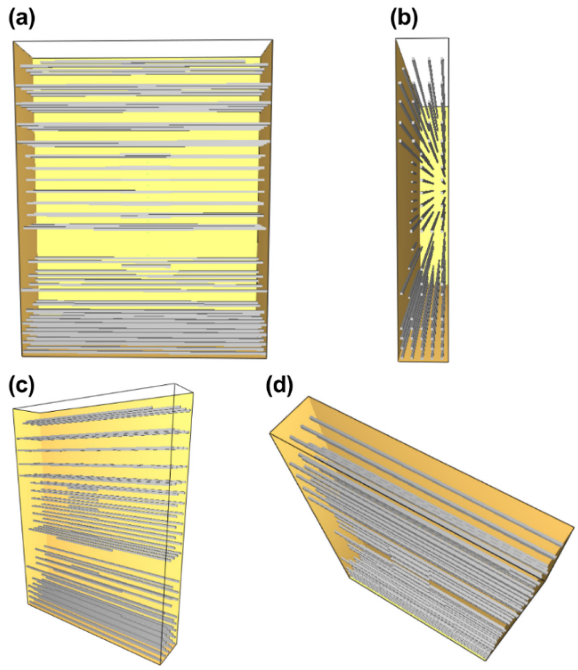

Fig. 6. Simulation design for trench structure. (a) Trench structure illustration (Front); (b) Trench structure illustration (Side); (c) Trench structure illustration (Side); (d Trench structure illustration (Top).

By conducting the FDS, LPG was analyzed to change its concentration continuously over time. The simulation represented the accident site to be 10 m wide, 2 m long, and 12.5 m high. It was assumed that a torch was positioned 5 m high in the trench before the accident occurred. The nozzle diameter, which was used at the site, was 0.9 mm, and LPG leakage flow rate was 360 L/hr. Table 3 presents the input data used in the simulation.

Fig. 6 shows the structure of the trench used in the simulation. The front of the trench structure is (a), its sides are (b) and (c), and its top is (d).

4. Results and Discussion

4-1. Concentration and time prediction for explosion range by FDS

The simulation showed that the concentration range between the LEL (2.08%) and UEL (9.41%) was verified by isosurface, and a device was installed at every 0.5 m to check concentration change.

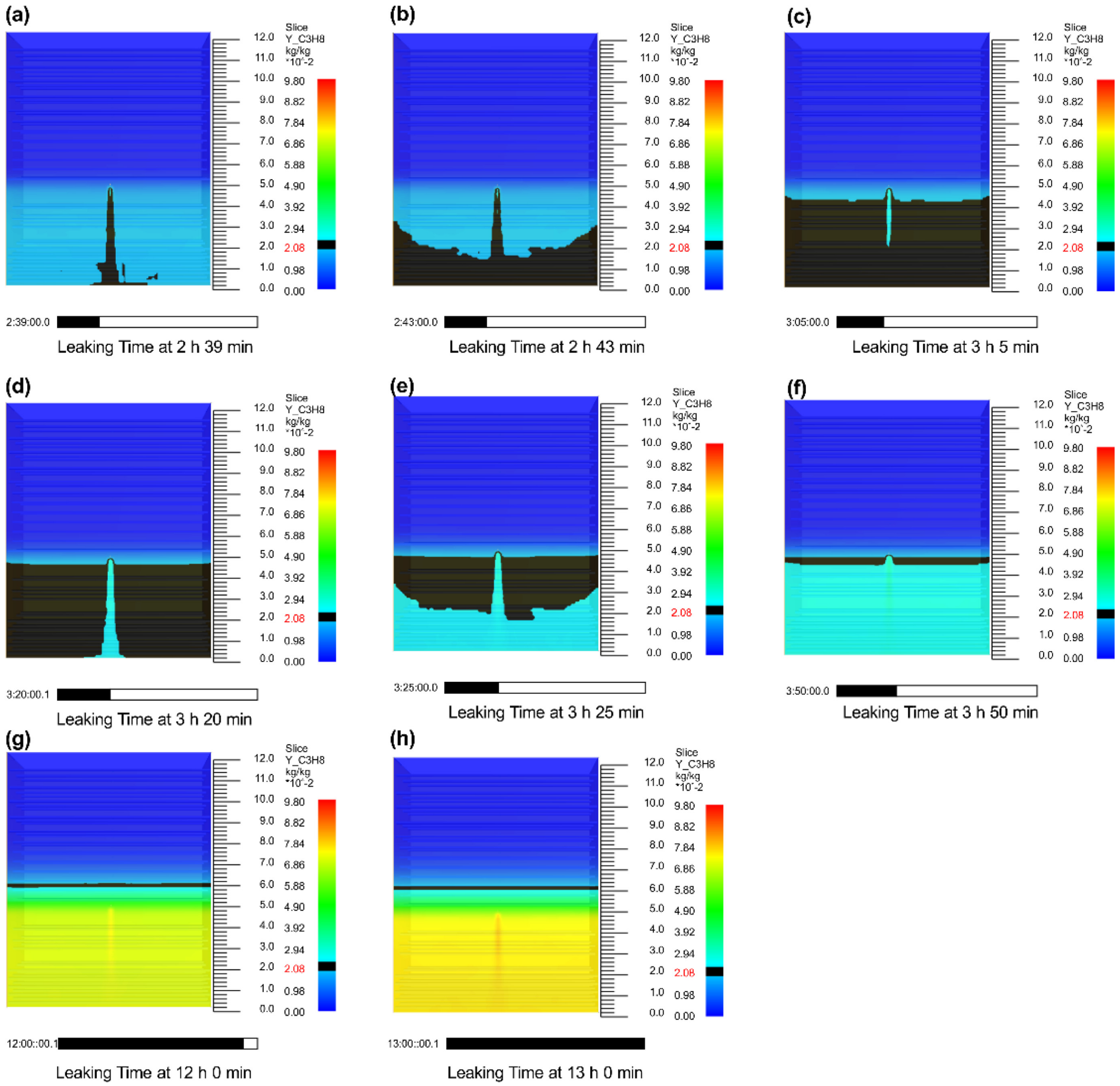

Fig. 7. LPG leakage analysis simulation according to heights in trench.

When the LPG leakage at the accident site was modeled by FDS, it took two hours and 39 minutes to reach the lower limit. The explosion range was satisfied after 13 hours (the ending time of work on the day before the accident).

Fig. 7 shows the change in the LPG concentration from along with the increase in time.

Fig. 7 [a]-[h] shows the LPG concentration accumulated in the trench from two hours and 39 minutes to after 13 hours.

Fig. 8 shows the Graph of LPG concentration and accumulation height change in the trench over time. The X axis represents the change of time and the Y axis represents the change of the LPG concentration and the LPG accumulation height.

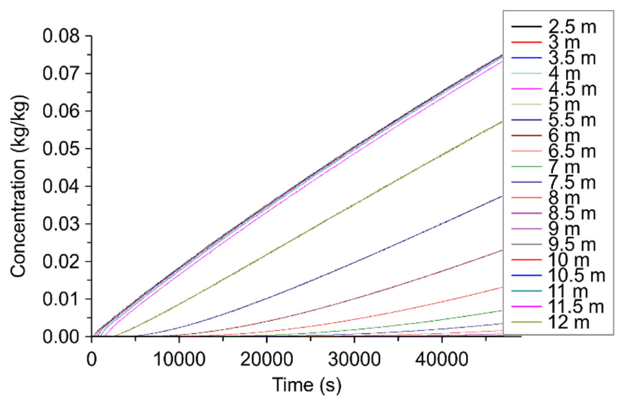

Fig. 8. LPG concentration and accumulation height change in trench over time.

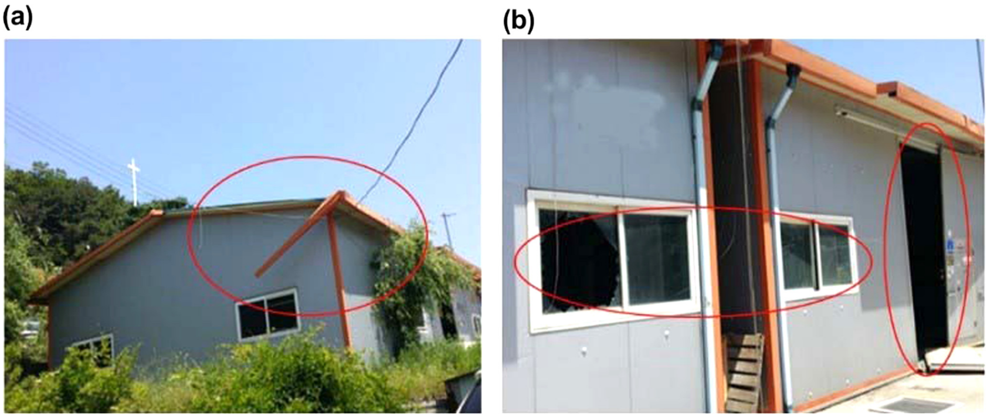

Fig. 9. Warehouse damage.

Table 4. Results Summary of explosion power by DDESB (TNT equivalent mass of 13.23 kg)

Explosion Site (ES)		Open Storage		Type of Weapon		Bulk/Light Cased	
Type of Explosive		TNT		Total NEQ (kg)		13.23	
Range (meters)	Time of arrival (ms)	Incident pressure (kPa)	Incident impulse (Pa-s)	Positive duration (ms)	Reflected pressure (kPa)	Reflected impulse (Pa-s)	Dynamic pressure (kPa)
70.0	183.39	3.63	25.51	15.61	7.39	45.04	0.05
50.0	125.49	5.69	35.58	14.29	11.56	64.03	0.12
60.0	154.38	4.51	29.74	15.00	9.10	52.93	0.07
70.0	183.39	3.63	25.51	15.61	7.39	45.04	0.05
80.0	212.29	3.01	22.28	16.15	6.12	39.15	0.03
90.0	240.86	2.55	19.66	16.69	5.14	34.57	0.02
100.0	out of range	2.20	17.58	out of range	out of range	out of range	out of range
125.0	out of range	1.60	13.87	out of range	out of range	out of range	out of range
150.0	out of range	1.24	11.43	out of range	out of range	out of range	out of range
200.0	out of range	0.83	8.42	out of range	out of range	out of range	out of range
250.0	out of range	0.61	6.64	out of range	out of range	out of range	out of range
300.0	out of range	0.47	5.47	out of range	out of range	out of range	out of range
350.0	out of range	0.38	4.65	out of range	out of range	out of range	out of range
400.0	out of range	0.31	out of range	out of range	out of range	out of range	out of range
450.0	out of range	0.26	out of range	out of range	out of range	out of range	out of range

4-2. Verification of LPG Explosion Impact by DDESB

In the case where the gas explosion occurred at the height of the ignition source between 4.0 m and 5.5 m, the TNT equivalent mass was estimated between 13.23 kg and 64.96 kg. This calculation was verified by the blast effect computation program made by the DDESB. We compared the results from the DDESB program and the damage (straight distance: 70 m, explosion overpressure: 3.45 kPa) for verification.

Fig. 9 Photographs of a broken warehouse located 70 meters from the explosion point.

4-2-1. Case 1: TNT equivalent mass: 13.23 kg

TNT equivalent mass of 13.23 kg and range of 70 m were input. Further, the experimental data of the summary table was 50 m, the altitude was 100 m (Namyangju-si, Gyeonggi-do), and the temperature was 19.8 °C (on the day of the accident).

The calculation results are presented in Table 4. The building from the civil complaint in Fig. 9 was affected by the explosion overpressure of 3.63 kPa. In this case, the probability of window damage (total area: 0.975 m^3) was almost 100%. Accordingly, TNT equivalent mass of 13.23 kg was sufficient to reproduce the damage shown in explosion overpressure at 3.45 kPa.

4-2-2. Case 2: TNT equivalent mass: 64.96 kg

TNT equivalent mass of 64.96 kg and the range of 70 m were input. Further, the basic value of the summary table was 50 m, the altitude was 100 m (Namyangju-si, Gyeonggi-do), and the temperature was 19.8 °C (on the day of the accident).

The calculation results are presented in Table 5. The building from the civil complaint shown in Fig. 9 warehouse damage was affected by the explosion overpressure of 7.26 kPa owing to the TNT equivalent mass of 64.96 kg. In this case, the window (0.975 m^3) could be broken with 100% probability. Accordingly, the damage to the building (explosion overpressure 3.45 kPa) could be sufficiently explained by the explosion power of the TNT equivalent mass 64.96 kg.

In this study, we calculated TNT equivalent mass of 13.23-64.96 kg

Table 5. Results Summary of explosion power by DDESB (TNT equivalent mass of 64.96 kg)

Explosion Site (ES)		Open Storage		Type of Weapon		Bulk/Light Cased	
Type of Explosive		TNT		Total NEQ (kg)		64.96	
Range (meters)	Time of arrival (ms)	Incident pressure (kPa)	Incident impulse (Pa-s)	Positive duration (ms)	Reflected pressure (kPa)	Reflected impulse (Pa-s)	Dynamic pressure (kPa)
70.0	170.43	7.26	73.09	22.97	14.88	133.25	0.18
50.0	114.09	11.14	101.21	20.68	23.22	189.52	0.41
60.0	142.12	8.82	84.88	21.91	18.20	156.54	0.26
70.0	170.43	7.26	73.09	22.97	14.88	133.25	0.18
80.0	198.98	6.14	64.16	23.88	12.51	115.91	0.13
90.0	227.75	5.29	57.17	24.67	10.73	102.51	0.10
100.0	256.66	4.63	51.53	25.37	9.34	91.83	0.08
125.0	329.15	3.38	41.27	26.86	6.90	72.69	0.04
150.0	400.96	2.62	34.13	28.20	5.30	59.99	0.02
200.0	out of range	1.75	25.14	out of range	out of range	out of range	out of range
250.0	out of range	1.28	19.84	out of range	out of range	out of range	out of range
300.0	out of range	0.99	16.35	out of range	out of range	out of range	out of range
350.0	out of range	0.80	13.88	out of range	out of range	out of range	out of range
400.0	out of range	0.66	12.04	out of range	out of range	out of range	out of range
450.0	out of range	0.56	10.63	out of range	out of range	out of range	out of range
500.0	out of range	0.48	9.50	out of range	out of range	out of range	out of range
700.0	out of range	0.30	out of range	out of range	out of range	out of range	out of range
800.0	out of range	out of range	out of range	out of range	out of range	out of range	out of range

for the ignition source height of 4.0-5.5 m, and used the DDESB program to verify the calculation. Consequently, explosion overpressure of 3.63-7.26 kPa acted on the building of the civil complaint shown in Fig. 9 owing to the explosion with TNT equivalent mass of 13.23-64.96 kg. In this case, the civil complaint, including window damage (0.975 m^3), could be fully explained.

5. Conclusions

The leakage concentration and time of LPG gas used in the torch used in the welding and cutting work of trench structure of subway were estimated. LPG used in Korea is a mixed gas of propane (96%) and butane (4%). and the concentration of LPG was calculated using Le Chatelier's formula. The explosion range of LPG was calculated as the lower explosion limits (LEL) 2.08% and upper explosion limits (UEL) 9.41%. Using this, the LPG leakage concentration time was verified by FDS simulation. The result was that the explosion limit reached 2 hours and 39 minutes, and the explosion limit was reached after 13 hours. At this time, it is assumed that the worker's welding and cutting torch flame had become an ignition source. The impact caused by the LPG explosion destroyed the windows in the 70 m range, and caused the warehouse door, the window breakage, and the frame (beam) distortion. The DDESB program was used to estimate the explosion power above. In case of ignition source height 5 m, TNT equivalent mass is 13.23 kg~64.96 kg, and explosive overpressure is 3.63~7.26. And it can be seen that the damage of the windshield is possible. From this results, it will be useful for safety management to prevent accidents caused by LPG welding and cutting work at construction sites.

Acknowledgments

The study was partially supported by Seoul National University of Science and Technology.

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