Korean J. Chem. Eng., 28(6), 1322-1330 (2011)
DOI: 10.1007/s11814-010-0511-1

Safety distance analysis of dimethylether filling stations using a modified individual risk assessment method

Young-Hun Kim*, Won So*,**, Dongil Shin***,†, and En Sup Yoon*,****

*School of Chemical and Biological Engineering, Seoul National University, San 56-1, Shillim-dong, Gwanak-gu, Seoul 151-742, Korea
**Automation and Systems Research Institute, Seoul National University, San 56-1, Shillim-dong, Gwanak-gu, Seoul 151-742, Korea
***Department of Chemical Engineering, Myongji University, San 38-2, Namdong, Cheoin-gu, Yongin, Gyeonggi-do 449-728, Korea
(*Received 30 July 2010 • accepted 7 December 2010*)

Abstract−The physical properties of dimethylether (DME) are similar to conventional fuels such as LPG and diesel, so DME has been recently considered one of the most promising candidates for a substitute for them. Equipment failures in gas stations lead to accidents that pose significant threats to people and property. Therefore, prior to commercialization, safety standards for DME need to be developed based on risk analysis. In this study, we focused on safety distance in DME filling stations. A hypothetical DME filling station was modeled based on a DME-LPG mixed filling station designed by KOGAS, and safety distances were suggested from a semi-quantitative risk estimation approach using individual risk calculations. Modified individual risk calculations were performed with consequence analysis and failure mode under varying accident scenarios. Compared with existing individual risk analysis, the modified-individual risk approach is supplemented with a weighting factor to graduate each accident scenario by historical analysis. Subsequently, the outcome shows the individual risk that suggests a safety distance. To compare with conventional fuel, we also performed a comparative study on the filling station fuels LPG and DME. According to the quantitative risk estimation results, we propose a separation distance based on accident scenarios for each facility. In conclusion, safe distances for DME facilities are lower than those that dispense LPG. Therefore, a DME filling unit can be placed at conventional gas stations without increasing the safety distance. The results will also be useful in determining the standard for safety management of renewable and sustainable energy.

Key words: Safety Distance, Accident Scenarios, Modified-individual Risk, Semi-quantitative Method

INTRODUCTION

1. Research Background

Hazardous gas is one of the most common causes of accidents at filling stations. The types of accidents are mainly explosions, fires, and leaks. In Korea, 2-3 accidents occur annually at filling stations. According to historical accident data, the Bucheon and Iksan gas explosions caused a large number of casualties and property damage. To reduce the impact of such accidents, it is very important to ensure proper safety distance, and ongoing safety management is needed.

Gas stations today mainly use propane (household gas) or butane (vehicle gas). Propane usage is most common, and accounts for more than 70 percent. Recently, the international price of propane has been rising continuously, so it is urgent to find alternative filling station fuels. Price competiveness and environmental issues are always important in selecting alternatives to propane.

Dimethyl Ether (DME) is considered one of the most promising candidates for a substitute for LPG and Diesel fuel. Its physical properties are similar to those of liquefied petroleum gas (LPG), so it can exploit existing land-based and ocean-based LPG infrastructures with minor modifications. Compared with other fuels, combustion of DME produces much less pollutants such as hydrocarbons and carbon monoxide. Moreover DME's combustion efficiency is higher than that of other hydrocarbon fuel.

Because filling stations are located at the periphery of urban districts, they involve various hazard factors, resulting from either simple accidents or full-scale accidents. In this study, based on filling station accident histories from 1987 to 2003, we generated possible accident scenarios and analyzed the extent of damage. On the basis of this given information, we tried to determine the proper safety distance of a DME filling station.

The working notions about safety distance in industrial fields are tied up to the level of ignorance concerning the behavior of some technologies. As a consequence, a certain level of protection was established. As of now, there are effectively two methods of estimating safety distance. The first way is estimating harmful distance based on theoretical calculations, and the second way is determining safety distance by empirical approach. The latter approach is more common because the first way often takes considerable time, cost, and human resources.

In Korea, at present, since the Bucheon and Iksan gas explosions, charging equipment and storage tanks legally must keep a safety distance (17 m-10 ton basis) to boundary offices. In the surroundings of filling stations, the distance from the protection building must be greater than that from the office boundary. Table 1 shows the criteria of building protection in South Korea according to law.

In this study, we generated proper accident scenarios based on past-accident historic data, and based the frequency of accidents on K-RDB (Korea-Reliability-Database) and FTA (fault tree analysis). Simultaneously, as a probit analysis, we calculated the fatalities in

†To whom correspondence should be addressed.
E-mail: dongil@mju.ac.kr

Table 1. The criteria of protection building in South Korea

Protection building	Division
First-class	1. School, kindergarten, academy, hospital, playground, library, market, hotel, etc. 2. Accommodation building which area is more than 1000 square meter 3. Movie theater, church, or building that accommodates more than 300 people. 4. Social welfare organization[facility]accommodating more than 20 people 5. Listed building, cultural asset
Second-class	1. House 2. Residence building with an area of more than 100 square meters and less than 1,000 square meters

the DME filling station. After considering weather conditions and location factors, we calculated the modified-individual risk to hypothetical members of selected population groups with weighting factors from historical data. The aim of calculating the individual risk is to provide a safety distance to distinct dangerous areas in and around filling station.

2. Theoretical Background

2-1. Safety Distance

The term "safety distances," even though broadly used in both the technical field and in the juridical field, has different shades of meaning in each of these fields. Moreover, as for the term "Risk," safety distance is perceived in different ways depending on the context (culture, person, etc.) in which it is used [1].

In South Korea, safety distance is defined in such a way as to reduce casualties and property damage from accidents. Safety distance is generally divided into two parts. The first part is the minimum separation distance for a gas facility, which is similar to an office boundary distance, and the second part is the distance from the protection building to the gas facility. In a gas filling station, safety distance mainly depends on the type of protection building and the gas capacity.

Table 2. The minimum separation distance for LPG storage (unit: m)

Capacity of storage (ton)	Korea	Japan	U.S.A.	Italy	
	LPG filling station	LPG filling station	Storage tank	Storage tank	Tank lorry
10	17	17	15	25	15
20	21	20.8	15	25	15
30	24	24	15	30	15
40	27	26.9	15	30	15
50	30	29.4	23	30	15
100	30	30	30	30	25
200	30	30	38	40	25
400	30	30	122	40	25

Table 2 shows the minimum separation distance for LPG storage in various countries. South Korea defines a protection building according to law (see Table 1), and the distance from a filling station to a protection building is maintained atis misiiidd 1-2 times as large as the office boundary distance [2].

2-2. Individual Risk

The large quantity of frequency and consequence information must be integrated into a presentation that is relatively easy to understand and use. Risk presentation provides a simple quantitative risk description useful for decision making. The individual risk is the risk to a person in the vicinity of a hazard. This includes the nature of the injury to the individual, the likelihood of the injury occurring, and the time period over which the injury might occur [3]. In this study, we applied the individual risk method to give a semi-quantitative risk index.

The completed individual risk provides a useful, graphical portrayal of the risks presented by the system under study. The risks associated with the various events plotted may be ranked and actions prioritized accordingly [4].

Uniquely, this study used a slightly different version of CPQRA individual risk. We applied the Health and Safety Executives individual risk, which is a modified internal factor. Table 3 shows the comparison of CPQRA & HSE individual risk.

2-3. DME Properties

Dimethyl ether (DME), the simplest ether, is considered to be a substitute fuel that could potentially replace petroleum-based fuels. The structure of DME chemical compound leads to very low emissions of particulate matter, NO_x, and CO during combustion. For these reasons, as well as being sulfur-free, DME meets even the most stringent emission regulations. Furthermore, the physical properties of DME are similar to those of liquefied petroleum gas (LPG), which could enable exploitation of existing land-based and ocean-based LPG infrastructures with minor modifications. Table 4 shows a comparison of the properties of DME& LPG.

We estimated properties of DME using the Aspen HYSYS property package (PR-Twu). The PR-Twu property package is based on Peng-Robinson and incorporates the Twu Eos Alpha function. The initial conditions of DME and LPG were obtained from KOGAS

Table 3. The comparison of CPQRA & HSE individual risk

Source	Health and safety executive	CPQRA
Calculation form	Frequency x probability	Frequency x probability
Calculation items	1. Accident frequency 2. Population existence probability 3. Weather condition 4. Geographical factor 5. Existing population working time	1. Accident frequency 2. Population number 3. Weather condition 4. Geographical factor
Population factor	Fraction of time & possible presence	Population number
Tolerance limits	10^{-3}-10^{-4}	10^{-6}

Table 4. The properties comparison of DME & LPG

Property	DME	LPG
Formula	CH3OCH3	C3H8
Storage pressure (atm)	15.837	15.837
Liquid density @ 30 °C, kg/m^3	598	486.2
Vapor density @ 30 °C, 1 atm (kg/m^3)	1.915	1.833
Lower heating value, MJ/kg	28.8	46.35
Cetane number	>55	-
Autoignition temperature, °C	235	470
Boiling point (C)	−25.1	−42.0
Heat of combustion (kJ/kg)	26500	44000
Explosion limit (%)	3.4-17	2.1-9.4

process data.

2-4. Hazard Model

2-4-1. LFL Analysis

The distance of lower flammability limit (LFL) can be obtained by a jet momentum model proposed by Ricou and Spalding, Long and Cude (Loss Prevention in the Process Industries, 1996) [5]. The shape of a jet is supposed to be conical. Gas leakage rate from the leakage point can be expressed as in Eq. (1):

$$m_0 = \frac{\pi}{4} d_0^2 \rho_0 u_0 \quad (1)$$

Where the subscript 0 indicates the leak point, u is the linear velocity of gas at the leak point. Mass velocity at the axial distance x from the origin of the jet is expressed as the following Eq. (2).

$$m_x = \frac{\pi}{4}(2x\tan\beta)^2 \rho_0 u_0 \quad (2)$$

Where β is the half-angle of the jet and u_x is the mean velocity of gas at x. By momentum balance in the jet, we can obtain Eq. (3) by integrating Eq. (1) and (2).

$$\frac{m_x}{m_0} = \frac{u_0}{u_x} = k_1 \frac{x}{d_0}\left(\frac{\rho_x}{\rho_0}\right)^{1/2} \quad (3)$$

Generally, k_1 is 2tan β, which is approximately 0.32 [5]. Concentration of gas is in an inverse proportion to volumetric flow, so Eq. (4) is expressed as the following equation.

$$\frac{c_x}{c_0} = \frac{u_0}{u_x(k_1 x)^2} = \frac{1}{k_1}\left(\frac{x}{d_0}\right)^{-1}\left(\frac{\rho_x}{\rho_0}\right)^{1/2} \quad (4)$$

If a Gaussian concentration profile is assumed vertically, the above equation may be rewritten as Eq. (5).

$$\frac{c_{xr}}{c_0} = k_2\left(\frac{x}{d_0}\right)^{-1}\left(\frac{\rho_x}{\rho_0}\right)^{1/2} \exp\left[-\left(\frac{k_3 r}{x}\right)\right]^2 \quad (5)$$

Experimentally, the values of k_2 and k_3 were found to be 6 and 5. The density of x is equated to air density (1.22 kg/m^3). The distance of the gas jet from the hole to the lower flammability limit (LFL) was calculated as Eq. (6).

$$l = 6d_0\left(\frac{c_{LFL0}}{c_0}\right)^{-1}\left(\frac{\rho_x}{\rho_0}\right)^{1/2} - \frac{d_0}{0.32} \quad (6)$$

If an ignition does not exist around the filling station, the length of the lower flammability limit can be found by referring to the guide for safety distance. Even though the LFL distance cannot be expressed as an individual risk factor, it reflects the separated distance between each facility [5].

2-4-2. Fire

There various types of fire accident that can happen at a filling station. Historically, based on past-accident data, most fires arise from leaked gas ignition. In this study, we first calculated the gas release rate from each facility and, based on the quantity of leaked gas, estimated the radiation effect from the flame center to the location of interest. Generally, DME is stored in the compressed liquid state. When gas leaks from each facility, we assume that the gas flow of the leak is a flashing flow.

In the absence of significant frictional losses (as is generally the case in the nonequilibrium and equilibrium regimes), flashing flows are generally always chocked and can be approximated by Eq. (7) [6].

$$Q = \frac{\Delta H_V A}{v_{fg}} \sqrt{\frac{g_c}{NTC_P}} \quad (7)$$

Where Q is the mass flow rate, ΔH_V is the latent heat of vaporization. v_{fg} is the change in specific volume going from the liquid to the vapor state, T is the absolute temperature, C is the liquid's specific heat, and N is a nonequilibrium parameter given by Eq. (8).

$$N = \frac{\Delta H_V^2}{2\Delta P \rho_l K^2 v_{fg}^2 TC_P} + 10L \quad (8)$$

ΔP is the total available pressure drop, ρ_l is the liquid density, K is the discharge coefficient, and L is the duct length, we assume that the leak hole is similar to a sharp edged orifice with K~0.61.

The above equation simply reflects that the degree of nonequilibrium is taken to vary directly with the residence time. For L/D=0 the residence time is zero, resulting essentially in no flashing, and the equation reduces to the well known orifice Eq. (9) for incompressible liquid flow.

$$Q = 0.61A\sqrt{2\Delta P \rho_l} \quad (9)$$

Historically, leak size subdivides into three types (12.5 mm, 25 mm, and 50 mm). So, leak quantity also varies with leak size and equipment operating pressure. In the filling station, most equipment operates at an average of 16 kgf/cm^2. The leak quantity from each leak size is shown in Table 5.

The radiation effect from fire depends on the leaked gas quantity. Based on gas quantity, the heat flux at a given distance from the fire source, which is defined by the receiver per unit area, can be calculated as suggested in Eq. (10) [7]. The calculated radiation is applied to probit analysis for estimating fatality.

$$I = \frac{\eta \tau_a Q_h H_C}{4\pi r^2} \quad (10)$$

where I is the radiation heat flux at the location of interest, η is

Table 5. The gas leak quantity varying leak size

Leak size	S (12.5 mm)	M (25 mm)	L (50 mm)
Leak quantity (kg/s)	2.61	10.42	41.69

the ratio of total heat radiated to total heat released from fire, τ_a is atmospheric transmissivity, Q_h is effective gas release rate from the hole, H_c is the heat of combustion, and r is the radial distance from flame centre to the location of interest. The radiation fraction (η) cannot be estimated theoretically and is normally estimated from the data measured with a radiometer. For methane, laboratory experimental data suggests it to be 0.2 [8]. Atmospheric transmissivity is a measure of how much radiant heat is absorbed and reflected by the atmosphere between the fire and the location of interest. It is dependent upon the amount of water vapor in Eq. (11) [9].

$$\tau_a = 2.02(P_W\overline{H}r)^{-0.09} \tag{11}$$

The Republic of Korea lies on the east coast of the Eurasian Continent, adjacent to the West Pacific. The annual mean temperature is about 12.1 °C and the humidity is about 65%. By using the vapor pressure of water corresponding to the average temperature and the average humidity as 3,086 N/m^2, the transmissivity can be expressed with radial distance from the flame source to the location of interest using Eq. (12) [7].

$$\tau_a = 1.0189r^{-0.09} \tag{12}$$

2-4-3. Explosion

The extent of damage from an explosion was calculated by the TNT equivalency method. However, compared to actual gas explosion accidents, results of theoretical calculations tend to be greatly exaggerated. In the method used in Japan for calculating the impact of a vapor cloud explosion, it is assumed that approximately 16% of TNT equivalency contributes to an explosion blast. Generally, 2-10% of flammable gases combustion energy contributes to the blast [9,10]. In this study, we assumed that 2% of the combustion energy contributes to the blast. For filling stations, we assume that the gas quantity in the explosion is equal to the quantity of leaked gas from equipment, because approximately 3 min is enough time from recognizing an accident to an emergency procedure response. Leaked DME is converted to TNT equivalency. The equivalent mass of TNT is estimated using Eq. (13) [10].

$$W_{TNT} = \frac{\eta M_f H_C}{H_{C(TNT)}} \tag{13}$$

H_c is heat of combustion. Experiments with explosives have demonstrated that overpressure can be estimated using an equivalent mass of TNT, denoted W_{tnt}, and the distance from the ground-zero point of the explosion, denoted r. The empirically-derived scaling law is used in Eq. (14).

$$z_e = \frac{r}{W_{(TNT)}^{1/3}} \tag{14}$$

Where z_e is scaled parameter and the peak side-on overpressure is represented by the empirical Eq. (15).

$$\frac{p_o}{p_a} = \frac{1616\left[1+\left(\frac{z_e}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{z_e}{0.048}\right)^2}\sqrt{1+\left(\frac{z_e}{0.32}\right)^2}\sqrt{1+\left(\frac{z_e}{1.35}\right)^2}} \tag{15}$$

P_a is the ambient pressure, and overpressure is used for probit analysis in estimating consequences.

2-4-4. Fatality Calculation

∴ Probit method

Death probability

Response versus dose curves can be drawn for a wide variety of exposures, including exposure to heat, pressure, radiation, impact, etc. Typically, probit analysis is widely used to estimate the response-dose curve. In probit analysis, the probability of death from an accident (explosion, fire) can be calculated by the following Eq. (16) [10].

$$P = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Y-5}\exp\left(-\frac{u^2}{2}\right)du \tag{16}$$

The equation provides a relationship between probability P and the probit variable Y, which characterizes the dose-response relationship resulting from accidents, and such recipient probabilities as death or injuries as Eq. (17).

$$Y = a + b\ln V \tag{17}$$

Where a and b are empirical constants for a number of different types of exposure. The causative factor represents the dose V. V is a dose of the load for a given exposure time.

Fatalities by heat effect and explosion impact can be expressed using the following Eq. (18), (19), (20)

Heat Effect

$$Y = -14.9 + 2.56\ln\left(\frac{t_e I_e^{4/3}}{10^4}\right) \rightarrow \text{heat effect} \tag{18}$$

Where t_e is the exposure time and I_e is the radiational heat flux at a specified location of interest.

The duration of exposure depends on so many circumstances that it would not be possible to establish any specific rule to evaluate the degree of harm. Rausch recommends a value of 30 s as exposure time for people [11].

Explosion

$$Y = -46.1 + 4.82\ln(J) \rightarrow \text{Deaths from impact} \tag{19}$$

$$Y = -77.1 + 2.56\ln(P) \rightarrow \text{Deaths from lung hemorrhage} \tag{20}$$

where J is the impulse and P is the peak overpressure at a specified location of interest. Impulse is defined as the integral of a force with respect to time. The duration of impulse depends on time to reach peak pressure, so we refer to the vapor explosion data of the test apparatus. The maximum pressure was reached in approximately 0.1 seconds. Overpressure (P) was calculated by the TNT equivalent method [10].

PROPOSED ANALYSIS TECHNIQUE

1. Modified-individual Risk

To assess a simple and semi-quantitative risk, one not only examines a problem from accident results but also considers frequency. In this study, we introduced a modified individual risk estimation method. The difference between individual risk and modified individual risk is applying a weighting factor by heuristic data. Individual risk is valuable in figuring the risk contours according to risk range. Subsequently, we analyzed the safety distance according to allowable risk range.

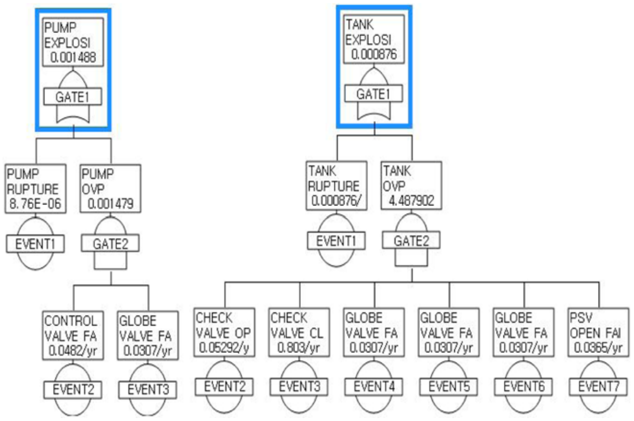

Fig. 1. Fault tree analysis.

The modified individual risk calculation may be divided into two parts. First, the individual risk to hypothetical people who are present at each of the locations of interest for all of the time (i.e., 24 hours a day, every day of the year) is estimated. Second, the individual risk which combines accident frequency, weather probability, fatality, and direction probability present a frequency of fatality at a location of interest. The second term, 'Frequency of Fatality' is used here for convenience. For a given location of interest, the Frequency of Fatality is given by Eq. (21)

$$\mathrm{FoF}_i = \sum_j f_{eoj} \cdot p_{fat,i,j} \cdot p_{weather,i,j} \cdot p_{direction,i,j} \tag{21}$$

Where FoF_i is the frequency of fatality at location i, f_{eoj} is the frequency of event outcome j, and Fig. 1 shows the fault tree analysis used to calculate the f_{eoj}. $p_{fat,i,j}$ is the probability of fatality at location i produced by event outcome j, $p_{weather,i,j}$ is the probability of the weather conditions required to produce the event outcome at j, and $p_{direction,i,j}$ is the probability of event outcome j being directed at location i above f_{eoj} is calculated by fault tree analysis (FTA). As shown in Fig. 1, and the reliability data is referenced from K-RDB (Korea Reliability Data Base). In this section, we assume that weather is independent of events and that the probability of event outcome is Omnidirectional. FoF_i is converted into an individual risk term using Eq. (22).

$$\mathrm{IR}_{i,k} = \theta_k \cdot p_{loc,i,k} \cdot \mathrm{FoF}_i \tag{22}$$

Where $\mathrm{IR}_{i,k}$ is the individual risk to a hypothetical member of population group k at location i, θ_k is the overall fraction of time that the hypothetical member of population group k spends in the area of interest, and $p_{loc,i,k}$ is the probability that the hypothetical member of population group k is at location i. Gas filling stations generally operate for 24 hours, so we assume that θ_k and $p_{loc,i,k}$ are 1.

Combining above-mentioned Eqs. (21) and (22), simply gives Eq. (23). To grade each accident scenario, we apply the weighting factor, which is equal to accident occurrence probability by historical data. We assume that one accident must occur in a filling station, so the summation of weighting factor (α_j) is 1. The weighting factors dimension is the probability of accident scenarios, which is estimated based on past accident data. Accidents are comprised of two types: fire and explosion. Specifically, fires are caused by leak accidents, and the impact of fire is commensurate with the quantity of leaked gas. We also consider the leak probability to vary with leak size.

$$\mathrm{IR}_{i,j,k} = \alpha_j \cdot \theta_k \cdot p_{loc,i,k} \cdot f_{eoj} \cdot p_{fat,i,j} \cdot p_{weather,i,j} \cdot p_{direction,i,j} \tag{23}$$

The total individual risk in the area of interest is equal to the sum of the individual risks from Eq. (24), where n is the total number of incident outcome cases considered in the analysis. $\mathrm{IR}_{i,j,k}$ is the individual risk of fatality at location i from incident outcome case j to a hypothetical member of the population k.

$$\mathrm{IR}_{i,total,k} = \sum_{j=1}^{n} \mathrm{IR}_{i,j,k} \tag{24}$$

2. Safety Distance Analysis

2-1. Estimation Procedure

Specific studies on DME safety distance do not currently exist, because filling stations currently supply LPG, and DME is not used in daily life. Recently, the government has pushed to use DME in LPG filling stations, so we estimated DME safety distance based on the previous research on LPG safety distance. According to previous studies, safety distance correlates with lower flammability limit (LFL) and jet flame length [5]. In this study, we analyzed the hypothetical DME filling station following a simple procedure. As shown in Fig. 2.

1) Select facility

Select the facility for estimating safety distance in the filling station.

2) Hazard identification

Identify the facility that is vulnerable to accidents (fire and explosion).

3) Frequency, Consequence analysis

① Frequency analysis

Determine the types of accident that cause casualties and property damage and construct the fault tree, taking into account the interaction between critical factors and the initiating event.

② Consequence analysis

Design and evaluate the resulting accidental events and calculate fatalities based on accident effects using the probit method.

4) Historical approach

Analyze past accidents at filling stations and select a suitable haz-

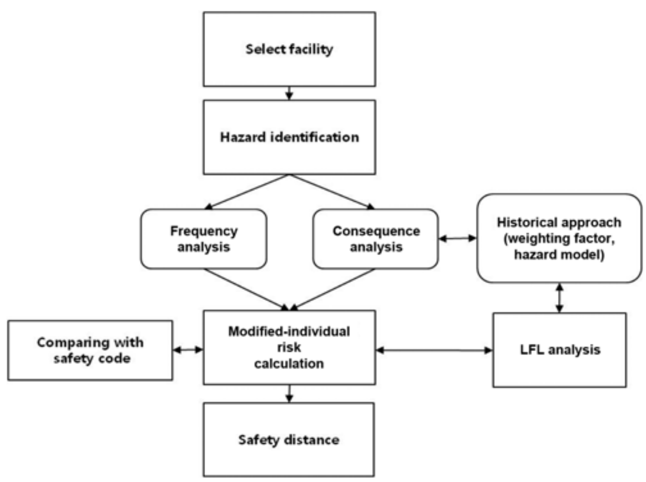

Fig. 2. Safety distance estimation algorithm.

Table 6. The ratio of accident type

The accident type	Explosion	Fire	Leak	Rupture	Total
The cases of accidents	11	14	17	2	25
CA ratio (%)	44	56	none	none	100

Table 7. The ratio of the leak accident varying leak size

Leak size	S (12.5 mm)	M (25 mm)	L (50 mm)	Total
The cases of accidents	20	11	4	35
Ratio (%)	57.1	31.4	11.4	100

ard model based on past accident data.

5) LFL Analysis

Calculate the distance of lower flammability limit from the momentum-jet model.

6) Modified individual risk calculation

Calculate the modified-individual risk for

7) Safety code (HSE individual risk)

Compare calculated modified individual risk to the tolerance limit of individual risk varying with distance.

8) Safety distance

Estimate the safety distance satisfied with tolerance limit of individual risk.

2-2. Historical Data

To estimate DME filling station safety distance, accident data for LPG filling stations from 1987 to 2003 were analyzed [5,2], including impact analysis of accidents, which is possible for fires and explosions. The proportion of each accident type is shown in Table 6. In this table, because leak and rupture was not propagated to the dangerous accident. These two types of accidents are not considered to analyze the accident consequence.

When analyzing the effects of fire, leaked gas quantity must be considered. Generally, leaked gas quantity varies with the size of the equipment leaking. We classified the leak size referring to historical leak size data in LPG filling stations from 1987 to 1998 [5]. The ratio of leak size is shown in Table 7. In parentheses, the leak size ratio is also multiplied in the individual risk calculation. The basis of giving weighting factor α_j is relative, because of various filling station accident data in South Korea.

CASE STUDY

1. DME Filling Station

We considered a hypothetical DME filling station based on actual DME-LPG mixed fuel storage process data. A DME filling station consists mainly of four parts: storage vessel, compressor, dispenser, and pump. Fig. 3 shows the schematic diagram of DME filling station.

① Storage vessel

(a) Structure

The capacity of the cylindrical storage tank is usually fixed by law. A buttress is installed to fix the storage tank in place. The main components are safety-valve, measuring instrument, valve, sprinkling equipment, etc.

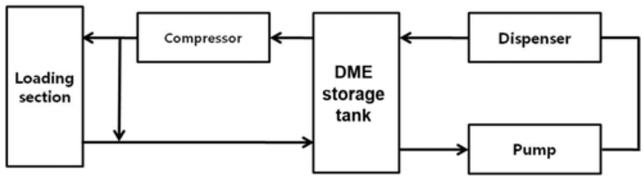

Fig. 3. Schematic diagram of DME filling station.

The material of the storage tank and buttress is thermostable. A sprinkler system or cooling system is installed 5 m away from the storage tank and buttress, although not in small storage tanks.

(b) Distance

Each storage tank is kept a quarter of the distance of the combined maximum diameter of two storage tanks (if a quarter of the distance of the combined maximum diameter of two storage tanks is lower than 1 m, a distance of more than 1 m should be maintained). Gas storage tanks with installed sprinkler systems are an exception.

② Compressor

To transport the gas from vehicles to the storage tank, a compressor pressurizes the gas in the storage tank or withdraws the gas from vehicles to the storage tank. The filling station mainly uses 7.5HP motors.

Gas compressors are used frequently to transfer gas to the tank or dispenser. After loading liquefied gas, it also withdraws the remaining gas from the tank lorry by controlling.

③ Dispenser

According to rule, hose length is less than 5 m. To prevent accidents, the dispenser must have antistatic equipment installed, and safeguards are needed to protect the gas injector and dispenser. The dispenser is mainly composed of a flow meter, thermostat, valve, etc.

④ Pump

A pump is used to compress the gas from the tank to the dispenser or other vessel charger. It is installed vertically in the tank. Standard pump capacity is 7.5HP (5.5 kW).A liquid pump is installed at the auxiliary tank near the storage tank.

In this study, we analyzed the normal operation conditions of DME filling stations based on actual DME-LPG mixed fuel storage process data, as shown in Table 8. The operation pressure is calculated by a process engineering standard. Generally, the designed pressure is equal to 1.1 times the maximum pressure. The majority of the pipeline is laid in a basement or protected by a dike, so a pipeline was not considered in this study for estimating safety distance. Four vulnerable filling station facilities were selected for estimating safety

Table 8. The process information of DME filling station

Equipment	Capacity	Temperature (°C)	Pressure
Storage vessel	8.13 m^3 (4.9 ton)	30	18 kg/cm^2g<design>
Dispenser	55 L/min	30	18 kg/cm^2g<design>
Compressor	360 L/min	30	18 kg/cm^2g<design>
Pump	200 L/min	30	10.5 kg/cm^2g<discharge>

distance. To compare DME with LPG, we assumed that DME and LPG have equivalent operation conditions.

2. Safety Distance Analysis

1) LFL analysis

While comparing DME safety distance to that of other materials, at the same time we also analyzed LPG safety distance. The calculated distance forming a lower flammability limit (LFL) varies with the phase of the leaked material. Table 9 shows the LFL distance with varying leak size and phase. In the case of a gas-phase leak, the LFL distance is about 6 m (LPG 11 m). To prevent leak-based accidents for some equipment, the distance from equipment is more than 6 m (LPG 11 m).

2) Modified-individual risk

The modified individual risk varies with the distance from equipment. Fig. 4 shows the modified individual risk with risk limit to figure out safety distance for each facility. We identified the modified individual risk of each facility varying with distance.

The graphical result shows that each facility needs a different safety distance. Even though the DME's individual risk is somewhat distinct from LPG, we determined that DME needs almost the same distance as LPG does.

Table 9. LFL distance of DME & LPG

Material	LPG		DME	
Phase / Size	Liquid	Vapor	Liquid	Vapor
S	0.13	2.7	0.05	1.47
M	0.26	5.4	0.1	2.94
L	0.51	10.81	0.2	5.87

Table 10. Safety distance of DME & LPG with IR tolerance (worker)

Equipment	Distance (m)		IR	
	DME	LPG	DME	LPG
Tank	14	17	0.00099	0.00099
Dispenser	13	16	0.00098	0.00093
Pump	7	8	0.00077	0.00085
Compressor	25	30	0.00085	0.00088

Table 11. Safety distance of DME & LPG with IR tolerance (public)

Equipment	Distance (m)		IR	
	DME	LPG	DME	LPG
Tank	28	33	7.70E-05	9.08E-05
Dispenser	27	33	8.33E-05	7.66E-05
Pump	12	13	5.54E-05	8.84E-05
Compressor	30	37	9.87E-05	7.59E-05

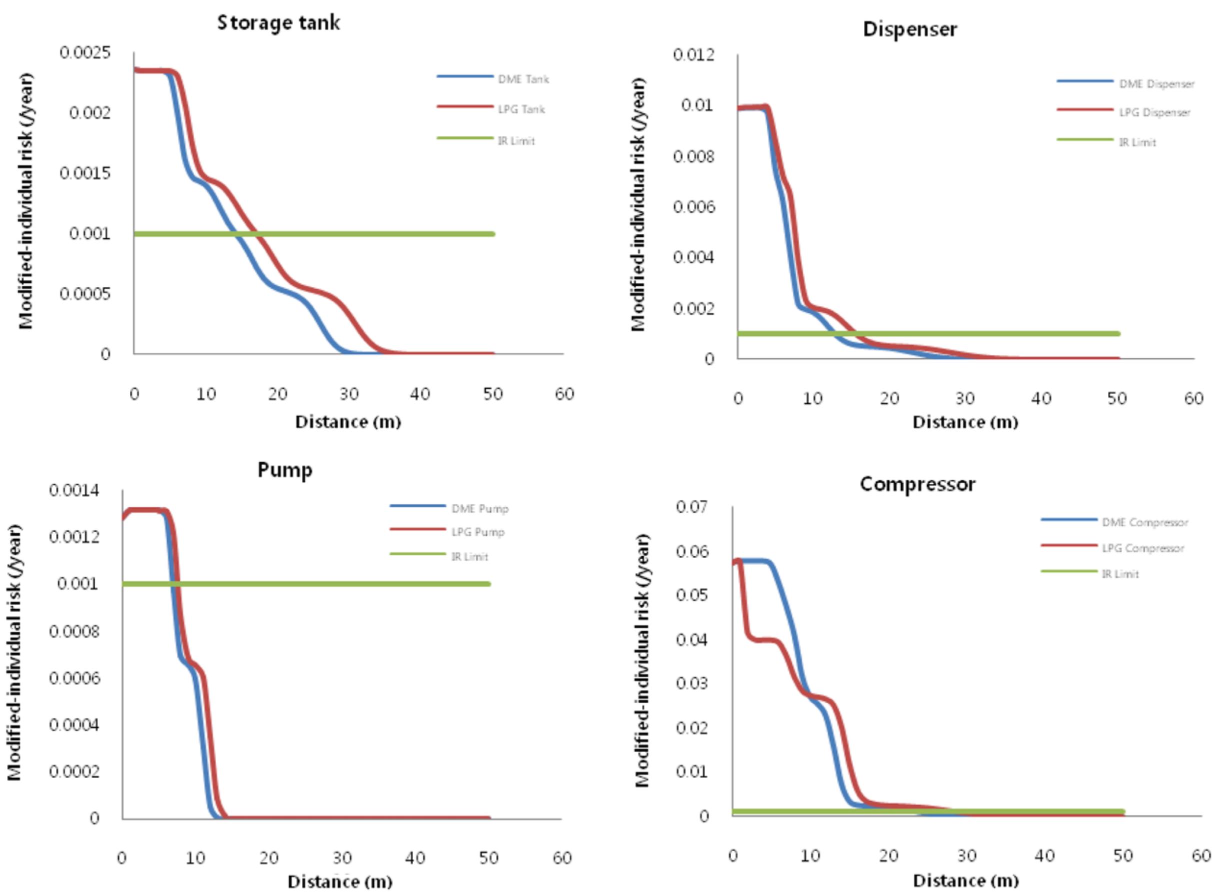

Fig. 4. The modified-individual risk of gas filling station.

Modified individual risk safety criteria subdivide two parts. The tolerance limits of individual risks are 10^{-3}/year for workers and 10^{-4}/year for the public. The safety distance is expressed in integer form that does not exceed the tolerance limit; see Tables 10 and 11 [4].

CONCLUSION

We have suggested a logical basis for safety distance for DME filling stations based on past-accident data through integrated risk analysis. Also, we have suggested a semi-quantitative risk estimation approach by a modified individual risk calculation. The modified-individual risk calculation was performed with consequence analysis and failure mode under varying accident scenarios.

Most of the modified individual risk calculations for DME are satisfied by standard LFL safety distances. We also obtained distinct safety distances for each type of equipment. As a result, DME filling stations can exploit existing LPG infrastructures with minor modifications. Also, using a modified individual risk calculation, we determined that the most vulnerable facility is the compressor section. These results give appropriate parameters for disaster prevention in filling stations. To supplement the safety distance results, rich reliability data on equipment is needed, as well a hazard and operability study (HAZOP) based fault tree analysis (FTA). Subsequently, the filling station layout may be constructed applying the modified individual risk contour. Analysis of corrosion effects, toxic effects, and domino effects is also needed.

This study contributes a safety distance analysis of DME filling station using modified-individual risk. A filling unit for DME can be placed at conventional gas stations without increasing safety distance. The result of separation distance also will be useful to determine facility layout and safety management of a filling station. And the suggested methodology will be useful in establishing the following standard of renewable and sustainable energy: separation distance, priority decision for installation of safety device, building permit, legislation.

ACKNOWLEDGEMENTS

This work was funded by the Brain Korea 21 Program and supported by the Institute of Chemical Process and Automation and Systems Research Institute in Seoul National University.

NOMENCLATURE

FoF_i : frequency of fatality at location i
f_{eoj} : frequency of event outcome j
$p_{fat,i,j}$: probability of fatality at location i produced by event outcome j
$p_{weather,i,j}$: probability of the weather conditions required to produce the event outcome at j
f_{eoj} : frequency calculated by the fault tree analysis (FTA) and the reliability data is referring to K-RDB (Korea Reliability Data Base).
$IR_{i,k}$: the individual risk to a hypothetical member of population group k at location i
θ_k : overall fraction of time that the hypothetical member of population group k spends in the area of interest
$p_{loc,i,k}$: probability that the hypothetical member of population group k is at location i
α_j : weighting factor
$IR_{i,j,k}$: individual risk of fatality at location i from incident outcome case j to hypothetical member of population k
m_0 : mass velocity of gas at the leak point
U_0 : linear velocity of gas at the leak point
D_0 : leak diameter
ρ_0 : gas density at leak point
m_x : mass velocity of gas at the axial distance x from the origin of the jet
β : half-angle of the jet
u_x : mean velocity of gas at x
ρ_x : gas density at the axial distance x from the origin of the jet
k_1 : 2tan β
k_2, k_3 : experimental constants
c_0 : concentration of gas at the leak point
c_x : concentration of gas at the axial distance x from the origin of the jet
c_{LFL} : concentration of to the lower flammability limit (LFL)
l : distance of the gas jet from the hole to the lower flammability limit (LFL)
Q : mass flow rate
ΔH_V : latent heat of vaporization
v_{fg} : change in specific volume going from the liquid to the vapor state
T : absolute temperature
C : liquid specific heat
N : nonequilibrium parameter
ΔP : total available pressure drop
ρ_l : liquid density
K : discharge coefficient
L : duct length
I : radiation effect from fire
η : ratio of total heat radiated to total heat released from fire
τ_a : atmospheric transmissivity
Q_h : effective gas release rate from the hole
H_c : heat of combustion
r : radial distance from flame centre to the location of interest
P_w : vapor pressure of water
$\overline{H}$: humidity
W_{tnt} : equivalent mass of TNT
z_e : scaled parameter
P_a : ambient pressure
P_o : peak side-on overpressure
P : probability
Y : probit variable
a, b : empirical constants for a number of different types of exposure
V : dose of the load for a given exposure time
t_e : exposure time
I_e : radiational heat flux at a specified location of interest
P : peak overpressure at a specified location of interest
J : impulse

REFERENCES

1. A. Marangona, M. Carcassia, A. Engeb and S. Nilsen, *Safety dis-*

tances: Definition and values, Int. J. Hydrog. Energy (2007).
2. Y. G. Lee, J. C. Han and S. W. Lee, Standard of LPG gas filling station, KGS (2005).
3. CPQRA. Guideline for chemical process quantitative risk analysis, ISBN 0-8169-0402-2, The Center for Chemical ProcessSafety of American Institute of Chemical Engineers (1988).
4. A. R. Franks and A. T. Maddison, *Simplified method for the estimation of individual risk*, IChem (2006).
5. Y. D. Jo, *J. Korean Inst. Gas*, **3**(2), 24 (1999).
6. H. K. Fauske, Flashing Flows or Some Practical Guidelines for Emergency Releases, Plant/Operation Progress (1985).
7. Y. D. Jo and D. A. Crowl, Individual risk analysis of high-pressure natural gas pipelines, Loss Prevention (2008).
8. Y. D. Jo and R. H. Kim, *Gas leak dispersion model and estimation of explosion effect, Chem. Ind. Technol.* (1996).
9. TNO Yellow Book, Methods for the calculation of the physical effects of the escape of dangerous material, Chapter 6, TNO Rijswijk, The Netherlands (1989).
10. D. A. Crowl and J. F. Louvar, *Chem. Process Safety*, 2nd, Prentice Hall, 225 (2002).
11. A. H. Rausch, N. A. Eisenberg and C. J. Lynch, *Continuing development of the vulnerability model (VM2)*, Department of Transportation, United States Coast Guard, Washington DC, and Report No. CG-53-77, Feb. (1977).
12. CCPS Guidelines for Hazard Evaluation Procedure 3rd, WILEY, 142 (2008).
13. A. J. C. M. Matthijsen and E. S. Kooi, Safety distance for hydrogen filling station, Loss Prevention (2006).
14. Y. D. Jo and B. J. Ahn, *Analysis of hazard areas associated with high-pressure natural-gas pipelines*, Loss Prevention (2002).
15. Health and Safety Executive, Reducing risks, protecting people - HSE's decision making processes, HSE Books (2001).
16. AIChE/CCPS Guideline for chemical process quantitative risk analysis, ISBN0-8169-0720-X (2nd ed.), Center for Chemical Process Safety of American Institute of Chemical Engineers (2000).