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Explosion Hazard Analysis in Partially Confined Area

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Abstract−A fuel gas leak in a partially confined area creates a flammable atmosphere and gives rise to an explosion, which is one of the most common accidents in a chemical plant. Observations from accidents suggest that some explosions are caused by a quantity of fuel significantly less than the lower explosion limit (LEL) amount required to fill the whole confined area, which is attributed to inhomogeneous mixing of leaked gas. The minimum amount of leaked gas for explosion is highly dependent on the mixing degree in the area. This paper presents a method for analyzing the explosion hazard in partially confined area with very small amount of leaked gas. Based on explosion limit concentration, the Gaussian distribution model is used to estimate the minimum amount of leak which yields a specified explosion pressure. The method will help in analyzing hazards to develop new safe devices as well as for investigating accidents.

Key words: Explosion, Hazard Analysis, Gaussian Distribution Model, Explosion Model, Flammable Gas

INTRODUCTION

Since a number of process plants operate in partially confined areas, it is necessary to consider explosions occurring inside such confined areas [Khan et al., 1998]. A leak of flammable gas or liquid may create a flammable atmosphere inside a partially confined area and give rise to an explosion. Such a leak may occur from plant processing flammable fluids, from activities involving such fluids, or from fuel gas supplies. In enclosed conditions, the degree of dispersion of the leaked gas is poor and the hazard is therefore much enhanced. The injury-yielding mechanisms of an explosion include mechanical effects such as air blast, missiles and structure collapse, and thermal effects such as flames and radiant heat. An important characteristic for evaluating the mechanical effect of an explosion is the explosion pressure. It is highly transient variable which rises and falls very rapidly during the course of an explosion. The explosion pressure generated by the combustion wave depends on how fast the flame propagates and how the pressure can expand away from the gas cloud, which is governed by confinement. The consequences of gas explosions range from no damage to total destruction. The pressure build-up caused by the gas explosion can damage people and material, or it can lead to accidents such as fires and BLEVE's (Boiling Liquid Expanding Vapor Explosions). Fires are very common events coming just after a gas explosion. When a gas cloud is ignited the flame propagates in two different modes through the flammable parts of the cloud: deflagration (subsonic combustion wave) and detonation (supersonic combustion wave). Deflagration is known to be the more common mode in industrial accidents and is the focus of this paper.

A simple conceptual model for a confined deflagration has been studied in a room filled with a flammable gas of stoichiometric concentration. This explosion scenario will be called the stoichiometric explosion model. For typical hydrocarbon fuels, the maximum explosion pressure is roughly 10 bars [Lees, 1996]. This is an enormous pressure considering the strength of most industrial structures. For example, most industrial structures collapse at gauge pressure of 0.21 bars [CCPS, 1996]. An explosion pressure of 0.07 bars is often quoted as that at which a typical brick building may be destroyed. Therefore, with a stoichiometric explosion pressure of 50 times larger than the failure pressure of a structure, it is reasonable to expect that the stoichiometric explosion projects the building rubble quite a long distance from the epicenter. Accident investigations show that some injurious or fatal explosions are caused by a quantity of fuel gas significantly less than that required to fill the entire enclosed volume to the stoichiometric condition [Bjerketvedt et al., 1997]. The development of a method for calculating the minimum fuel quantity required to cause a specified damage level would be useful in accident investigation and hazard analysis.

One approach often used is to calculate the quantity of fuel filling the enclosed volume up to the lower flammability limit (LFL) concentration homogeneously. This approach, referred to as the LFL explosion model, results in a fuel quantity which is less than the stoichiometric amount. For hydrocarbons, the LFL condition results in explosion pressures equivalent to 5-6 bars [Jo et al., 1999]. This is still much higher than the failure pressure of most industrial structures. A more conservative approach for calculating a minimum fuel quantity is to consider the enclosure volume to be only partially filled with flammable gas.

Consider an enclosure filled with air at ambient temperature and pressure. A finite quantity of flammable gas is released into the enclosure with sufficient momentum to mix with a portion of the surrounding air to achieve a stoichiometric condition.

As studied by Ogle, the volume of a stoichiometric fuel-air mixture pocket is assumed to be totally isolated in the enclosed volume [Ogle, 1999]. The final explosion pressure is calculated by two consecutive events: constant volume burning of isolated gas pocket followed by the adiabatic mixing of burnt gas with the surrounding

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air in the enclosure. The concentration distribution of released gas is expressed by Gaussian distribution [Park, 1979]. However, the adiabatic mixing model by Ogle assumed that the inside of the gas pocket was a stoichiometric fuel-air mixture and the outside was fuel free. This will result in overestimation of the maximum explosion pressure in a partially confined explosion.

This paper presents a method for estimating the explosion pressure in an enclosure partially filled with flammable gas with a Gaussian concentration distribution. This method, called the Gaussian distribution model, can be a useful analytical tool for safety engineering to calculate a minimum fuel quantity required to cause the observed explosion damage.

MODELLING OF EXPLOSION

The explosion pressure can be calculated by an adiabatic mixing model as follows. The initial state is defined as the instant when constant volume combustion is completed in the stoichiometric gas pocket. The final state is defined as the instant when adiabatic mixing is complete between the burnt gas volume and surrounding air in enclosure. The final state pressure can be calculated by force balance.

$$P=\frac{1}{V}[P_a(V-V')+P_E V'] \tag{1}$$

where V is the enclosed volume, V' is the volume of stoichiometic gas pocket, P_a is the initial enclosure pressure, P_E is constant volume explosion pressure of stoichiometic air mixture, and P is the final explosion pressure.

The volume of a stoichiometic gas pocket is calculated as:

$$V'=\frac{V_F}{X_F} \tag{2}$$

where V_F is fuel volume and X_F is mole fraction of fuel at the stoichiometric concentration.

A volume ratio may be defined

$$\Phi=\frac{V'}{V} \tag{3}$$

Then the final state pressure of adiabatic mixing model is

$$P=P_a(1-\Phi)+P_E\Phi \tag{4}$$

where Φ is ratio of the volume of stoichiometic air mixture to the enclosure volume.

Generally, the concentration distribution of released gas is Gaussian in form. The following treatment is based on a Gaussian concentration profile.

$$C=Ae^{-ax^2} \tag{5}$$

where A and a are constants, x is the distance from the ceiling for a buoyant gas (or the floor for a dense gas).

Therefore, the ratio of the volume of explosion zone to the fuel volume is calculated by integration of Eq. (5).

$$\omega=\frac{\int_{x|_{C_{UEL}}}^{x|_{C_{LEL}}}dx}{\int_0^\infty Ae^{-ax^2}dx} \tag{6}$$

where ω is the ratio of the volume of explosion zone to the fuel volume, C_{LEL} is lower explosion limit concentration, and C_{UEL} is upper explosion limit concentration.

Integration of Eq. (6) gives

$$\omega=0,\ A\le C_{LEL} \tag{7}$$

$$\omega=\frac{\sqrt{-\ln\left(\frac{C_{LEL}}{A}\right)}}{\frac{A\sqrt{\pi}}{2}},\ C_{LEL}\le A\le C_{UEL} \tag{8}$$

$$\omega=\frac{\sqrt{-\ln\left(\frac{C_{LEL}}{A}\right)}-\sqrt{-\ln\left(\frac{C_{UEL}}{A}\right)}}{\frac{A\sqrt{\pi}}{2}},\ A\ge C_{UEL} \tag{9}$$

The volume of the explosion zone is increased with A and it will be maximum when A is at C_{UEL}.

$$\omega_{max}=\frac{2\sqrt{-\ln\left(\frac{C_{LEL}}{C_{UEL}}\right)}}{\sqrt{\pi}C_{UEL}} \tag{10}$$

where ω_{max} is the ratio of the volume of explosion zone to the fuel volume when the volume of explosion zone is maximum in the confined area.

The maximum explosion pressure can be calculated by Gaussian distribution explosion model with the following assumption. The volume of the explosion zone acts as a stoichometric concentration gas pocket in the adiabatic mixing model suggested by Ogle. The assumption can be considered as a conservative approach for calculating the maximum explosion pressure. The concentration of near stoichiometric obtains maximum explosion pressure [Oh et al., 1999].

Therefore, the maximum explosion pressure of the Gaussian distribution model can be calculated as the following by modification of Eq. (4).

$$P=P_a(1-\omega_{max}\phi)+P_E\omega_{max}\phi \tag{11}$$

where φ is ratio of the fuel volume to the enclosed volume.

The above equation may be applied when the wall of the lower concentration side does not affect the gas distribution. Generally, there is no the wall effect on gas concentration distribution at the initial stage of gas leaking. This approach can be used to calculate the minimum fuel quantity which will yield a specified explosion pressure.

EXPERIMENTAL

The experiment about leaked gas concentration distribution in a confined area was studied earlier at the safety engineering association in Japan [Safety Engineering Association, 1971]. The confined area consisted of 9 m height and 3 m×3 m in cross-section. The flammable gas concentration distribution test was done with methane. Methane was fed downward from the center of the top with 12.91 m/sec (0.0493 m^3/min) during 30 minutes. The gas concentration was checked at the points of 1, 2, 3, 4, 5, 6 m from the ceiling and

Table 1. Distance (m) from ceiling of a specified concentration with time

Time (min) \ Concentration (vol%)	5.0	4.0	0.2	0.1
10	-	0.5	1.2	2.0
15	-	1.0	2.0	2.8
20	1.0	-	2.1	3.0
25	1.25	-	2.15	4.1
30	1.3	-	2.5	6.0

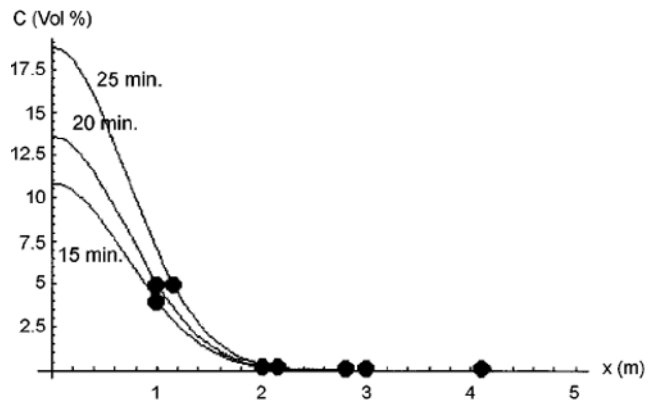

Fig. 1. Concentration (vol%) profile of methane with time.

0.5, 1, 1.3 from the horizontal center of container. A high concentration tends to build up at the top of container, and the concentration is slightly decreased from the horizontal center of the container. Therefore, the concentration is assumed to be changed with height. A specified concentration was moved downward with time as shown in Table 1 and Fig. 1.

RESULTS AND DISCUSSION

The dispersion of leaked gas is determined by buoyancy and momentum. If the momentum of the material issuing from an orifice on a plant is high, the dispersion in the initial phase can be considered by the momentum, and the emission is described as a momentum jet. The jet is conical and apparently diverges from a virtual point source of the orifice. The jet is diluted by turbulent mixing and the concentration profile is approximately Gaussian [Jo, 1999]. If the momentum is low enough, the dispersion is due to buoyancy.

For a gas lighter than air such as methane (specific density is 0.56 based on air) and momentum is low, the buoyancy force is predominant. A high concentration tends to build up in the space of top in the partially confined area. By the experiment, the concentration profile is approximately Gaussian with height and homogeneous with the horizontal until the bottom effect on the concentration profile as shown in Table 1.

Fig. 1 shows the volumetric concentration of methane plotted against the distance from the ceiling at 15, 20, 25 min. The experimental points are well correlated by Eq. (5) as normal concentration distribution (a=1). The maximum concentration of methane ($C|_{x=0}$=A) is observed at the ceiling and increasing with time as se-

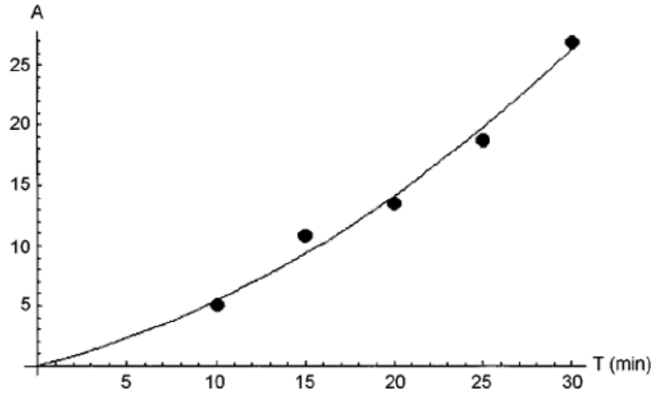

Fig. 2. Change of the constant a with time.

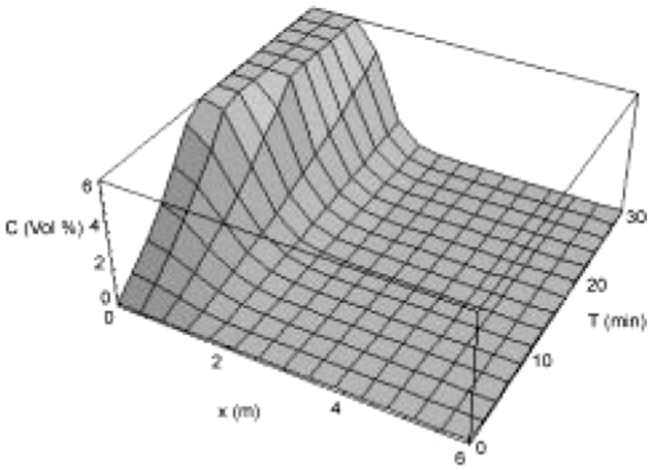

Fig. 3. Concentration distribution with time.

cond order (see Fig. 2). Therefore the experimental results can be expressed as the following equation:

$$C=(0.3720t+0.0169t^2)e^{-x^2} \quad (2)$$

Fig. 3 shows the concentration against the time and the distance from the ceiling in three dimensions. The lower explosion limit (LEL) concentration of methane is formed at the ceiling in about 9 minutes and it moves slowly downward with time. The upper explosion limit (UEL) concentration was formed at the ceiling in about 21 minutes. The volume of the explosion zone can be calculated simply by integration from LEL concentration to UEL concentration. It has some value after LEL concentration formed and has maximum value (9.5 m^3) when the UEL concentration was formed at the ceiling as shown in Fig. 4. The maximum fraction of explosion zone in the enclosure is about 0.176 at 21 minutes. The maximum explosion pressure may occur when the explosion will happen at the maximum volume of the explosion zone [Jo et al., 1999]. In the above experimental result, the maximum explosion pressure will occur when the quantity of leaked methane is about 1 m^3 (21 min×0.0493 m^3/min). It is lower than the explosion limit quantity of leaked methane calculated by LFL model. According to the LFL model, 2.7 m^3 of methane should be leaked. Therefore, the maximum explosion pressure, in inhomogeneous flammable gas distribution, can occur by a quantity of fuel gas less than that calculated

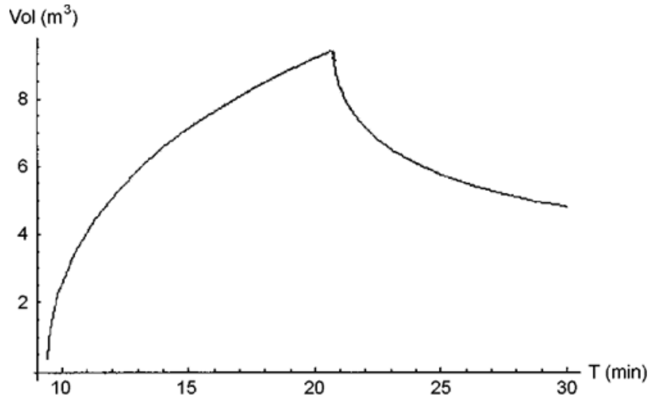

Fig. 4. Enclosure volume associated within LFL and UFL.

Table 2. Change of constant A with time

Time (min)	10	15	20	25	30
A	5.06	10.87	13.58	18.77	27.11

Table 3. Damage criteria for gas explosion

Damage criteria	Hazard
Minor damage (ΔP>0.03 bar)	Significant cosmetic damage to structure. Building repair is possible. Possible minor personnel injury due to glass breakage or scabbing
Moderate damage (ΔP>0.07 bar)	Possible deformation of structural members, short of failure. Building may be reusable without repair. Possibly some debris formed. Personnel injury from debris is likely
Major damage (ΔP>0.14 bar)	Possible failure of isolated structural members. Partial building collapse. Building cannot be reused and must be replaced. Possible serious injury or fatality of some building occupants
Catastrophic damage (ΔP>0.21 bar)	Complete collapse of structure. Probable serious injury or fatality of all occupants

by LFL model.

The ω_{max} is always lower than the $1/X_F$ as shown in Table 4. This means that the volume of the explosion zone is lower than the volume of fuel stoichiometric air mixture calculated by Eq. (2). Therefore, the fuel volume calculated by the adiabatic mixing model requires less than that by gaussian distribution explosion model to achieve specified explosion pressure. The adiabatic mixing model is a very conservative approach for calculating a minimum fuel quantity to the failure pressure of industrial structure.

Damage criteria for typical industrial structures are presented by CCPS in terms of explosion pressure. The damage criteria in Table 3 are based on the premise that the greatest hazard to personnel is posed by the failure of the structure, which leads to the projection of missiles and falling debris [Ogle, 1999].

The set of calculations, summarized in Table 5, is a comparison of the volume of fuel required by the Gaussian distribution model, adiabatic mixing model and LEL explosion model to cause a specified damage level (or explosion pressure). Across the range of damage levels, the LEL explosion model requires 15 to 170 times the fuel volume required by adiabatic mixing model or gaussian distribution model. As described in Table 5, the volume of fuel required to achieve a specified damage level is a very small quantity on the order a fraction of one percent of the enclosure volume. The fuel quantities calculated by adiabatic mixing model are lower for a given damage level than that by the gaussian distribution model. The adiabatic mixing model may underestimate the fuel quantities to a specified damage level by assuming isolated homogeneous stoichiometric mixing. This method, called the Gaussian distribution model, can be a useful analytical tool for safety engineering to calculate a minimum fuel quantity required to cause the observed explosion damage.

CONCLUSIONS

The Gaussian distribution model can be a useful analytical tool for safety engineering to calculate a minimum fuel quantity required to cause the observed explosion damage. The LEL model significantly over-estimates the fuel quantity and the Gaussian distribu-

Table 4. Summary of combustion data for fuel gases

Chemical	LFL (Vol. fraction)	UFL (Vol. fraction)	X_F	ω_{max}	$1/X_F$	P_E
Methane	0.050	0.150	0.0947	7.88	10.56	8.97
Acetylene	0.025	1.00	0.0772	2.17	12.95	9.95
Ethene	0.027	0.36	0.0654	5.04	15.29	9.37
Ethane	0.030	0.124	0.0564	10.84	17.73	9.02
Propene	0.024	0.11	0.044	12.66	22.73	9.63
Propane	0.021	0.095	0.0402	14.59	24.88	9.51
n-Butane	0.018	0.084	0.0312	16.67	32.05	9.59
Benzene	0.013	0.079	0.0277	19.19	36.10	9.58
n-Hexane	0.012	0.074	0.0216	20.57	46.30	9.67
n-Octane	0.0095	0.070	0.0165	22.78	60.61	9.72

ω_{max}: The ratio of the volume of explosion zone to the fuel volume when the volume of explosion zone is maximum

$$\frac{1}{X_F} = \frac{\text{the volume of stoichiometric air mixture}}{\text{the fuel volume}}$$

Table 5. Comparison of the Gaussian distribution model against adiabatic mixing model: volume of fuel gas as percent of total enclosed volume

Chemical	Gaussian distribution model				Adiabatic mixing model				LEL explosion model
	Minor	Moderate	Major	Catastrophic	Minor	Moderate	Major	Catastrophic	
Methane	0.047	0.11	0.23	0.34	0.035	0.083	0.17	0.25	5.0
Acetylene	0.16	0.36	0.72	1.1	0.026	0.060	0.12	0.18	2.5
Ethene	0.070	0.17	0.33	0.49	0.023	0.055	0.11	0.16	2.7
Ethane	0.034	0.080	0.16	0.25	0.021	0.049	0.099	0.15	3.0
Propene	0.027	0.065	0.13	0.20	0.015	0.036	0.072	0.11	2.4
Propane	0.024	0.056	0.113	0.169	0.014	0.033	0.066	0.099	2.1
n-Butane	0.019	0.050	0.098	0.15	0.010	0.026	0.051	0.076	1.8
Benzene	0.018	0.043	0.085	0.13	0.0097	0.023	0.045	0.068	1.3
n-Hexane	0.017	0.038	0.079	0.12	0.0076	0.017	0.035	0.053	1.2
n-Octane	0.015	0.035	0.072	0.11	0.0056	0.013	0.027	0.040	0.95

tion model moderates it. The catastrophic structure damage in a partially confined area can be occur with a volume of fuel gas which is less than 1 percent of the total enclosed volume. The Gaussian distribution model will be a useful tool for hazard analysis to develop safe devices as well as for accident investigation.

REFERENCES

Bjerketvedt, D., Bakke, J. R. and Wingerden, K. V., "Gas Explosion Hand Book," *J. of Hazardous Materials*, **52**, 1 (1997).

Center for Chemical Process Safety (CCPS), "Guideline for Evaluating Process Plant Buildings for External Explosion and Fire," American Institute of Chemical Engineers, New York, 40 (1996).

Jo, Y. D., "A Study on the Minimum Safe Separation Distance from LPG Filling Station," *KIGAS*, **3**(2), July, 24 (1999).

Jo, Y. D., Cho, J. H., Kim, S. S. and Oh, S. K., "A Study on the Improvement of Simulator for the Effect of Indoor Gas Explosion," KOGAS (1999).

Khan F. K., Rani, J. D. and Abbasi, S. A., "Accident Simulation as a Tool for Assessing and Controlling Environmental Risk in Chemical Process Industries: a Case Study," *Korean J. Chem. Eng.*, **15**, 124 (1998).

Lees, F. P., "Loss Prevention in the Process Industries," 2nd Edition, Butterworth-Heinemann, Oxford, **22**, 17/32 and 17/37-38 (1996).

Oh, K. H., Kim, H., Rhie, K. W., Kim, J. B., Lee, S. E., Kim, S. S. and Jo, Y. D., "A Study on the Pressure Behavior of Vented Gas Explosion," 1st Conference of Association of Korean-Japanese Safety Engineering Society, November 22 (1999).

Ogle, R. A., "Explosion Hazard Analysis for and Enclosure Partially Filled with a Flammable Gas," *Process Safety Progress*, **18**(3), 170 (1999).

Park, O. H., "The Variation of Normality of Lateral Impurities Concentration Profile with Distance," *HWAHAK KONGHAK*, **17**, 345 (1979).

Safety Engineering Association, The Experimental Report of Flammable Gas Distribution in Confined Area, Japan, 35 (1971).