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Risk Analysis of Explosion in Building by Fuel Gas

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Leaking of fuel gas in a building creates flammable atmosphere and gives rise to explosion. Observations from accidents suggest that some explosions are caused by quantity of gas significantly less than the lower explosion limit amount required to fill the whole confined space, which might be attributed to inhomogeneous mixing of the leaked gas. The minimum amount of leaked gas for explosion is highly dependent on the degree of mixing in the building. This paper proposes a method for estimating minimum amount of flammable gas for explosion assuming Gaussian distribution of flammable gas.

Keywords : *gas explosion, gaussian distribution explosion model, flammable gas, explosion model, explosion risk*

1. Introduction

Leakage of fuel gas may create flammable atmosphere inside partially confined space and give rise to serious explosion. Such leaks may occur at plant processing flammable fluids, activities involving such fluids or fuel gas supplies. In enclosed condition, dispersion of the leaked gas is poor and the hazard of explosion is therefore much enhanced. The injury-producing mechanisms of explosion include mechanical effects such as air blast, missiles, structure collapse, and thermal effects such as flames and radiant heat. An important characteristic in evaluating the mechanical effect of explosion is explosion pressure. It is highly transient variable which rises and falls drastically during the course of 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 governed by confinement. The pressure build-up caused by the gas explosion can damage on person and facilities. And it also can lead to other accidents such as fires and leak of hazardous materials by domino effect in process industries. Fires are very common events following gas explosion. When gas cloud is ignited, the flame can propagate in two different modes through the flammable parts of the cloud. These modes are deflagnation(subsonic combustion wave) and detonation (supersonic combustion wave). The deflagnation is more common in a confined space.[1)]

A simple conceptional model for confined deflagnation is postulated by taking a room filled with flammable gas at stoichiometric concentration. This explosion scenario is defined as stoichiometric explosion model. For typical hydrocarbon fuels, the maximum explosion pressure is roughly 10 bars.[1)] This pressure is enormous considering the strength of most industrial structure. For example, most industrial structures collapse at gauge pressure of 0.21 bars.[2)] Explosion pressure of 0.07 bars is often considered as that at which a typical brick building may be destroyed. On the other hand, normal building has walls containing weaker components which will be broken during pressure buildup and provide vents so that the explosion pressure does not rise as high as the case of without venting. However, it is reasonable to expect that with stoichiometric explosion, pressure is very high comparing with the failure pressure of structure, the stoichiometric explosion should project the building rubbles long distances from the epicenter. Accident investigations show that some injurious or fatal explosions are caused by quantity of fuel gas significantly less than that required to fill the entire enclose volume to the stoichiometric condition.[3)] Therefore, it would be useful to introduce a method for calculating the minimum gas quantity required to cause a specified damage level of explosion to prepare counter measures in accident investigation and hazard analysis.

One approach often used is to calculate the quantity of fuel which corresponds to filling the enclosure volume to the lower flammable limit(LFL) concentration. This approach, referred to the LFL explosion model, results in gas quantity which is less than the stoichiometric amount. However, for hydrocarbons, the LFL condition results in explosion pressures on the order of 5-6 bars.[4] This is still much greater than the failure pressure of most industrial structures. A more conservative approach to calculate minimum gas quantity is to consider the enclosure volume to be only partially filled with flammable gas. A finite quantity of flammable gas is released into the enclosure with sufficient momentum to be mixed with a portion of the surrounding air, and then reach to stoichiometric concentration. The volume of stoichiometric gas-air mixture is assumed to be totally isolated and less than the enclosed volume. The final explosion pressure of partially filled with the isolated stoichiometric gas-air mixture is calculated by two consecutive events: constant volume burning of isolated gas pocket followed by the adiabatic mixing of burnt gas with the surrounding air in the enclosure. This approach referred to the adiabatic mixing explosion model(AMEM) proposed by Ogle.[5] In general, the concentration distribution of released gas has inhomogeneous distribution or Gaussian distribution.[6] On the other hand, the AMEM assumed that the inside of gas pocket has uniform distribution of stoichiometric gas-air mixture and outside is gas free. It may cause to overestimation of the maximum explosion pressure in confined explosion.

Therefore, it is necessary to consider the concentration distribution in order to estimate the minimum amount of flammable gas with the level of explosion damage. This work focused on estimating the amount of flammable gas for explosion with Gaussian concentration distribution and on analyzing explosion hazard in engineering sense.

2. Model of confined explosion

The LFL explosion model is generally used to estimate the amount of flammable gas to be exploded in an enclosed space. For gas lighter than air, such as methane, with downward ventilation pattern, the buoyancy acts in opposite direction with ventilation and the gas tends to build up in the whole space of the enclosure. In this case, the LFL explosion model may be appropriate to estimate the minimum amount of leaked gas for explosion. On the other hand, with upward ventilation pattern, high concentration will tend to build up at the ceiling of the enclosure and the LFL explosion model can not be applied properly any more to estimate the minimum amount of gas for explosion. Therefore, the LFL explosion model is only valid for the extreme case of gas concentration distribution as homogeneous mixing in the enclosure. The concentration distribution of leaked gas in the enclosure is affected by the density of gas, release velocity, the height of the leak source, and ventilation pattern. The relationship between concentration distribution and minimum amount of flammable gas for explosion is discussed in the following sections.

2.1 Adiabatic mixing explosion model(AMEM)

This model was proposed by Ogle in order to estimate the minimum amount of flammable gas for a given damage level of building by explosion. It was derived by assuming that leaked gas forms isolated gas cloud of stoichiometric mixing with air in enclosure. This assumption is an extreme case of gas distribution, leaking rate of flammable gas is so large into a small dead space inside of the enclosure that the released gas and air are mixed stoichiometrically and it leads to an isolated gas cloud in the enclosure.

Explosion pressure with the AMEM is estimated by assuming that the pressure of the isolated gas cloud increases up to maximum explosion pressure at constant volume and then immediately expanded adiabatically as shown in Fig. 1. After explosion, the pressure can be estimated by the following equation.

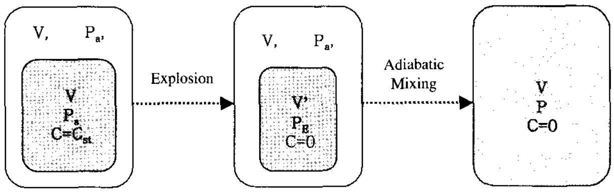

Fig. 1. Adiabatic mixing explosion model for confined gas explosion

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

where V is the volume of enclosure, $\bar{V}$ is the volume of isolated gas mixture at stoichiometric concentration, P_a is atmospheric pressure, and P_E is the explosion pressure of stoichiometric mixture of explosive gas and air at constant volume.

The volume of stoichiometric gas pocket, $\bar{V}$, is estimated by the amount of flammable gas and stoichiometric volume fraction of the gas. The explosion pressure solving above equation is somewhat overestimated due to considering that all flammable gas combustion in the enclosure contribute to buildup the explosion pressure. By using the AMEM, therefore, the minimum amount of flammable gas is always underestimated comparing with that in real situation.

2.2 Gaussian distribution explosion model(GDEM)

The GDEM is developed by modification of the AMEM with considering that the gas concentration has Gaussian distribution and the combustion of some part of gas cloud in the enclosure contributes to buildup the explosion pressure. The part contributing explosion pressure is assumed as the gas within the flammable limits, i.e., LFL and upper flammable limit(UFL). The fraction of released gas within the flammable limits depends on the properties of gas, ventilation pattern, the location of release point, and the momentum of release. If light gas is leaked in enclosed space, the space of flammable zone is formed initially at the ceiling of the enclosure. The flammable zone expands rapidly with release until a certain time before the maximum concentration reaching UFL and is reduced slowly with release.[6),7)] The gas in rich zone above UFL may not contribute generally to buildup the explosion pressure because of very low combustion rate. If the confined space stands until the gas in rich zone is burning completely, the rich zone contributes to the maximum explosion pressure. But if a weak part of the enclosure, such as window or door of building, is broken during the explosion process and acts as a vent, the rich gas may not contribute to the explosion pressure. The rich zone may be cause of fire after explosion rather than buildup the explosion pressure, which has been observed from small scale experiment.[4),8)] Therefore, the maximum explosion pressure can be estimated by assuming the gas within the flammable zone to be burned completely and to be mixed adiabatically as shown in Fig. 2.

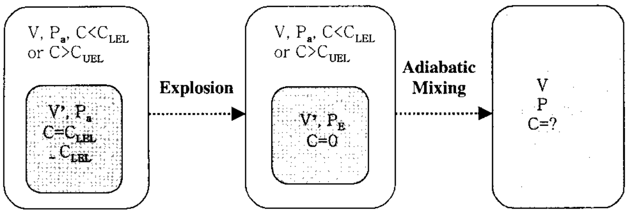

Fig. 2. Gaussian distribution explosion model for confined gas explosion

When heavy gas or light gas releases in an enclosure, the gas concentration shows horizontally uniform at given height with Gaussian distribution in vertical direction of the enclosure.[6)] Without wall effect of the bottom for lighter gas(or ceiling for heavy gas), the one-dimensional concentration distribution can be expressed as Gaussian.

$$C = Ae^{-kx^2} \tag{2}$$

where A and k are constants of Gaussian distribution, x is distance from maximum concentration.

By assuming that the concentration profile is reflected by the bottom and ceiling of the enclosure, the concentration can be expressed as the following equation.

$$C = e^{-k\bar{x}^2} + \sum_{i=1}^{\infty}\left(e^{-k(2i-\bar{x})^2} + e^{-k(2i+\bar{x})^2}\right) \tag{3}$$

where $\bar{x}$, which is scaled with the height of the enclosure, is dimensionless distance from the ceiling for light gas(or bottom for heavy gas).

The term of summation in Eq. (3) represents the reflection from bottom and ceiling of the enclosure. The gas concentration can be made as dimensionless group with maximum concentration as the following equation.

$$\bar{C} = \frac{e^{-k\bar{x}^2} + \sum_{i=1}^{\infty}\left(e^{-k(2i-\bar{x})^2} + e^{-k(2i+\bar{x})^2}\right)}{1 + 2\sum_{i=1}^{\infty} e^{-4ki^2}} \tag{4}$$

where $\bar{C}$ is dimensionless gas concentration scaled with the gas concentration at ceiling for lighter gas(or bottom for heavy gas).

The above equation can be reduced into homogeneous distribution by assuming k as zero. The average concentration of flammable gas is total volume of the gas divided by the volume of the enclosure.

$$C_{av} = \frac{G}{V} = C_0 \int_0^1 \bar{C} d\bar{x} \tag{5}$$

where G is total volume of flammable gas in the enclosure and C_0 is maximum concentration which is located at $\bar{x} = 0$.

When flammable zone is formed in the enclosure, the volume fraction of the flammable zone in the enclosure is simply estimated from the location of LFL and UFL of the flammable gas.

$$\Phi = \bar{x}_{LFL} - \bar{x}_{UFL} \tag{6}$$

where and $\bar{x}_{UFL}$ are the position of UFL and LFL in the enclosure, respectively. The $\bar{x}_{UFL}$ is zero when the maximum concentration is lower than UFL. The $\bar{x}_{LFL}$ is unity when minimum concentration is greater than LFL. The position of UFL and LFL will be discussed in later section.

The fraction of the flammable gas contributing to the explosion pressure, which is ratio of the gas within the flammable zone to the total amount of the gas in the enclosure, is estimated by using Eq. (4).

$$\omega = \frac{\int_{\bar{x}_{UFL}}^{\bar{x}_{LFL}} \bar{C} d\bar{x}}{\int_0^1 \bar{C} d\bar{x}} \tag{7}$$

The volume fraction of isolated cloud with stoichiometric concentration corresponding to the amount of gas within the flammable zones is solved by using the above equation.

$$\Phi_{st} = \frac{\omega C_{av}}{C_{st}} \tag{8}$$

where C_{st} is stoichiometric volume concentration of gas.

For given average concentration in an enclosure, the volume fraction of the explosion zone(Φ) and the volume fraction with stoichiometric gas concentration corresponding to the amount of gas in flammable zone(Φ_{st}) will be changed by changing the parameter k of the Gaussian distribution. For the average concentration lower than LFL, the Φ_{st} is maximum when the maximum concentration is UFL, and the Φ is maximum before the maximum concentration is UFL.

The explosion pressure can be estimated simply from modification of the AMEM by substituting of $\omega\bar{V}$ to the $\bar{V}$ in Eq. (1).

$$P = P_a\left(1 - \omega\frac{\bar{V}}{V}\right) + P_E\omega\frac{\bar{V}}{V} = P_a(1 - \Phi_{st}) + P_E\Phi_{st} \tag{9}$$

where $\omega\bar{V}$ is volume of the gas mixture at stoichiometric concentration associated with the amount of gas within the flammable limits.

The maximum explosion pressure for given amount and concentration distribution of gas is solved implicitly by using Eq. (9). This method may be still overestimated comparing with real situation since the gas in the flammable zone assumed to be as mixture of stoichiometric concentration. The minimum average concentration of flammable gas to specified damage criteria is estimated by using Eqs. (8) and (9).

$$C_{av} = \frac{C_{st}}{\omega}\left[\frac{P_{max} - P_a}{P_E - P_a}\right] \tag{10}$$

where P_{max} corresponds to the maximum explosion pressure for given damage criteria.

Assuming that the total amount of released gas in the enclosure contributes to the explosion pressure, i.e., $\omega = 1$, the Eqs. (9) and (10) are reduced to the AMEM which was suggested by Ogle. Otherwise, assuming that the distribution parameter, k, is zero, those equations are reduced into LFL explosion model. Therefore, the GDEM is considered to be generalized model for the previous two models. The average concentration for a given damage level of explosion depends inversely on the fraction of gas contributing the explosion pressure, and the fraction, ω, is function of the average concentration and the parameter k. Assuming the parameter k as constant, the average concentration can be estimated implicitly for a given damage level of explosion by using the Eqs. (4), (5), (7), and (10). For given average concentration, the span of k for exceeding a given damage level of explosion also can be solved. Generally, the lower limit of the k occurs when the maximum concentration is lower than UFL, and the other limit occurs when the maximum concentration is grater than UFL. At lower range of average concentration, the values of those limits are very large and decrease with average concentration. It means that the bottom or ceiling effect on the concentration distribution may be negligible for analyzing explosion hazard with small amount of leaked gas.

3. Minimum amount of gas explosion

The ratio of flammable gas within the LFL and the UFL to the total flammable gas within the enclosure can be estimated approximately as the following:

$$\omega = \frac{\int_{\bar{x}_{UFL}}^{\bar{x}_{LFL}} e^{-kx^2} dx}{\int_0^1 e^{-kx^2} dx} \approx \mathrm{Erf}\left[\mathrm{Re}\left[\sqrt{\ln\left(\frac{C_0}{C_{LFL}}\right)}\right]\right] - \mathrm{Erf}\left[\mathrm{Re}\left[\sqrt{\ln\left(\frac{C_0}{C_{UFL}}\right)}\right]\right] \tag{11}$$

where the operator Erf is error function.

The above equation depends on the parameter k, which is included implicitly in the maximum concentration for given average concentration, and it is assumed that the k is great enough to ignore the bottom or ceiling effect. The explosion of gas in the confined space may be highly affected by the concentration distribution. The maximum fraction of gas that contributed to explosive mixture was found as about 3/4 by experiments.[8] It is lower than theoretically estimated value with Eq. (11) as shown in table 1.

The GDEM shows that only small amount of gas leaking may result in serious gas explosion accident.

Table 1. Minimum average concentration of flammable gas for explosion as percent of total enclosed volume

Chemical	Gaussian Distribution Explosion Model					Lower Limit Concentration (Vol%)
	ω_{max}	Minor	Moderate	Major	Catastrophic	
Methane	0.862	0.040	0.096	0.197	0.290	5.0
Propane	0.918	0.015	0.036	0.072	0.108	2.1

4. Conclusion

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

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