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Consequence analysis of blast wave from accidental gas explosions

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Abstract

Recently, consequence analyses of accidental gas explosions are often carried out to assess the risk of chemical plants, hazardous-materials sites and new energy systems. In these consequence analyses, it is indispensable to adequately predict the blast-wave (pressure-wave) intensity from gas deflagrations. Some prediction models already exist; however, most of them are based on the theory for explosives and adjusting parameters are needed for evaluating gas deflagrations. In this study, new prediction methods for gas deflagrations were developed. From theoretical analysis of blast-wave generation by a gas deflagration, an evaluation equation of the blast-wave intensity was derived. As the scale of gas deflagration becomes larger, flame front instability (especially hydrodynamic instability) would be more effective and the flame propagating velocity starts to be accelerated. Therefore, the equation was modified considering the effect of flame instability. The evaluations by this modified equation agreed well with the results of large scale experiments. By this analysis, it was found that not only total energy release but also combustion reaction rate has to be introduced into the prediction of gas deflagrations. Using this concept, a modified scale model to predict the blast-wave intensity was developed by improving the previous scale model introducing the term of combustion reaction rate as burning velocity. Furthermore, scale analysis was performed to develop the new scaling law. The universal relationship between scaled distance and overpressure has been realized by this new scaling law for gas deflagrations. In summary, these results provide new methods for accurate prediction of the blast-wave intensity from gas deflagrations.

Keywords: Gas explosion; Deflagration; Blast-wave intensity; Consequence analysis; Hydrodynamic instability

1. Introduction

Recently, risk assessment is introduced into the safety management in chemical plants, hazardous-materials sites and so on. Especially risk assessments become indispensable to propose new energy systems. The reliable risk assessment is a key point to achieve effective safety management. For the reliable risk assessment, accurate analysis

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of the consequences of potential hazards is essential. In a plant or site where flammable gases are handled, an important potential hazard is accidental gas explosion. Therefore, the consequence analysis of the possible damages by an accidental explosion has to be performed. Main damages by accidental explosions are caused by pressure increase, blast wave, fragment scattering, high temperature gas, and so on. The damage caused by a blast wave can spread quickly and widely, and become a significant consequence of the accidental explosion around the explosion point. The consequence analysis of the blast-wave is focused in this study. Some models have been already developed to predict the intensity of the blast wave [1–3]; however, most models are based on the theory for explosives and adjusting parameters are needed for evaluating gas deflagrations. On the other hand, the explosion phenomena can be simulated by recent CFD techniques. However, the CFD simulation is usually not suitable for risk assessment because CFD needs much time, cost and detailed information about the explosion conditions.

The target of this study is to develop a more accurate and general prediction methods for gas deflagrations. In this study, new prediction models were proposed and the comparisons with available data from large scale experiments were performed [4,5].

2. Previous models

2.1. Previous models for evaluating blast wave

Several models have been proposed to predict the intensity of the blast wave induced by an explosion. The major models are "TNT equivalency model", "TNO multi-energy model", and "Modified Baker model" [1–3].

"TNT equivalency model" is based on the assumption of equivalence between the flammable material and TNT (trinitrotoluene). The equivalent mass W is calculated by the following equation based on the total heat of combustion of flammable material.

$$W = \frac{\eta M E_C}{E_{\mathrm{TNT}}}, \tag{1}$$

where η is an empirical explosion efficiency, M the mass of flammable material, E_C the heat of combustion of flammable material, and E_{TNT} the heat of combustion of TNT. It is mentioned that the explosion efficiency becomes 2% to 15% for gas deflagrations. The effects (consequences) of explosion can be evaluated by the reference experimental data of TNT of the equivalent mass. In this model, the scaled distance Z is given as Eq. (2) using $W^{1/3}$, and the evaluation can be performed conveniently,

$$Z = \frac{R}{W^{1/3}}, \tag{2}$$

where R is the distance from the explosion point. The prediction is given as the semi-empirical curves on the coordinate system of the scaled distance Z and maximum overpressure $P_{\max}$.

"TNO multi-energy model" provides a detailed procedure for the prediction. In the procedure, multi-energy sources of explosion are considered. In the energy evaluation, different factors are used for detonation and deflagration, respectively. The scaled distance (Sachs-scaled distance) is calculated by the following equation, which is under the same concept of "TNT equivalency model", i.e. based on the total heat of combustion of flammable material,

$$\bar{R} = \frac{R}{(E/P_0)^{1/3}}, \tag{3}$$

where $\bar{R}$ is Sachs-scaled distance, E the charge combustion energy, P_0 the ambient pressure. The prediction is given as the semi-empirical curves on the coordinate system of the Sachs-scaled distance $\bar{R}$ and non-dimensional maximum overpressure $P_{\max}/P_0$.

"Modified Baker model" uses also Eq. (3) of the "TNO multi-energy model". Differed from "TNO multi-energy model", the effects of reactivity, obstacle density, and geometry are introduced.

In these three models, the essential scaling concepts are based on "cube root scaling" shown in Eqs. (2) and (3), in which the scaled distances depend on the distance and cube root of total energy release (heat of combustion of flammable material). This concept has been developed for evaluating the detonation of explosives.

2.2. The comparisons with the results of large scale experiments

To verify these models, they were applied to large scale experiments. There are some available data measured in the large scale experiments performed by Japanese research organizations [6–8]. At first, the evaluation was made by "TNT equivalency model" under the condition that the empirical explosion efficiency η is unity, which corresponds to an elemental concept of these three models. In Fig. 1, the maximum overpressures measured in the experiments are compared with the evaluated value by "TNT equivalency model". The conditions of experiments are listed in Table 1. The flammable materials used in the experiments are flammable gas (hydrogen, city gas, LPG [Liquefied Petroleum Gas], DME [Di-Methyl Ether]) and explosives (Pentlite, Black powder). The propagation modes (Deflagration or Detonation) are also indicated in Table 1. The experiments for flammable gases were performed using a vinyl tent of almost square shape filled with flammable gas/