Letter

Estimation of blast wave pressures by flame propagation velocities for premixed gases

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Abstract

This study investigates blast wave pressures generated from explosions of premixed gases. The blast wave pressures were estimated using a blast model that utilizes the volume variations of a burnt gas as a pressure source. The volume variations were obtained by flame propagation velocities that were measured experimentally. Since the results of this model were in agreement with previous experimental and numerical calculation results, this model can be used to estimate quantitatively the blast wave pressures from a gas explosion using flame propagation velocities.

Keywords : blast wave, flame propagation velocities, peak overpressures, volume variation, blast model

1. Introduction

A gas explosion is a potentially serious hazard in chemical process industries such as hydrogen storage facilities, which are becoming the new source of clean energy for the next generation. Gas explosions occur occasionally, and when they do, they tend to be very destructive. The blast wave generated from such an explosion can cause serious damage over a considerable area.

Many researchers have been using the TNT equivalent model for studies on gas explosions[1)-3)]. This approach is an attractive one, as the blast pressures of TNT, which is a function of the distance from the explosion source, are well known. However, several studies have shown that there is probably no correlation between the amount of a gas mixture and the total energy released or the blast yield (i. e. the ratio of the energy that contributes to the blast wave to total energy of the gas mixture)[4)]. One of the reasons for this is that blast wave pressures are determined not only by the amount of burnt gas, but also by the accelerated flame propagation velocities as the flame propagates[5)]. Another reason is that a detonation generates an intense blast wave with a strong shock wave, causing an increase in entropy. A deflagration will produce a weaker shock wave or a continuous rise of pressure with a smaller increase in entropy, so that more energy is available in the blast wave at far distance.

In this study, blast wave pressures were estimated using a blast model[6)] that utilizes the volume variations of a burnt gas as a pressure source. It is considered that this model using an isentropic condition is suitable for gas explosion that is deflagration, since the entropy does not change significantly for a gas explosion with relatively lower flame propagation velocities. Furthermore, this model calculates the pressure with the acceleration in volume variations so that the effect of the change in energy released per unit time is included. There have been several studies[6),7)] using this model. However, the scales of the gas mixtures are as small as tens centimeters in diameter. In this study, the applicability of the model was investigated since experiments of different scales for different kinds of gas mixtures have been reported in previous years.

2. Blast model

For a simple monopole source radiating spherically, the static overpressure of a sound wave is given by the expression,

$$\Delta P\,(D,t) = P\,(D,t) - P_0 = \frac{\rho}{4\pi D}\frac{d}{d\tau}\left(\frac{dV}{d\tau}\right), \tau = t - D/C_0 \quad (1)$$

where, D, t, ρ, P_0, $dV/d\tau$, and C_0 are the distance from the source, time, atmospheric density, atmospheric pressure, volume variation velocity of an acoustic source and sound velocity of the atmosphere, respectively.

In this blast model, the following two assumptions are included : a gas mixture is ignited at the center and the flame propagates spherically with a much lower velocity than the sound velocity such that the pressure of the burnt gas is assumed to be constant. The burnt gas of the source behaves like an equivalent piston, and expands to a new volume as the flame propagates. The new volume is given by the expression,

$$\Delta V = (4/3)\pi r_f^3 (1 - 1/\beta) \tag{2}$$

where r_f and β are the flame position and expansion ratio (unburnt gas density / burnt gas density), respectively. Because the volume variation velocity can be re-expressed as the flame propagation velocity (dr_f/dt), the generated pressure at a far distance from the source is given by the expression[6],

$$\Delta P\,(R,t) = \frac{\rho_0\,(1-\beta^{-1})}{D}\left\{2r_f\,(\tau)\left(\frac{dr_f\,(\tau)}{d\tau}\right)^2 + r_f^2\,(\tau)\left(\frac{d^2 r_f\,(\tau)}{d\tau^2}\right)\right\} \tag{3}$$

In this calculation, dr_f/dt is obtained from the data of previous reports[8)–12)], and β is obtained by CEA (Chemical Equilibrium with Applications), which is a computer program for chemical equilibrium calculation[13)]. There are different values of β in previous studies[14),15)], but fortunately the effect of the expansion ratio on the blast wave pressure is not significant.

3. Results and discussions

3.1 Overview of data from previous reports

Table 1 shows the experimental conditions used in the previous reports for the different gas mixtures, with their equivalence ratios, and volumes[8)–12)]. The expansion ratio from CEA for each gas mixture is also shown in Table 1. The reports also included data on the flame propagation velocities and blast wave pressures.

Figure 1 shows the flame propagation velocities for different gas mixtures as it expands from an initial radius $r_{f,0}$ to a maximum flame radius $r_{f,\max}$. We assume that $r_{f,\max}$ is given by the conservation of mass within the flame as $r_{f,\max} = \beta^{-1/3} \cdot r_{f,0}$[7)]. The flame propagation behaviors are reported as a quadratic polynomial in previous reports[8),9)], thus the velocities are straight lines as shown in Fig. 1(A). However, the flame acceleration for the experiment with the volume of 4200 m^3 is not constant, but varies as shown in Fig. 1(B). It is considered that the polyethylene balloon membrane containing the gas mixture prevented the movement of unburnt gas by a pressure wave.

Table 1 Experimental conditions and expansion ratios.

Gas mixture	Equivalence ratio, ϕ	Volume [m^3]	Expansion ratio, β
CH_4/O_2	1.00	0.00677~0.259	13.9
CH_4/O_2	0.60	0.256	12.1
H_2/Air	1.00	0.125	7.5
H_2/Air	0.60	0.125	5.9
H_2/Air	0.42	0.125	4.9
H_2/Air	1.00	4200	7.5

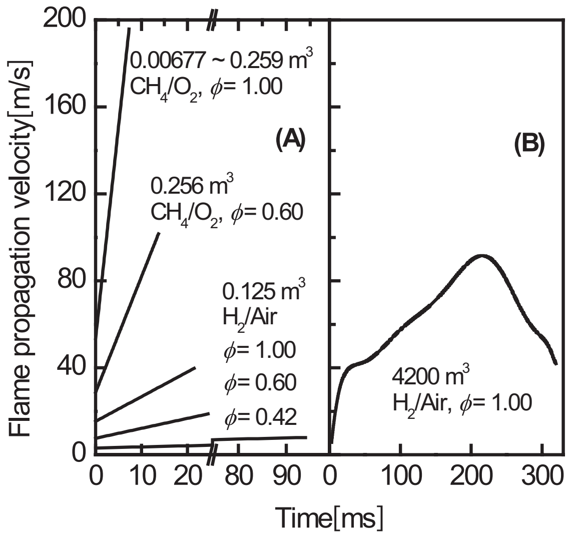

Fig. 1 Flame propagation velocities of previous reports for different gas mixtures.

Figure 2 shows peak overpressures represented as symbols. Most of the data were obtained by experimental measurements. Only the data for the hydrogen/air mixture of 4200 m^3 were obtained both experimentally and numerically by calculation. The experimental results were about 10% lower than the calculated results. The difference might be due to the fact that the pressure sensors were covered with a 2 mm layer of silicone grease[12)].

3.2 Comparison of this explosion model and previous reports

Figure 2 shows the calculated results of this model as a straight line. Fig 2 (A) shows the results for a methane/oxygen mixture of $\phi = 1.00$. As the volume of the gas mixture increases, the peak overpressures increase. It appears that the results of this model agree with the experimental results. However, attenuation behavior with respect to distance is different, so it cannot be said that this model can be used to estimate the pressure for this gas explosion. It is considered that because the blast wave was converted into the shock wave[8),9)], the peak overpressures of the experimental results are attenuated faster than those of sound waves due to increasing entropy.

On the other hand, when $\phi = 0.60$, the results of this model agree well with the experimental results, as shown in Fig. 2(B). This is considered to be because the flame propagation velocity was lower than those when $\phi = 1.00$, the blast wave was not converted into a shock wave ; thus the propagation characteristic of the blast wave was similar to that of a sound wave.

As for the different kinds of gas mixture, the results for a hydrogen/air mixture of 0.125 m^3 are shown in Fig. 2(C). The results of this model agree well with the data in previous reports. It is considered that this model can estimate the blast wave pressure regardless of equivalence ratio under the condition that flame propagation velocity is much lower than the velocity of a

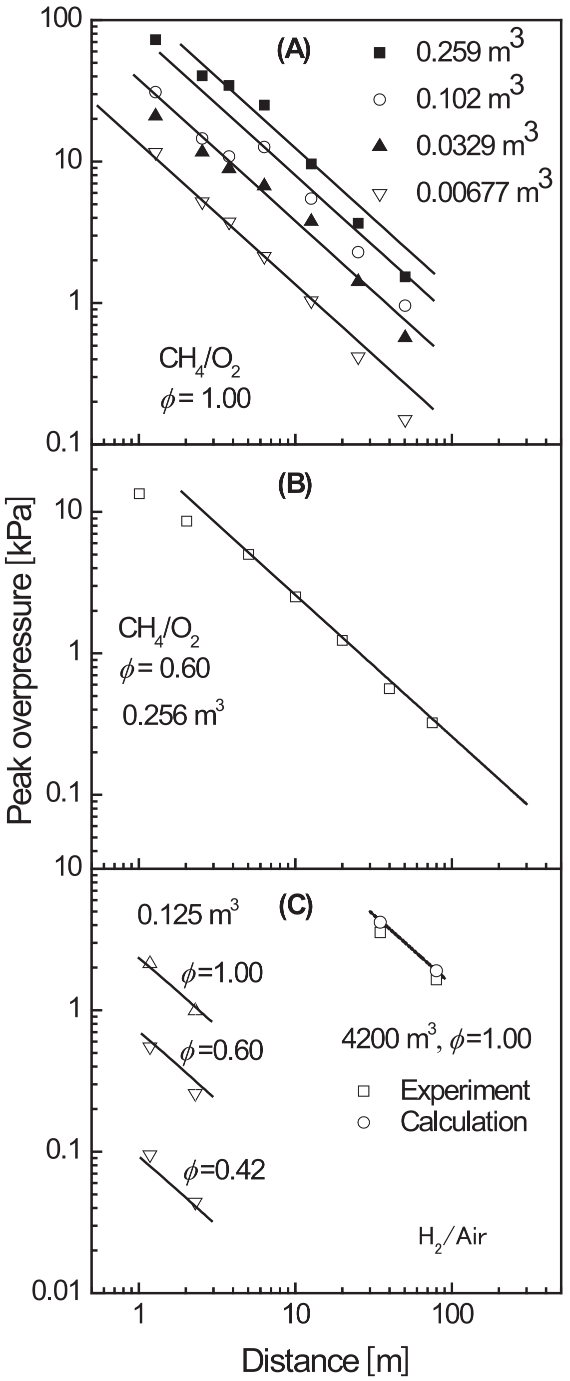

Fig. 2 Comparison of this model and previous reports for peak overpressures.

sound wave, so that the blast waves are not converted into a shock wave.

Finally, the blast wave pressure for a large-scale experiment of 4200 m^3 was also estimated as shown in Fig. 2(C). This model did not agree with the experimental results, but agree with the calculated results. Even though a little amount of data was collected, there is no reason to assume that this model would be inadequate for different scales.

4. Conclusions

This study investigates the relationship between blast wave pressures and flame propagation velocities using a simple blast model. The results showed that the blast wave pressure can be estimated quantitatively by the expansion ratio and the flame propagation velocities, regardless of the kind, amount, and equivalence ratio of gas mixtures, under condition that flame propagation velocity is much lower than the velocity of a sound wave, so that the blast waves are not converted into a shock wave.

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