EXPERIMENTAL STUDY ON GAS EXPLOSIONS IN ENCLOSURES

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ABSTRACTS

The explosion behavior has been studied experimentally using small scale test vessels. The effects of gas flow turbulence, gas concentration distribution, and flame front instability, which are the most probable causes to disturb the propagating flame front during gas explosions, on the flame behavior and pressure variation have been examined. It is shown that the gas flow turbulence increases the flame propagating velocity and the pressure rising rate. When the flow is turbulent the pressure rise $p-p_0$ is proportional to about the 3.6th power of the time from ignition t, while when the flow is quiescent it is proportional to the 3rd power of t. When the concentration distribution of a combustible gas was non–uniform, the gas explosion behavior strongly depends on the local concentration. The rate of the pressure rise increases with the nonuniformity of the combustible gas concentration. The flame front becomes unstable by an interaction with a pressure wave and generated flame front disturbance grows rapidly by acceleration of the gas induced by a following pressure wave in the direction toward the unburned gas side, so that the flame propagating velocity and the pressure rising rate are extremely increased. In this case, the pressure rise is proportional to the 6.4–6.8th power of t.

KEYWORDS: Gas explosion, Turbulent flow, Non–uniform mixture, Flame front instability

Nomenclature

A	Area
A_e	Effective area of opening
A_f	Area of flame front
C	Constant
p	Pressure in vessel
p_0	Pressure in vessel at ignition
s	Slope of pressure rise on log scale ($s=\log(p-p_0)/\log t$)
S	Burning velocity
t	Time from ignition
t_d	Time from end of injection to ignition
u_e	Gas flow velocity at opening
V	Volume of vessel
V_b	Volume of burned gas
V_u	Volume of unburned gas
X_f	Concentration of combustible gas
γ_b	Specific heat ratio of burned gas
γ_u	Specific heat ratio of unburned gas
ρ_b	Density of burned gas
ρ_u	Density of unburned gas
ϕ	Fuel equivalence ratio

INTRODUCTION

A large number of accidental gas explosions have happened every year and caused serious damages. Most of the explosions have occurred in an enclosure such as a room or a vessel, because the concentration of combustible gas is easy to increase in these spaces. When an accidental gas explosion happens in an enclosure, the damage is caused mainly by the pressure rise in the space. Recently rooms tend to be more airtight, therefore, the pressure rise might become larger and the damage must be more serious. The pressure rise is caused by heating of gas confined in a space by combustion. Therefore, the pressure variation is closely related to behavior of the flame front where heat release occurs. Since the flame front behavior depends on the concentration and flow field of the unburned mixture and the flame front instability, appropriate understanding of the effects of these factors on the flame behavior is necessary to predict the pressure variation during a gas explosion.

So far, the pressure variation and flame behavior during a gas explosion have been studied by several researchers[1–9]. However, the flame behavior during a gas explosion has been still ambiguous, and the satisfactory method for estimating the pressure variation have not been established yet. In this study, therefore the effects of gas flow turbulence, gas concentration distribution, and flame front instability on the behavior of a propagating flame have been examined to a further extent.

PRESSURE BUILDUP

When a flammable mixture in a room is ignited by an ignition source, flame starts to propagate. The burned gas is generated whose volume is several times larger than that of the consumed unburned gas. Then the pressure in the room starts to rise. In general, a window or door of the room is likely to be an opening or an opening might be generated by a breakage of a weak part of a wall of the room due to the pressure rise, and the pressurized gas in the room flows out through it.

In the case when the pressure is uniform throughout the room and only unburned gas is assumed to be flown out through the opening, the time differential of the volume of the unburned gas (dV_u/dt) and burned gas (dV_b/dt) can be given respectively as,

$$\frac{dV_u}{dt} = -\int_{A_f} S dA - \frac{V_u}{\gamma_u p}\left(\frac{dp}{dt}\right) - u_e A_e \frac{\rho_e}{\rho_u} \quad , \qquad (1)$$

$$\frac{dV_b}{dt} = -\int_{A_f} S\left(\frac{\rho_u}{\rho_b}\right) dA - \frac{V_b}{\gamma_b p}\left(\frac{dp}{dt}\right) \quad , \qquad (2)$$

where t is the time from ignition, p the pressure in the room, γ the heat capacity ratio, V the volume of the room, A the area, A_f the area of flame front, S the burning velocity, u_e the flow velocity at the opening, A_e the effective area of the opening, ρ_u the density of unburned gas, and ρ_b the density of burned gas. The first term in the right hand side of these equations represents the effect of combustion and the second term represents the effect of compression. The third term of Eq.(1) represents the effect of an outward flow through the opening. Since the effects of the opening on the pressure variation are not the subjects to elucidate in this study we examined only the cases when no opening exists, then this third term of Eq.(1) is zero in this analysis.

Using the relation $dV_u/dt+dV_b/dt=0$, then p is expressed as the following equation.

$$p = p_0 + \int_0^t \frac{\gamma_u p\left\{\int_{A_f}\left(\frac{\rho_u}{\rho_b}-1\right)SdA\right\}}{V\left\{1+\left(\frac{V_b}{V}\right)\left(\frac{\gamma_u}{\gamma_b}-1\right)\right\}}dt \quad , \tag{3}$$

where p_0 is the pressure at ignition(t=0). The effect of the flame behavior is expressed as the term $\int_{A_f}(\rho_u/\rho_b-1)SdA$. If the disturbance appears on the flame front, the value of $\int_{A_f}(\rho_u/\rho_b-1)SdA$ becomes larger and the pressure rises more rapidly.

If any disturbance does not exist on the flame front propagating spherically, the pressure rise $p-p_0$ during starting($V_b \ll V$) period can be expressed as the following simple equation,

$$p - p_0 = \frac{Cp_0S^3t^3}{V} \quad , \tag{4}$$

where C is a constant coefficient.

CAUSES TO DISTURB FLAME FRONT

When the flame front is disturbed, the pressure rises more rapidly than estimated by Eq(4). The most probable causes to disturb the flame front are as follows:

i) Gas flow turbulence

Usually there is some gas flow in the space where a gas explosion happens and the gas flow rarely be laminar but turbulent.

ii) Non–uniformity of concentration distribution of combustible gas

Usually combustible gas leaked from some point source, and mixed with surrounding air. In such a case, the concentration distribution might be non–uniform.

iii) Flame front instability

A propagating flame front tends to become unstable by several causes. The considerable phenomena which can occur during a gas explosion are the following two cases. One is the instability induced by the interaction between the flame and a pressure wave. The other is the instability caused by the preferential diffusion mechanism.

The effects of the above causes on the flame front behavior have been examined in this study.

EXPERIMENTS

The effects of the gas flow turbulence on the flame behavior and the pressure variation is examined using a small scale explosion vessel. The schematic of the vessel is shown in Fig. 1. The dimensions of the vessel are 80 mm x 80 mm x 80 mm. The gas flow turbulence is generated by injecting the flammable mixture into the vessel through a small nozzle. The diameter of the nozzle is 1.0 mm. The generated turbulence will be diminishing as the time passages from the end of the injection. The intensity of the turbulence can be controlled by changing the time t_d which is the time from the end of injection to the ignition by an electrical spark. The injecting mixture is of the

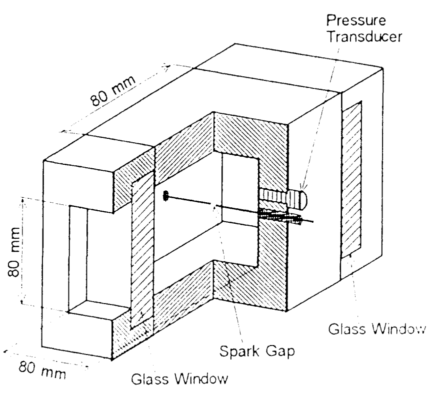

Figure 1 Schematic of the combustion vessel.
(for examining flow turbulent and non−uniformity of the mixture)

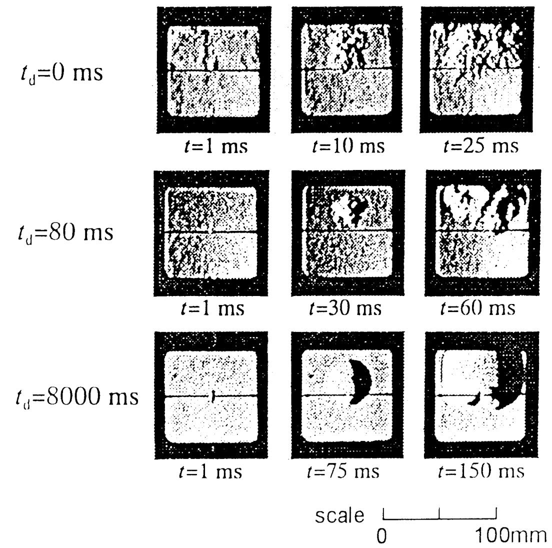

Figure 2 Aspects of the flame front behavior.
Mixture : uniform methane/air with flow turbulence (injecting the mixture into the vessel),
Concentration X_f=6.1%(ϕ=0.62)
t_d : time from the end of injection to ignition
Combustion vessel : 80mm x 80mm x 80mm

same concentration as the mixture in the vessel, therefore the concentration distribution in the vessel is uniform.

Figure 2 shows schlieren photographs which represent the aspects of the propagating flame. In this case, the mixture is of methane/air and the concentration of methane X_f is 6.1%(the fuel equivalence ratio ϕ=0.62). It is seen that the intensity of flame front turbulence becomes weaker and their scale becomes larger when t_d becomes smaller. In the case of t_d= 8000 ms, no disturbance is found on the propagating flame front. Under this condition, the mixture is considered to be quiescent at ignition. The pressure variation in the vessel is shown in Fig. 3. As the time t_d become smaller, the pressure rises more rapidly. The pressure rise($p-p_0$) is plotted against the time on a log scale in Fig. 4. It is shown that the pressure rise in the case of t_d= 8000 ms behaves as a line whose slope, s=log($p-p0$)/log t is about 3, as expected by Eq(4). In the cases of t_d=0 and t_d=80 ms, the slopes s are about 3.6

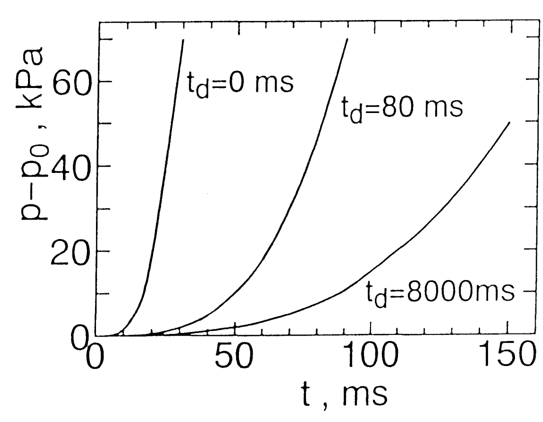

Figure 3 Pressure variation for various t_d value.
t_d : time from the end of injection to ignition
Mixture : uniform methane/air with flow turbulence, (injecting the mixture into the vessel)
Concentration X_f=6.1%(ϕ=0.62)
Combustion vessel : 80mm x 80mm x 80mm

and 3.4 respectively. It should be noted that the gas flow turbulence can make the pressure rising rate significant larger.

The effects of non-uniformity of the concentration distribution of the flammable mixture on the flame behavior and the pressure variation were examined by using the same vessel as shown in Fig. 1. In this experiment, the combustible gas was injected into the vessel which was filled with air. The condition is realized when the concentration distribution is non-uniform and the gas flow is turbulent (condition A). The effects of non-uniformity can be evaluated by comparing the result with that of the experiment under the condition of uniform concentration distribution and turbulent gas flow (condition B). For comparison, experiments were also performed under the condition when the gas flow is quiescent and the concentration distribution is uniform by making t_d larger

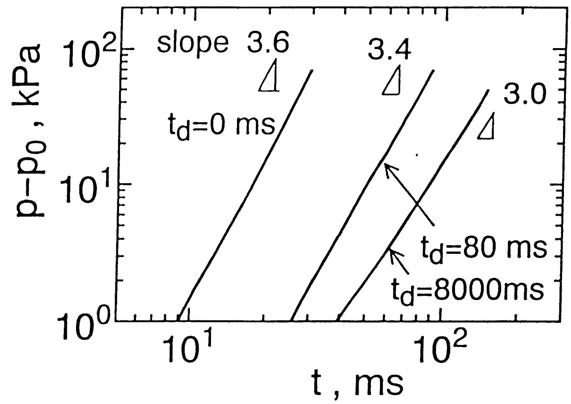

Figure 4 Pressure variation for various t_d value (on log scale).
t_d : time from the end of injection to ignition
Mixture : uniform methane/air with flow turbulence (injecting the mixture into the vessel)
Concentration X_f=6.1%(ϕ=0.62)
Combustion vessel : 80mm x 80mm x 80mm

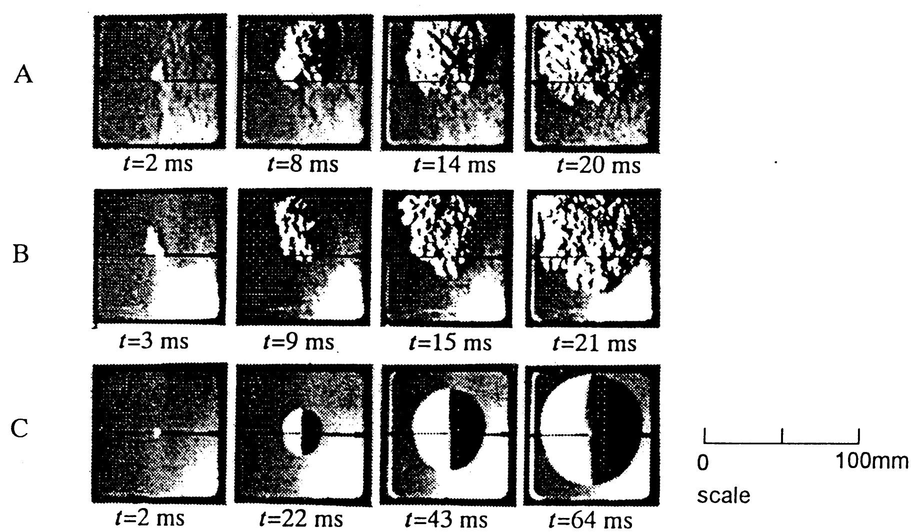

Figure 5 Aspects of the flame behavior.

	Mixture	Gas flow
A	non-uniform	turbulent
B	uniform	turbulent
C	uniform	quiescent

Mixture : Methane/air, average concentration $\overline{X}_f$=7.3%($\overline{\phi}$=0.75)
Combustion vessel : 80mm x 80mm x 80mm

than 8 s (condition C).

Series of high speed schlieren photographs for the cases A, B, and C are shown in Fig. 5. The mixture is methane/air and the average concentration in the vessel $\overline{X_f}$ is 7.3%($\overline{\phi}$=0.75). In the case A, the flame front propagates faster than that in the case B just after the ignition(t=8 – 9ms) and becomes slower at the later stage. In this case, methane concentrates around the ignition point. Thus, just after the ignition flame propagates in the mixture where the burning velocity is higher than that in the case B and then in the mixture where the burning velocity is lower. The measured pressure variations are shown in Fig. 6 where the pressure variations are plotted on a normal scale and also on a log scale. The average concentration $\overline{X_f}$ is 7.3%($\overline{\phi}$=0.75) for Fig. 6a and 10.5%($\overline{\phi}$=1.12) for Fig. 6b. When $\overline{X_f}$ is 7.3%($\overline{\phi}$=0.75, Fig. 6a), the pressure rises rapidly just after the ignition and slowly at the later stage in the case A. This pressure variation can be interpretable

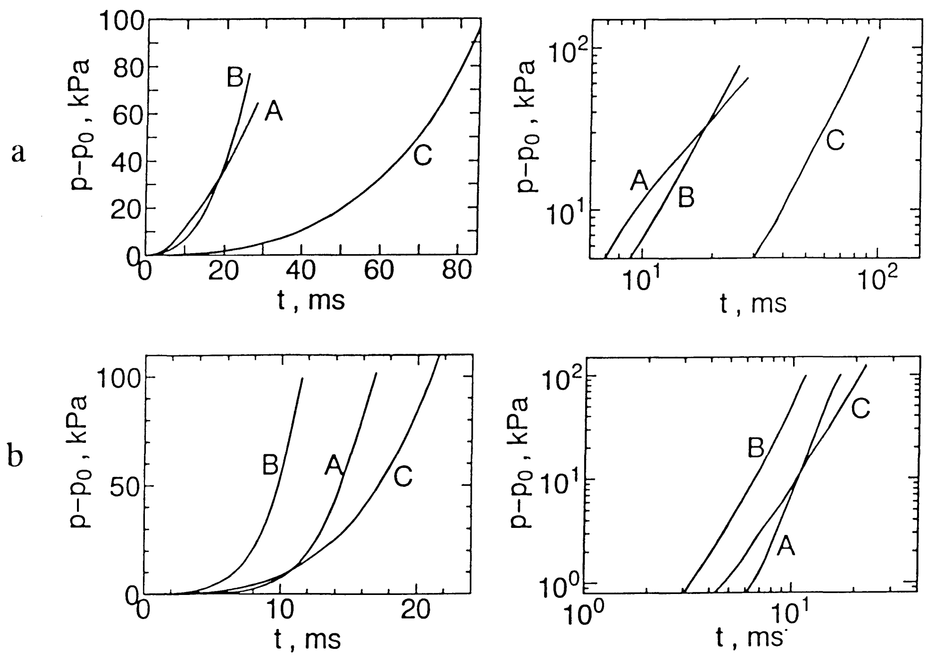

Figure 6 Pressure variation of mixture A, B, and C (on normal and log scale).
t_d : time from the end of injection to ignition
Mixture a : Methane/air, average concentration $\overline{X_f}$=7.3%($\overline{\phi}$=0.75)
b : Methane/air, average concentration $\overline{X_f}$=10.5%($\overline{\phi}$=1.12)
Combustion vessel : 80mm x 80mm x 80mm

on the basis of the flame front behavior. When $\overline{X_f}$ is 10.5%($\overline{\phi}$=1.12, Fig. 6b), the pressure increase slowly just after the ignition and fast in the later stage. In this case, the concentration around the ignition point is so high that the burning velocity become rather lower.

These results indicate that the flame behavior strongly depends on the local concentration of the combustible gas, thus the pressure variation is strongly influenced by the non–uniformity of the concentration distribution. If the non–uniformity of the concentration distribution exists, a rapid pressure rise can be realized even if the average concentration is rather low.

The effects of the flame front instability on the flame behavior and the pressure variation

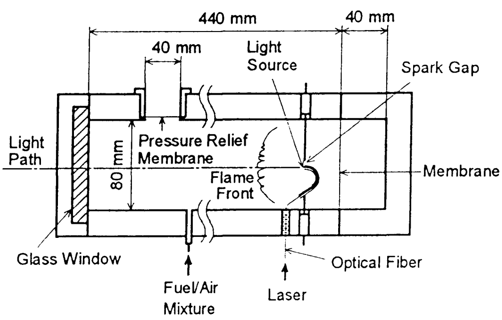

Figure 7 Schematic of the combustion vessel (for examining the flame front instability).

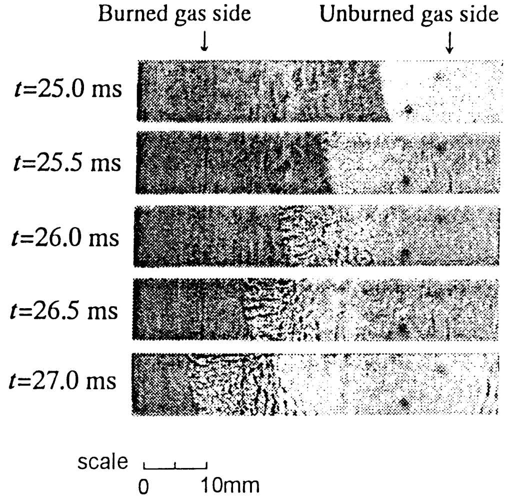

Figure 8 Aspects of the flame behavior when it is interacted by a pressure wave.
Mixture : uniform methane/air mixture
Concentration, X_f=9.5%(ϕ=1.0)
Combustion vessel : 80mmx80mmx440mm

were examined by using the vessel shown in Fig. 7 [7,9]. The dimensions of the vessel are 80 mm x 80 mm x 440 mm. A small chamber is attached and a paraffin paper separates the vessel and the small chamber. After ignition by an electrical spark, the pressure in the vessel starts to rise and $p-p_0$ reaches to about 35 kPa, then the paper breaks immediately and a pressure wave starts to propagate. When the flame front is accelerated by passing this wave, fine disturbances appear on the flame front. A series of high speed schlieren photographs are shown in Fig. 8. In this case, mixture is methane/air and the concentration X_f is 9.5%(ϕ=1.0). This disturbance glows rapidly and the flame front becomes fully turbulent in a few milliseconds. The pressure variation in the vessel is shown in Fig. 9. The pressure variation measured in the condition when any pressure wave is not generated is also shown in this figure for comparison. After the breakage of the paper, the pressure in the vessel starts to oscillate and the pressure rises at a higher rate than in the case without the pressure wave. In the log scale plot in Fig. 9, the pressure behaves linearly and their slopes s is about 3 before the generation of pressure wave. After the generation of the pressure wave, the slope s change to be about 6.4. It is found that the pressure rising rate changes to be lager in a very short duration when the flame front becomes unstable.

Figure 10 shows the pressure variation measured under the condition when the mixture is of propane/air of X_f=5.9%(ϕ=1.5). In this case, the slope s of the pressure rise on a log scale is about 3 before the breakage of the paper and becomes 6.8 after it. This value 6.8 is larger than in the methane/air mixture of X_f=9.5%(ϕ=1.0). As the pressure rising rates before the initiation of the instability are almost same in these two conditions, it is shown that the effect of the passage of pressure waves in the case of this propane/air mixture on the pressure rise is more active. It is considered that the effect of the interaction of the flame front with a pressure wave on the flame front disturbance is intensified by the preferential diffusion mechanism which is observed in a rich

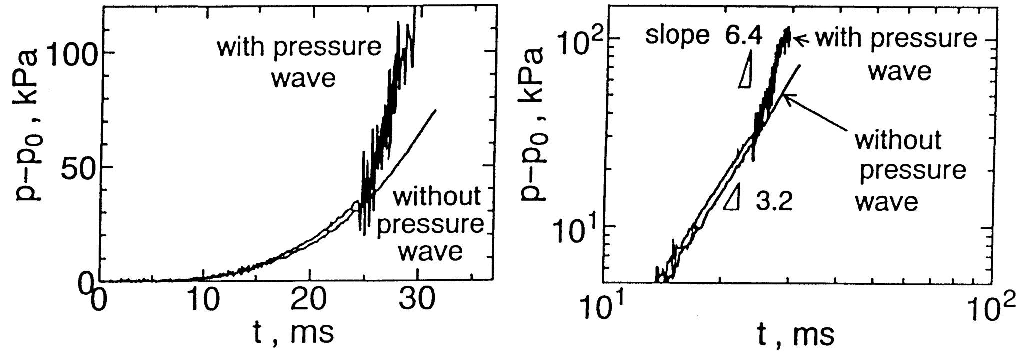

Figure 9 Pressure variation when the flame front is interacted with a pressure wave (on normal and log scale).
Mixture : uniform methane/air mixture, concentration, X_f=9.5%(ϕ=1.0)
Combustion vessel : 80mm x 80mm x 440mm

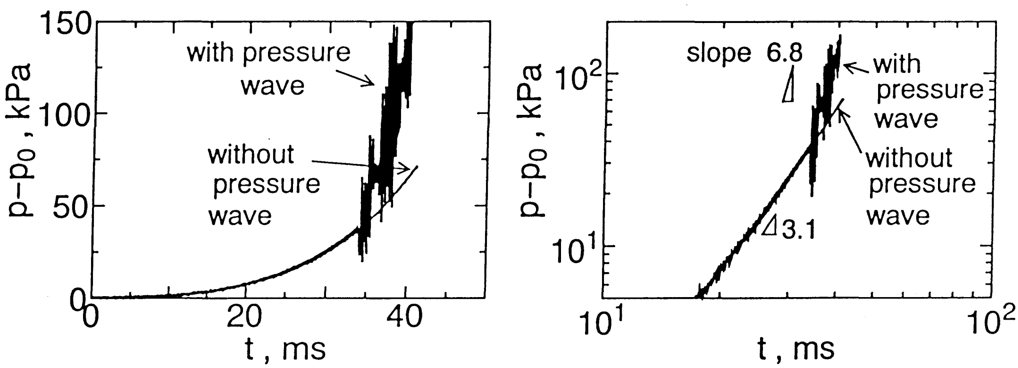

Figure 10 Pressure variation when the flame front is interacted with a pressure wave (on normal and log scale).
Mixture : uniform propane/air mixture, concentration, X_f=5.9%(ϕ=1.5)
Combustion vessel : 80mm x 80mm x 440mm

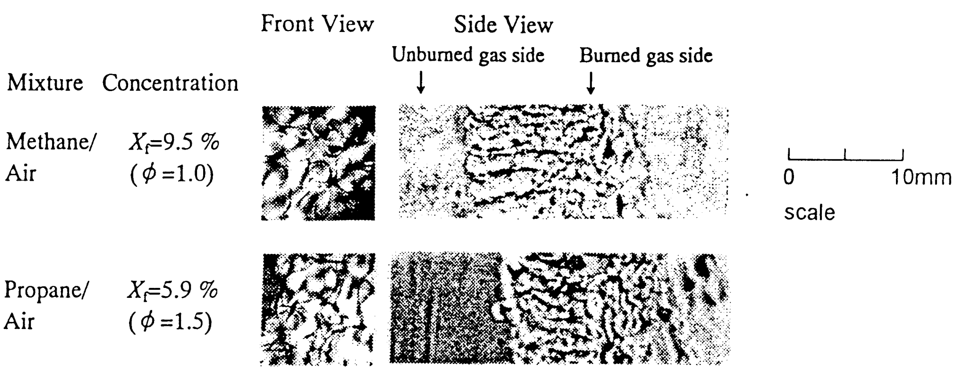

Figure 11 Schlieren photographs taken in different two directions.
Combustion vessel : 80mm x 80mm x 440mm

propane mixture. Pairs of schlieren photographs taken in the direction normal and parallel to the flame front are shown in Fig. 11, which represent the structures of the flame front disturbance. In the case of a methane/air mixture, it is observed that the structure of flame front disturbances is of circular spikes, which are of a typical shape induced by the interaction between a flame front and a pressure wave(Rayleigh–Taylor instability)[7,9]. On the other hand, in the case of a propane/air mixture, the structure of the flame front disturbance is seen very complicated. In this case, the effect of the Rayleigh–Taylor instability and the effect of the preferential diffusion mechanism might interact each other to make the flame front disturbance more complicated.

CONCLUSIONS

The effects of the flame front disturbance on the pressure variation were examined experimentally and the following conclusions have been drawn.

(1) The gas flow turbulence increases the flame propagating velocity and the pressure rising rate. In this experiment, $p-p_0 \propto t^{3.6}$ when the flow is turbulent, while $p-p_0 \propto t^3$ when the flow is quiescent.

(2) When the concentration distribution of a combustible gas is non–uniform, the flame behavior strongly depends on the local concentration. Even if the average concentration is low, a rapid pressure rise can occur.

(3) When the flame front becomes unstable by an interaction with a pressure wave, the flame front disturbance starts to generate quickly. The flame propagating velocity and the pressure rising rate increases rapidly. After the interaction, the pressure variation behaves as $p-p_0 \propto t^{6.8}$.

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