Propagation of Pressure Waves Initiated by Flame and Detonation in a Tube*

Shigeharu OHYAGI**, Eiji NOHIRA***, Tetsuro OBARA**, Pin CAI** and Teruo YOSHIHASHI**

Pressure waves produced by explosions of combustible mixtures formed by the accidental spillage of fuel gases have attracted considerable attention from the safety point of view. In order to assess damage caused by such explosion hazards, real-scale experiments are necessary. However, it is often difficult to perform such experiments because of space limitations and experimental safety. Small-scale experiments are preferred if an appropriate scaling law can be verified. The objectives of this study are to elucidate the decay processes of planar blast waves initiated by deflagration and detonation waves in a tube and to assess the applicability of the energy-based scaling law to these phenomena.

Key Words: Combustion, Shock Wave, Detonation

1. Introduction

Pressure waves initiated by premixed combustion waves have attracted attention recently because the use of gaseous fuels such as natural gas, liquefied petroleum gas (LPG) and hydrogen gas will be extended in the future for ecological reasons. The spillage of these fuel gases in urban areas will cause accidental explosions resulting in serious damage for both humans and infrastructure. In actual situations prior to such accidents, these gases spill from their storage and diffuse into a chamber or room where they will mix with air to form a combustible mixture. In the presence of an ignition source, the mixture will ignite and a flame will appear if the mixture is within the flammability limit. The flame will develop into a turbulent flame, and if the fuel is sensitive, it will develop into a detonation wave depending on the boundary and initial conditions. These flames will emit pressure waves that will propagate outside of the chamber through windows or doors, or in a severe case, they will destroy ceiling or walls to produce blast waves in the surrounding air.

To assess the damage posed by such explosions, it is better to perform experiments on an actual scale, which will be inevitably large. Such large-scale tests should be prepared carefully because much money, work and space will be necessary. If we succeed in performing such a large-scale test, the obtained data will be limited to the particular conditions selected. Therefore, it is necessary to establish a method for reducing the scale of the test so that it can be performed in a laboratory.

In this scenario, the blast wave propagates in the three-dimensional space and it may be very complex in shape. To simplify the problem, many authors[1],[2] have assumed the spherical symmetry or the cylindrical symmetry of the waves. In this study, we focus our attention on a one-dimensional, planar blast wave. The reasons for this are (1) to simplify the phenomena and (2) to apply it to a particular situation that is considered to be one-dimensional. From the results of the one-dimensional planar experiment, we can estimate the characteristic distance of the decay of blast waves (explosion waves), which can be used to estimate the equivalent initiation energy for the three-dimensional case by dimensional analysis.

* Received 30th November, 2000

** Department of Mechanical Engineering, Faculty of Engineering, Saitama University, 255 Shimo-Ohkubo, Saitama 338-8570, Japan. E-mail: ooyagi@mech.saitama-u.ac.jp

*** Tokyo Electric and Power Co., Ltd., 9-2-1 Kurihama, Yokosuka 239-0381, Japan

It is easy to produce the planar blast wave using a tube in a laboratory. The second reason is to apply the results to the explosions in a tunnel where a gas pipeline is built. In designing such tunnels, it is important to assess the explosion hazard due to the spillage of fuel gas from the pipeline.

With this as the background, the objectives of this study are to elucidate the planar blast wave initiated by deflagration and detonation waves in a tube and to assess the applicability of the energy-based scaling law to these phenomena. In this study, the initiation and propagation of blast waves produced by the combustion of gaseous fuel-air mixtures are observed experimentally in a laboratory-scale test. The energy-based scaling law[(3)] with some modification is used to scale the results of experiments.

The gases used in the experiments are natural gas, liquefied petroleum gas (LPG) and hydrogen gas, which are the main sources of energy at present and in the near future. They are also typical gaseous fuels that will burn in the atmosphere as deflagration (natural gas and LPG) and detonation (hydrogen).

2. Experimental

Experiments are conducted using a stainless steel tube with a circular cross section, which is divided into the combustion section and the air section with a ball valve. Figures 1 and 2 show the schematics of the apparatus and details around the connecting ball valve, respectively. The diameter of the combustion

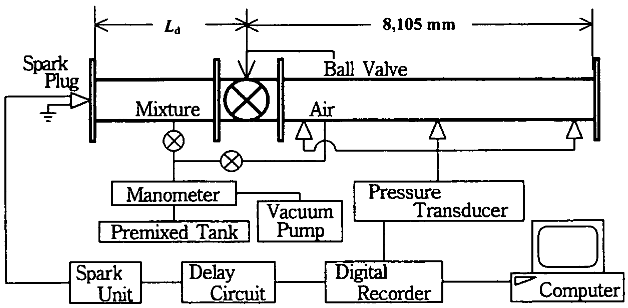

Fig. 1 Experimental apparatus

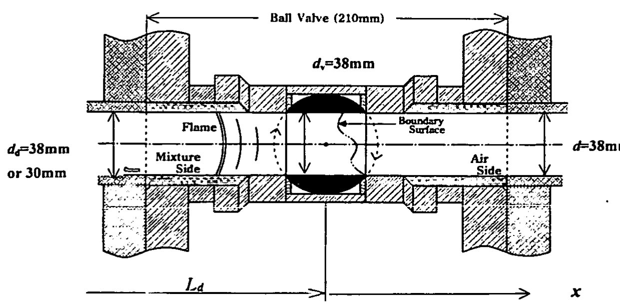

Fig. 2 Details of ball valve section

Table 1 Experimental conditions

Fuel gas	Natural gas ,Hydrogen, LPG
Length of combustible section(mm) Diameter(mm)	2105, 1105, 700 38, 30, 30
Length of air section(mm) Diameter(mm)	8105 38
Equivalence ratio ϕ	0.8, 1.0, 1.2

section, d_d is 38 mm or 30 mm depending on the length of the section while that of the air section, d, is fixed at 38 mm. The length of the fuel section, L_d, is varied from 700 to 2 105 mm and that of the air section is fixed at 8 105 mm. The inner diameter of the valve, d_v, is 38 mm and there is no obstacle or area change in the ball valve section when it is opened if the 38 mm combustion section is used. Gases are introduced from needle valves equipped on the sidewall of each section and their pressure are monitored with a manometer. The end plate of the combustion section is equipped with an igniting plug. The sidewall of the air section is equipped with pressure transducers (PCB 113A24) whose signals are stored in a digital recorder triggered by a signal delayed from the igniting circuit. The experimental conditions are summarized in Table 1. The combustible mixtures used here are natural gas/air, hydrogen/air and LPG/air mixtures, which are prepared and stored in a mixing tank with a total pressure of 1 500 mmHg (=152 kPa). Partial pressures of the components are measured by a mercury manometer. Equivalence ratios are 0.8, 1.0 and 1.2. The accuracy of the equivalence ratio depends on that of the partial pressure which is 1 mmHg (=1.33 kPa); thus, the accuracy of the equivalence ratio is about ± 0.003. Air is introduced from the atmosphere so that the pressure varies for each experiment around the one atmospheric pressure, that is, 101 ± 3 kPa. Temperature is not controlled and it is around 293 ± 6 K.

Experiments are carried out as follows. After the tube is evacuated, the gases are introduced into each section with the ball valve closed. The pressure of each section is set equal to the ambient pressure. The fuel gas is ignited soon after the ball valve is opened manually. The time interval between the opening of the valve and the ignition is not controlled exactly and it is less than 10 s. If turbulent mixing due to the movement of the valve is neglected, the hydrogen gas diffuses into the air as molecular diffusion. The diffusion coefficient D of hydrogen molecule into the air is about 60 mm²/s so that the characteristic distance $\sqrt{Dt}$ of diffusion is about 25 mm at t=10 s. Compared to the total length of the tube, this distance can be neglected. Data obtained by the pressure transducers are analyzed after each experiment. The pressure transducers can be mounted at twelve locations, namely P1, P2 etc. The distances between the

Table 2 Measuring points (Distance x from the center of the ball valve in mm)

Measuring point	P1	P2	P3	P4	P5	P6
Distance from the ball valve, x(m)	605	1105	1605	2605	3105	3605
Measuring point	P7	P8	P9	P10	P11	P12
Distance from the ball valve, x(m)	4605	5105	5605	6605	7105	7605

Table 3 Heat content Q_{CJ} of the mixtures (NG/air, LPG/air : CJ deflagration, H_2/air : CJ detonation)

	ϕ	Q_{CJ}(MJ/kg)
Natural gas/air	0.8	26.18
	1.0	32.10
	1.2	31.04
LPG/air	1.0	66.91
H_2/air	0.8	7.904
	1.0	9.598
	1.2	10.82

Table 4 Initiation energy for each condition

Gas	d_d(mm)	L_d(mm)	ϕ	E_0(MJ/m^2)
NG/air	38	2105	0.8	102
	38	2105	1	124
	38	2105	1.2	119
	30	1105	0.8	33.4
	30	1105	1	40.6
	30	1105	1.2	38.9
	30	700	0.8	21.2
	30	700	1	25.7
	30	700	1.2	24.7
LPG/air	38	2105	1	276
	30	1105	1	90.3
	30	700	1	57.2
H_2/air	38	2105	0.8	24.2
	38	2105	1	27.7
	38	2105	1.2	29.6
	30	1105	0.8	7.91
	30	1105	1	9.06
	30	1105	1.2	9.67
	30	700	0.8	5.01
	30	700	1	5.74
	30	700	1.2	6.13

center of the ball valve and these locations are listed in Table 2. Because the valve is opened manually, some uncertainties will be expected so that the experiment is repeated at least 10 times under each condition. The reproducibility for hydrogen cases is good and almost three experiments are sufficient to say that the deviation is within 1%. However for the other two gases, it is not as satisfactory because, as explained later, the combustion waves in the tube are deflagration waves for these gases, while that for hydrogen is a detonation wave. The deflagration waves may be influenced considerably by conditions before the wave and by that of the wall. Even after the ten experiments under the same conditions, the maximum deviation is as large as 10%, and more repetitions cannot reduce the deviation any further.

It is well known that the decay of the blast wave is governed by the initiation energy of the explosion. In the present experiments, the initiation source is combustion in a tube, so that the initiation energy can be estimated by the heat content of the mixture in the tube, which is defined here as the chemical heat release Q_{CJ} of the Chapman-Jouguet detonation wave or deflagration wave. Table 3 shows the values obtained by chemical equilibrium calculations. Then nominal initiation energy can be written as $1/4\pi d_d^2 L_d \rho_d Q_{CJ}$, where ρ_d denotes the initial density of the initiator combustible gas. If the initiated explosion wave is assumed to be a planar wave, the initiation energy should be evaluated as the energy per unit area. Then, the initiation energy is defined here as

$$E_0 \equiv \frac{1/4\pi d_d^2 L_d \rho_d Q_{CJ}}{1/4\pi d^2} = \frac{d_d^2 L_d \rho_d Q_{CJ}}{d^2}, \quad (1)$$

which has a dimension of energy per unit area (e.g., MJ/m^2). In Table 4, the thus-calculated initiation energies are listed under all investigated conditions. Due to human error in setting the experimental conditions, an error of 5% will exist in the initiation energy E_0.

3. Results and Discussions

3.1 Effects of confinement

Most of the present experiments were performed with the end of the air section closed. To investigate the effect of the closed end, some experiments were carried out with an open ended air section. Although the tube is long, it is not possible to ignore the effects of confinement. Figure 3 shows typical pressure traces for the cases of closed end (a) and open end (b). The abscissa denotes elapsed time from ignition and the ordinate denotes the overpressure from the initial pressure, which is shifted for each measuring position. The ticks for the pressure correspond to a 10 kPa increase. Figure 4 shows the decay of the non-dimensional peak overpressure along the tube axis. The abscissa denotes the distance from the center of the ball valve and the ordinate denotes the non-dimensional peak overpressure, which is defined by $(p_{max}-p_0)/p_0$, where p_{max} denotes the maximum peak pressure. The peak overpressure decays gradually along the tube. For the closed case, pressure waves generated by the reflection from the end plate are observed and the maximum pressure increases to become twice that of the open end case where the

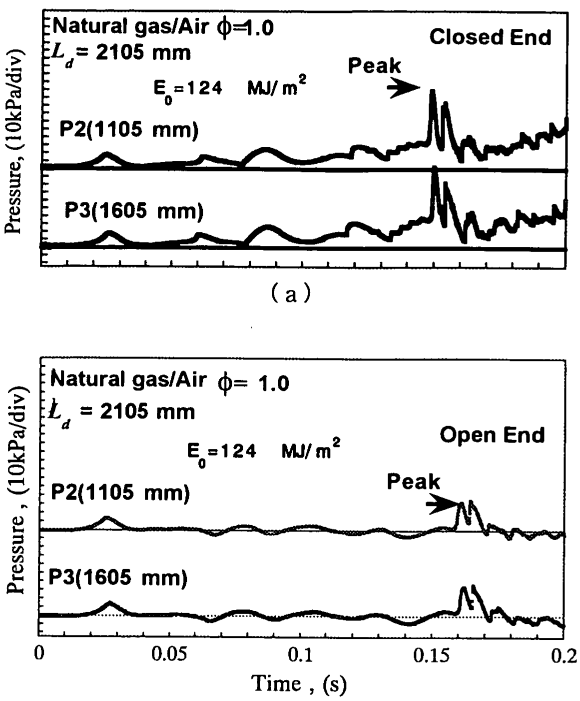

Fig. 3 Pressure records at P2 and P3 for natural gas/air (ϕ=1), and L_d=2 105 mm with (a) closed and (b) open ends

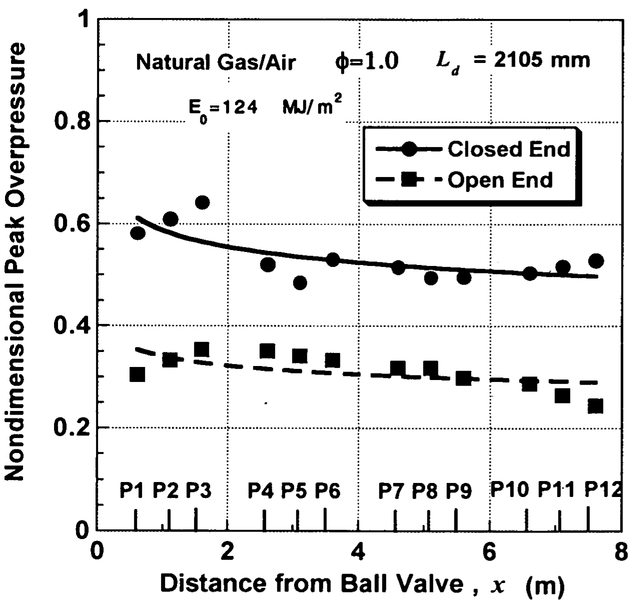

Fig. 4 Decay of maximum pressure along the tube for cases of closed end and open end

effects of expansion into the atmosphere reduce the peak overpressure.

Because of safety requirements, we were forced to conduct the experiments with the closed end condition. Therefore, in this study, it should be noted that the overpressure of the wave front includes the effects of the reflections from the end plate.

3. 2 Natural gas/air case

The combustion of natural gas/air mixture at atmospheric pressure usually occurs in the deflagration mode. A detonation of this mixture hardly occurs in the absence of a large amount of initiation energy. Figure 3 show pressure data obtained at the wall of P2 and P3. For both closed and open end cases, the first pressure peaks generated by flames are observed at 0.025 s or 0.028 s from the start of ignition. This wave is generated in the air by compression effects due to flame acceleration. The difference in arrival time should not be attributed to the end effects, rather, it might be due to differences in turbulent combustion processes in the initiator tube. After these waves, some waves reflected by the end of the air section occur. For the closed case, these reflected waves are compression waves, so that pressure level in the tube increases as a whole. For the open case, the average pressure level remains constant until a double peak pressure wave is observed at about 0.16 s with an overpressure of about 40 kPa. For the closed case, it was observed at about 0.15 s with the overpressure about 100 kPa for this experiment. Both waves are generated by the flame itself. Because the combustion waves are deflagration waves, pressure should not increase across the wave front in principle, while burned gas expands greatly due to high temperature. However, because the ignition end is closed for both cases, the burned gas cannot escape from it. This increases the pressure of the burned gas. This compression wave is transmitted from the combustion section into the air section, producing the maximum pressure peak of the wave system. The interaction of the pressure wave with a density discontinuity between the combustible gas and the air causes complex wave reflections resulting in such double peaks.

The effects of confinement are obviously shown by the 60 kPa (maximum) increase in the peak pressure due to the effect of the reflected pressure for the closed end case and of the expansion waves for the open end case. It should also include the effect of temperature increase due to adiabatic compression and expansion.

Figure 5 shows pressure traces at P4, P5 and P6. A maximum overpressure decays to about 50 kPa and the wave profile is complex at the front due to interactions of the waves at the ball valve section. In front of the wave with peak pressure, the pre-compression wave due to volume expansion of the burned gas exists. After the first peak, the second compression wave propagates from the end plate by reflection. The third one is flattened by complex interactions due to reflection and expansion from another end and/or the hot burned gas.

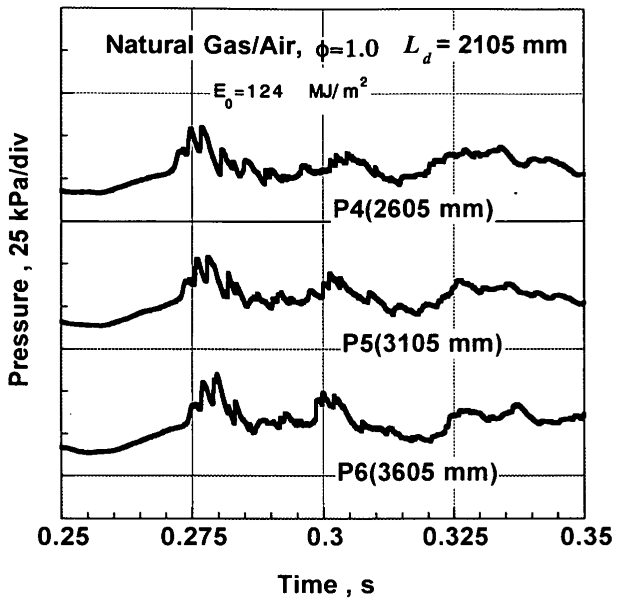

Fig. 5 Pressure records at P4, P5 and P6 for natural gas/air ($\phi=1$), and $L_d=2\,105$ mm with closed end

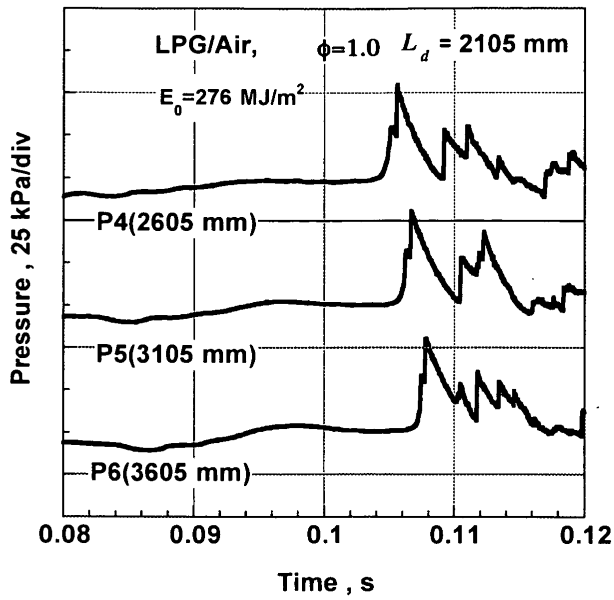

Fig. 7 Pressure records at P4, P5 and P6 for LPG/air ($\phi=1.0$), and $L_d=2\,105$ mm

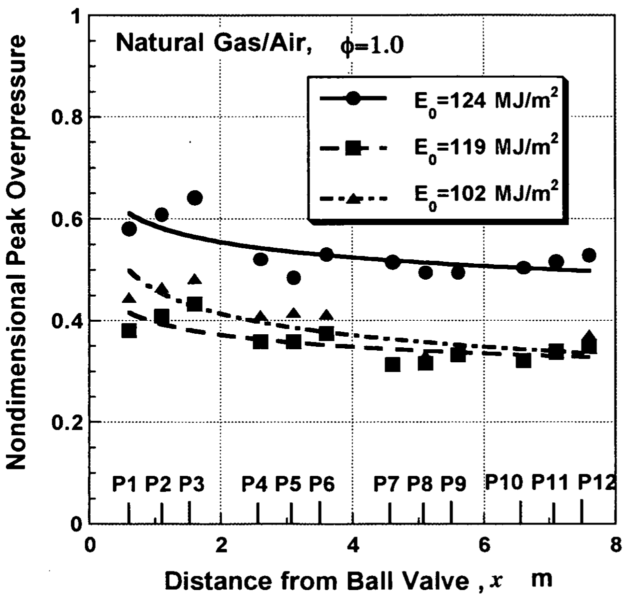

Fig. 6 Decay of maximum pressure along the tube for natural gas/air ($\phi=1$), $L_d=2\,105$, 1 105, 700 mm

Figure 6 shows variation of the maximum nondimensional overpressure $(p_{\max}-p_0)/p_0$ detected by the pressure transducers embedded along the tube at three different lengths of the combustion section. From P1 ($x=605$ mm) to P3 ($x=1\,605$ mm), the measured data of overpressure slightly increase for all three cases. In this region, the compression wave develops into shock-like waves. After this stage, the pressure decays with some oscillations. From P10 ($x=6\,605$ mm) to P12 ($x=7\,605$ mm), the overpressure increases slightly because it includes the effects of reflection from the end plate. For the longest combustion section ($L_d=2\,105$ mm), the highest overpressure is observed, while for $L_d=700$, and 1 105 mm, the overpressure is not proportional to the length. The initiation of these pressure waves is a very complicated phenomenon, and includes the effects of combustion as well as those of heat losses to the wall so that the initiation energy will not be exactly proportional to the chemical energy in the combustion section. This fact was pointed out previously by one of the authors[4] in a study of oxyhydrogen detonation initiators. If the combustion is in the deflagration mode, the effects will be enhanced due to a longer time required for the initiation.

The problem of decay of the explosion wave is idealized to be the blast wave problem[3] in which energy is released instantaneously from a point (3D), a line (2D) or a plane (1D). The decay of the blast wave depends on the initiation energy as well as the initial pressure and the isentropic index of the medium. However, in real explosions, the energy is released after some time from finite volume so that the whole energy cannot be effectively used to initiate the blast wave; therefore the resulting blast wave will be weaker in strength than the ideal explosion. Then, in the present experiments, it is expected that the shorter the combustion section is, the larger the efficiency for initiating the explosion wave will be. The word "efficiency" is defined here as the energy used to initiate the blast wave divided by the energy content in the initiator.

3.3 LPG/Air case

Figure 7 shows some examples of pressure profiles for LPG/air combustion at P4, P5 and P6.

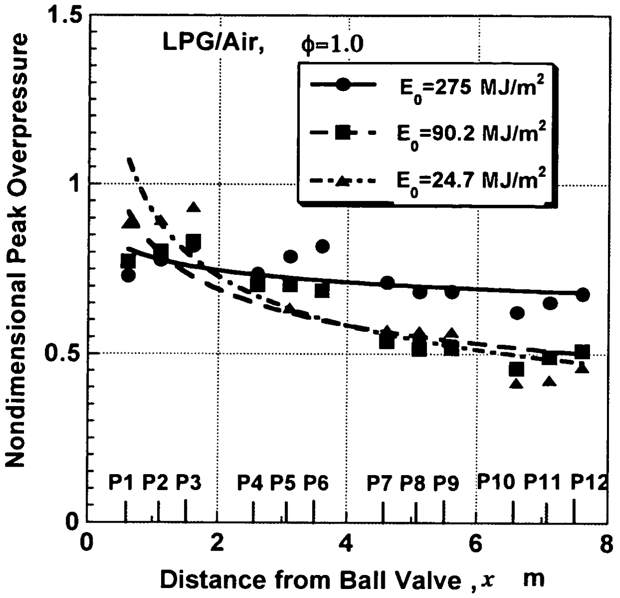

Fig. 8 Decay of maximum pressure along the tube for LPG/air (ϕ=1.0), L_d=2 105, 1 105, 700 mm

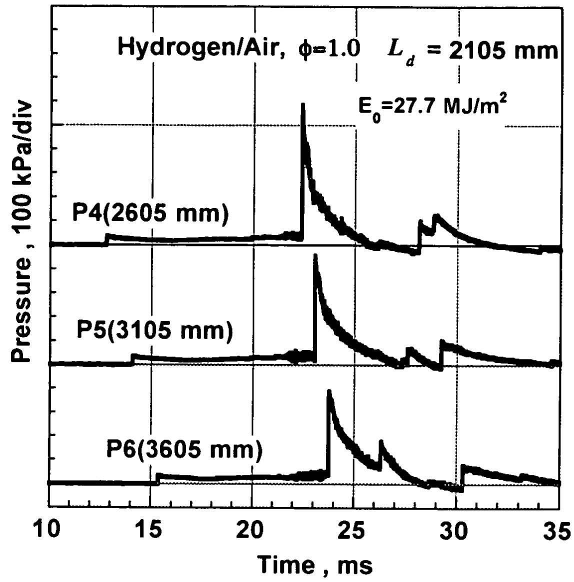

Fig. 9 Pressure records at P4, P5 and P6 for hydrogen/air (ϕ=1.0), and L_d=2 105 mm

The waveforms are essentially the same as the case of the natural gas at P2 and P3. The difference arises at P4, P5 and P6 in the steepness of the initial pressure rise because the flame in LPG/air propagates more rapidly than that in natural gas. These interactions of the combustion wave and the interface between the air and the mixture might cause several peaks in the wave front. The maximum pressures at each position are larger than those for natural gas under the same conditions. These findings should be attributed to the difference in chemical energy. However, the combustion wave in the initiator is still a deflagration wave so that the pre-compression wave affects the pressure. Figure 8 shows variation of the maximum overpressure divided by the initial pressure. Although the data are scattered, the pressures for LPG decay more rapidly than those for natural gas and the waves for the shorter combustion section decay more rapidly. As mentioned above, these findings indicate that the efficiency of initiation is high for the shorter combustion section.

3.4 Hydrogen/air case

This case is quite different from the previous two cases. Even in the shortest initiator with this mixture, the combustion waves develop into detonation-like waves. Figure 9 shows a typical example of the pressure profiles. At first, a shock wave propagates, preceding the main pressure wave. The overpressure of this preceding shock wave is about 30 kPa and the Mach number is about 1.12. The accelerating hydrogen/air flame in the combustion section creates pressure waves that accumulate to initiate this weak shock wave. For the other mixtures, it is only a

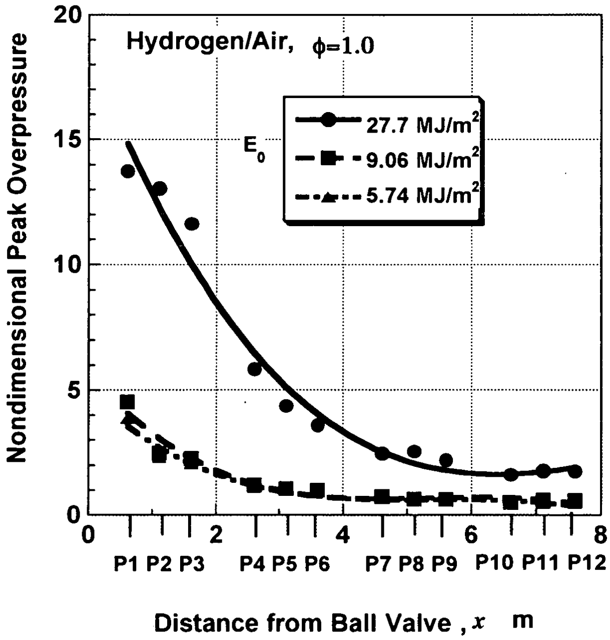

Fig. 10 Decay of maximum pressure along the tube for H_2/air (ϕ=1.0), L_d=2 105, 1 105, 700 mm

pressure wave with a gentle pressure rise because the acceleration is small. The shock pressure is maintained for about 10 ms until a strong blast wave is observed. The main blast wave has a steep wave front and a rarefaction wave behind it. Two weak shock waves are observed in the rarefaction wave. One is a retonation wave reflected from the ignition end (propagating downstream), and the other, which propagates upstream may be a reflection from a small cavity in the inner wall at tube-connecting flanges. These waves have a small influence on the main blast

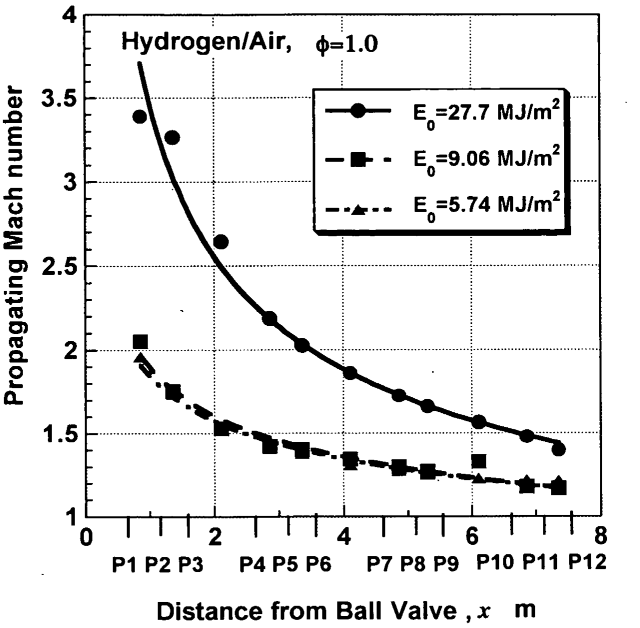

Fig. 11 Decay of propagating Mach number along the tube for H_2/air ($\phi=1.0$), $L_d=2\,105$, 1 105, 700 mm

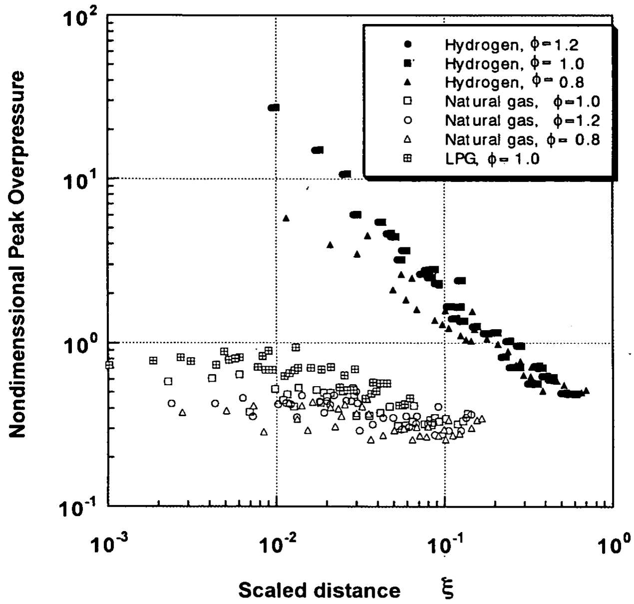

Fig. 12 Scaling of the decay processes with scaled distance

wave. Figure 10 shows the maximum overpressure along the tube wall. The wave decays rapidly from 15 to 2 of the nondimensional overpressure for $L_d=2\,105$ mm and from 5 to 1.5 for $L_d=1\,105$ mm and 700 mm. Figure 11 shows the decay of the propagating Mach number, which is defined as the propagating velocity divided by the initial acoustic speed. The tendencies are the same as those of the overpressure, as expected. It is interesting to note that the case for $L_d=2\,105$ mm shows a stronger blast wave than the other cases. Apparently, the strength is not proportional to the length of the combustion section. In this section, the transition from deflagration to detonation (DDT) process should occur. In the short combustion section of 700 or 1 105 mm, a well-established detonation wave is not obtained because the detonation induction distances for these mixtures are nearly 1 m. For the combustion section of 2 105 mm, it is certain that the Chapman-Jouguet detonation wave has been established. In addition, the diameter of these short tubes is 30 mm, which is smaller than that of the tube of 2 105 mm length. This is responsible for the difference in the initiation energy as well as the energy transforming efficiency, which is the ratio of available energy for initiating the blast wave to the chemical energy contained initially in the initiator section.

3.5 Scaling

In order to scale the decay of the pressure waves generated by the combustible gaseous mixtures described above, by using dimensional analysis (e.g., Ref.(3)), a nondimensional scaled distance[(3),(4)] ξ is defined based on the characteristic distance derived from the energy content in the initiator as

$$\xi\equiv\frac{2\gamma p_0}{E_0}x, \qquad (2)$$

where γ denotes the specific heat ratio of the air. The meaning of this scaling parameter is the ratio of the amount of internal energy of the air in the air section of length x to the chemical energy in the initiator of length L_d. The factor 2 in the numerator of Eq.(2) indicates that the blast wave propagates in a half space while the initiation energy acts in two directions. Figure 12 shows the nondimensional overpressure correlated with this non-dimensional scaled distance. For the hydrogen case, the decay rate is very high and can be predicted by the point (plane) source blast wave theory. Ohyagi et al.[(4),(5)] showed that the initiation energy of the planar blast wave could be estimated by using the quasi-similar solution of Oshima[(6)]. For the natural gas (NG) and the liquid petroleum gas (LPG) cases, they formed another group. The decay rates for these mixtures are very small and the data are considerably scattered. The data are correlated to fit an empirical formula with the power law as

$$\frac{p_{\max}-p_0}{p_0}=A\xi^{-n}=A\left(\frac{2\gamma p_0 x}{E_0}\right)^{-n}, \qquad (3)$$

where A and n are numerical parameters listed in Table 5 for each mixture. For hydrogen, the inverse exponent n is of order unity. For the equivalence ratio of 0.8, the exponent of about 0.65 is smaller than unity because the CJ detonation may not be formed completely in the initiator. For natural gas and LPG, the exponents are of order 0.1. The fifth column of Table 5 is for correlation coefficients r. For hydro-

Table 5 Estimated correlation parameters

	φ	A	n	r
NG/air	0.8	0.245	0.0917	0.522
	1.0	0.234	0.165	0.793
	1.2	0.260	0.104	0.594
LPG/air	1.0	0.322	0.164	0.715
H_2/air	0.8	0.341	0.647	0.960
	1.0	0.236	0.982	0.992
	1.2	0.221	0.982	0.992

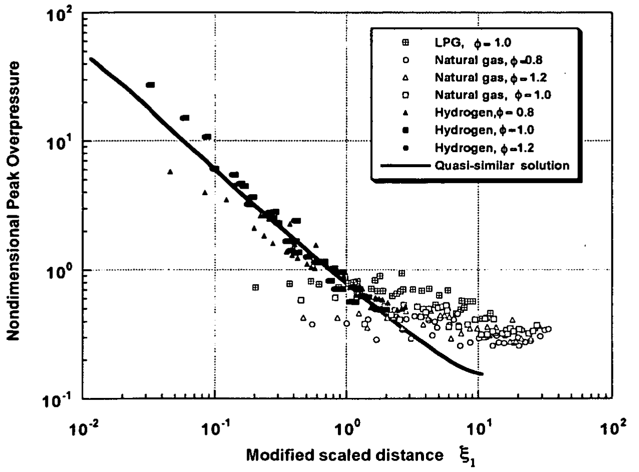

Fig. 13 Scaling of the decay processes with modified scaled distance

gen, the coefficients are near unity, which means that the correlation is good while for the other gases, they are smaller than unity, which means that the correlation of this formula (3) is poor. This poor correlation may be caused by the pre-compression wave mentioned above and also by the wall effects of the tube. These effects are marked in the case where the combustion wave is a deflagration wave.

Figure 13 shows a modified scaling with a modified scaled distance defined by

$$\xi_1 \equiv \frac{\xi}{\eta} = \frac{2\gamma p_0}{\eta E_0} x, \qquad (4)$$

where η denotes the energy transformation efficiency described in the previous section. This efficiency is a function of the properties of the combustible mixture as well as the configuration of the combustion section. Here, the blast wave data may be fitted by the quasi-similar solution. The quasi-similar solution is one of the approximate solutions for the blast wave problem, and was developed by Oshima[(6)]. The planar (one-dimensional) blast wave problem assumes that the energy is released instantaneously from the planar source, so it neglects the volume of the initiator as well as the time required to initiate the blast wave. For the hydrogen gas case, the combustion is performed fundamentally in the detonation mode so that most of the energy is released as short a time as 2 ms.

Table 6 Energy transformation efficiency of each condition

	φ	η
Natural gas/air	0.8	0.005
	1.0	0.005
	1.2	0.005
LPG/air	1.0	0.005
H_2/air	0.8	0.25
	1.0	0.3
	1.2	0.3

In Ref.(4), one of the authors measured this efficiency for the blast wave initiated by the oxyhydrogen detonation to obtain a value of about 0.3. For natural gas and LPG, the efficiencies are assumed to be 0.005, which means that a very small amount of energy is used to form the pressure wave. In these mixtures, a comparably long time (about 10 to 100 times the hydrogen case) is used for flame propagation in the combustion section, which will cause a considerable amount of energy loss to the tube. The efficiency values of used are listed in Table 6. With this modification, the data for all mixtures are correlated to be fitted to a single curve that is calculated using the quasi-similar solution, and are plotted in Fig. 13. Evidently, the data for natural gas and LPG are scattered and do not show good correlation with the hydrogen gas case, but they show a slight tendency, at least qualitatively. This curve shows that the decay rate of the overpressure should become small in a far field where the blast has decayed considerably. This tendency was verified by the point source blast wave theory solved by the quasi-similar hypothesis. For the hydrogen mixtures, the data correlate well fitting to the theoretical curve ; however, for the other two cases, the predicted overpressure is still smaller than the experimentally obtained values. Of course, this comparison with the point blast solution should be limited because it neglects the time and volume of the initiator. This should also be attributed to the effects of reflected pressure waves as well as to the fact that the waves are not purely shock waves but pressure waves with a gentle slope. The real situation is a non-ideal one. However, it should be noted that the simple analysis could predict fundamental phenomena.

4. Conclusions

Experiments were performed to elucidate the characteristics of pressure waves generated by flame or detonation waves in a tube. The data were correlated with the energy-based scaling law and the following conclusions were derived :

(1) For mixtures of natural gas or LPG with air, the pressure waves are formed due to the volume expansion of burnt gas as the deflagration wave is transmitted into the air section. For the mixture of hydrogen with air, the blast wave is generated by the detonation wave or the detonation-like wave in the initiator tube, which is preceded by a weak shock wave generated by the flame acceleration.

(2) The pressure waves generated by the deflagration waves decay negligibly and the data are scattered due to the existence of the pre-compression wave and/or the reflection waves. The blast waves caused by the detonation waves decay considerably due to the expansion waves emitted from the ignition end.

(3) Using the nondimensional scaled distance based on the energy content in the initiator correlates the overpressure data of the waves. The data are separated into two groups corresponding to detonation and deflagration. The data can be expressed by the inverse power law of which negative exponents are near unity for the detonation case and near 0.1 for the deflagration case.

(4) Introducing the energy transformation efficiency, which is a function of mixture properties and configurations, can correlate the two groups of the overpressure data. The efficiency for the deflagration group is smaller than that for the detonation group by an order of 1/100.

(5) The overpressure data of the two groups thus correlated can be expressed by a single curve that indicates that in the near field, the wave decays rapidly but in the far field, it decays very slowly. This agrees qualitatively with the decay characteristics predicted by the quasi-similar solution of the point source blast wave theory.

Acknowledgements

The authors express their sincere thanks to Messrs. Naoto Yoshida and Atsushi Kurashima who gave their greatest efforts to obtain the experimental data.

References

(1) Brossards, J., Leyer, J.C., Desbordes, D., Saint-Cloud, J.P., Hendrix, S., Garnier, J.L., Lannoy, A. and Perrot, J.L., Air Blast from Unconfined Gaseous Detonations, Dynamics of Shock Waves, Explosions and Detonations, edited by Bowen, J.R. et al., Progress in Astronautics and Aeronautics, Vol. 94 (1984), pp. 556-566, AIAA, New York.

(2) Brossards, J., Bailly, P., Desrosier, C. and Renard, J., Overpressures Imposed by a Blast Wave, Dynamics of Explosions, edited by Kuhl, A.L. et al., Progress in Astronautics and Aeronautics, Vol. 114 (1988), pp. 389-400, AIAA, New York.

(3) Sedov, L.I., Similarity and Dimensional Methods in Mechanics, (1959), Academic Press, New York.

(4) Ohyagi, S., Yoshihashi, T. and Harigaya, Y., A Study of Planar Blast Waves Initiated by Gaseous Detonations (Part 1) Estimation of Initiation Energy, Journal of Japan Society for Aeronautical and Space Sciences, (in Japanese), Vol. 33, No. 382 (1985), pp. 33-41.

(5) Ohyagi, S., Yoshihashi, T. and Harigaya, Y., Direct Initiation of Planar Detonation Waves in Methane/Oxygen/Nitrogen Mixtures, Explosions and Detonations, edited by Bowen, J.R. et al., Progress in Astronautics and Aeronautics, Vol. 94 (1984), pp. 3-22, AIAA, New York.

(6) Oshima, K., Blast Waves Produced by Exploding Wire, Rept. Aeronautical Research Institute, No. 358 (1960), pp. 137-194, University of Tokyo.