Title: Combustion Wave Propagation and Detonation Initiation in the Vicinity of Closed-Tube End Walls

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Abstract

There are not many studies on DDT with no obstacles and the initiation of DDT near the end of a closed tube. Therefore in the present study we experimentally investigate the mechanism of the combustion wave transition to a detonation wave when there are no obstacles. In particular, we show that a local explosion near the tube wall is necessary for the initiation of a detonation. Parameters that we varied are the wall configuration, distance between the ignition point and the wall, and initial filling pressure. The combustion waves and the compression waves are visualized using the Schlieren optical system. From the results, we found it is necessary for the combustion wave to reach four walls so that the detonation could be initiated by the local explosion. In the conditions of the present experiment, we exhibited that the local explosion did not occur in the vicinity of a single wall and four orthogonal walls; instead, the local explosion occurred in a situation with five orthogonal walls. The time of the local explosion and the detonation initiation is 2.6 ± 1.1 and 2.0 ± 0.1 times the characteristic time for the combustion wave to propagate hemispherically from an ignitor and reach the four walls.

（203 words）

Keywords

Detonation Wave, Detonation Initiation, Deflagration-to-Detonation Transition, Pulse Detonation Engine

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1. Introduction

In the typical DDT (Deflagration-to-Detonation-Transition) (J.H.S Lee [1-3], B.H.K. Lee and J.H.S. Lee [4], Urtiew and Tarver [5], Urtiew and Oppenheim [6], Kuznetsov et al [7, 8]) process, at first a laminar combustion wave which is not fully matured right after ignition transitions to a turbulent combustion wave as it propagates. After that, compression waves are formed in the propagating direction (ahead) by acceleration of the combustion wave and expansion of the burned gas. These compression waves accumulated to form shock waves ahead of the combustion wave. Local explosions occur in unburned gases compressed by the shock waves ahead of the combustion wave and in successful transitions that are finalized to a detonation wave. In the DDT process, obstacles are typically installed in the mixture for generating an accelerating turbulence for the laminar combustion wave. The interference between the combustion wave and shock waves as well as the DDT with obstacles have been studied (Chan et al. [9], Kumagai and Kimura [10], Gamezo et al. [11]). However, there are not many studies on the DDT with no obstacles and with the initiation of the DDT near the end of a closed tube (Leyer and Manson [12], Meyer et al. [13], Dorofeev et al. [14]). Obstacles cause high thrust losses may occur in the case of a DDT having a long length and heat losses in combustor applications such as a Pulse Detonation Engine (PDE) (Kailasanath [15, 16], Kasahara et al. [17-19], Sato et al. [20], Endo et al. [21, 22], Zitoun and Desbordes [23], Cooper [24]). Therefore, in the present study we experimentally investigate the mechanism whereby the combustion wave transitions to the detonation wave in which there are no obstacles.

Fig. 1 shows the generation mechanism of the initiation in the vicinity of closed-tube end walls. The combustion wave reaches each wall after ignition at the closed-tube end wall, as shown in Fig. 1 (a). The combustion wave has not reached the corner of the wall, and the premixed mixture is unburned in Fig. 1 (a), (b). At this time, the compression wave (the shock wave) propagates in both the same and opposite direction from that in which the combustion wave propagates. After this, the compressed unburned mixture in the corner ignites, and a local explosion occurs, as shown in Fig. 1 (c). The compression waves generated by the local explosion interfere with the combustion wave front ahead of the compression wave [Fig. 1 (c)]. This successful transition to a detonation is completed by the compression waves, which disturb the combustion wave front [Fig. 1 (d)]. These processes are different from a typical DDT process. The DDT process in our research showed a shorter run-up distance than the typical DDT. In the typical DDT process, compression or shock waves and their reflected waves from the closed end of the tube are usually observed just before the detonation initiation. In the typical DDT researches, Kuznetsov et al. [7, 8] focused on turbulent boundary layers and flame accelerations to estimate the run-up distance of such DDT. We focused on a detonation transition which occurred by interference between the compression wave generated from the local explosions and combustion wave pre-propagating in the vicinity of the closed end.

Using a high-speed video camera in this study, we conduct visualization experiments to investigate the local explosion under various wall conditions. In particular, we show that the local explosion near a tube wall is necessary for the detonation initiation shown in Fig. 1. The main parameters varied are the wall configuration, distance between the ignition point and the wall, and initial filling pressure. The combustion waves and the compression waves are visualized using the Schlieren optical system.

2. Experiment

Experimental Apparatus

Fig. 2 shows a schematic diagram of the experimental setup. It consists of an observation chamber, an evacuation chamber and an optical system. A couple of windows made with quartz glass with 10 mm thickness are installed in the observation chamber. A diaphragm (made with Polyethylene Terephthalate, 50 μm thickness) separates the observation chamber from the evacuation chamber, and the air within the evacuation chamber is evacuated. The observation chamber is filled with a premixed mixture, which is composed of a stoichiometric ethylene-oxygen or stoichiometric acetylene-oxygen mixture. The initial pressure of the premixed mixture is varied in the range of 40-70 kPa. The temperature is maintained at 299 ± 7 K. An automobile ignitor, ignites the mixture when it discharges accumulated electricity through a gap in the ignition source. The ignitor, the light source, and the high-speed video camera are synchronized by a signal from a pulse generator. The experimental conditions are shown in Table 1.

3. Results and Discussion

Closed-End Experiment

This experiment focusing on a detonation initiation at the closed-tube end was conducted as shown in Fig. 3. The left end of Fig. 3 is the closed-tube end of a rectangular cross section tube (observation chamber). The spark plug is fixed in the position shown in Fig. 3. The orthogonal linear axes (x, y, z) are placed with their origin at the position of the ignition spark, as shown in Fig. 3. This rectangular cross section is 50 mm-square. A stoiciometric ethylene-oxygen mixture was used in this experiment. The initial pressure is 60 kPa.

Fig. 3 shows images obtained from this experiment. Fig. 3 (a) is a pile-up image in a 32 μsec inter-frame time in the x direction of the vicinity of the closed-tube end ($0 \leqq x \leqq 17$ mm). Fig. 3 (b) is a pile-up image in a 32 μsec inter-frame time in the x direction of the downstream ($36 \leqq x \leqq 83$ mm). Though Fig. 3 (a) and Fig. 3 (b) are in the same condition, they are shot differently. The hemispherical combustion wave propagates from a place near the spark plug in Fig. 3 (a). The local explosion propagates obliquely on the wall, and a detonation wave initiated by the local explosion is confirmed. This detonation wave propagated from the upper left toward the right lower (503~519 μsec). Fig. 4 shows an x-t diagram of the combustion waves and the detonation wave shown in Fig. 3. The position of the combustion wave front on the x axis was plotted. In Fig. 4 the open symbols show the combustion wave, the open dot symbols show the combustion wave from the local explosion, and the closed symbols show the detonation waves. From Fig. 4, the speed of the detonation wave front along the x axis is 2990 m/sec, which is slightly higher than the C-J velocity of the mixture. This is a result of the over-driven state of the detonation wave or of a case where the propagation direction of the detonation wave is different from the x axis. Here $\bar{l}_{w1}$ is the average of the distances from the ignition point to the walls parallel to the x axis. It is considered that the detonation wave is initiated from the wall and propagates at the constant speed. Then from this figure the initiation time t_i is 498 ± 4 μsec from the point at the intersection of the solid line (detonation wave) with the broken line ($\bar{l}_{w1}$). At that time, the combustion wave is located at around 62 mm on the x axis, and it propagates in the z direction and reaches the upper wall and under wall ($z = 34$, -16 mm) [Fig. 1 (a)]. From the result of Fig. 4, we consider it is necessary for a portion of the combustion wave to reach the four walls at $y = \pm 25$ mm, $z = 34$, -16 mm so that the detonation can initiate in the closed-tube end, as shown in Fig. 1 (a) (There is no initiation of the detonation if the combustion wave does not reach the wall.) From Fig. 4 the initiation time $t_i = (2.0 \pm 0.1) t_{c1}$, where

the characteristic time is $t_{c1} = \bar{l}_{w1}/u$, and u is the velocity of the combustion wave from the static system.

Combustion Propagation in the Vicinity of Walls

Using the observation chamber with Configuration B as shown in Fig. 5, we observed whether the detonation wave is initiated only by the combustion wave reaching a single wall. The orthogonal linear axes (x, y, z) with their origin at the position of the ignition spark are placed as shown in Fig. 5. The wall, made with Polytetrafluoroethylene (PTFE), is put in the position of z_w=-2.25, -5.25, and -10.25 mm. The mixture used in this experiment is a stoichiometoric acetylene-oxygen mixture. The initial pressure is 70 kPa. Fig. 6 (a) shows the pressure histories of each experiment measured by a pressure sensor installed at the position of (x, y, z) = (0, 0, 25 mm). These pressure histories are smoothed by the method of a simple moving average which shows the average of a central value of around 1.2 μsec. Fig. 6 (b)-(d) is a pile-up image in a 16 μsec inter-frame time. The results in Fig. 6 (a) show that pressure increases are gradual and have almost no variation regardless of the wall distance. In the conditions of the present experiment, we exhibited that the local explosion does not occur in the vicinity of a single wall.

Next we plused the numbers of the walls and visualized the propagation process in the vicinity of the four orthogonal walls. Fig. 7 shows Configuration C of the observation chamber, in which the four orthogonal walls have a configuration with a pair of acrylic plates having a nip at the PTFE wall. The pair of acrylic plates are located at the fixed position of $y_w = \pm 10.25$ mm, and the PTFE wall is put in the position of (x_w, z_w) = (2.25, -2.25 mm), (5.25, -5.25 mm), (10.25, -10.25 mm). A stoichiometoric acetylene-oxygen mixture is used in this experiment. The initial pressure is 70 kPa. Fig. 8 (a) shows a pressure histories measured for each experiment. The pressure histories are smoothed by the simple moving average method in the same way as in Fig. 6 (a). Fig. 8 (b)-(d) is a pile-up image in a 16 μsec inter-frame time. The results in Fig. 8 (a) showed that the smaller the wall distance, the more rapid the pressure rises. In terms of the behavior of the combustion wave at the corner, a decrease in the propagation velocities is found. In this present experimental condition, we exhibited that the local explosion does not occur in the vicinity of the four orthogonal walls.

Finally, we visualized the propagation process in the vicinity of five orthogonal walls. Fig. 9 shows Configuration D of the observation chamber. A pair of acrylic plates are located at the fixed position of $y_w = \pm 10.25$ mm, with the PTFE wall put in the position of (x_w, z_w) = (2.25, $\pm$2.25 mm), (5.25, $\pm$5.25 mm), (10.25, $\pm$10.25 mm). A stoichiometoric acetylene-oxygen mixture is used in this experiment. The initial pressure is 40-70 kPa. Fig. 10 shows pictures shot in a 2 μsec inter-frame time and their diagrams. At the left below the pictures, the times from the ignition are shown. A small local explosion occurs in the closed end on the right in the picture at 76 μsec. After 78 μsec, it is found that the combustion wave from the local explosion (white arrowed line) has propagated in a negative direction (ahead) on the x axis at a slant to the wall clearly faster than the combustion wave which propagates ahead of the local explosion already. The position of the combustion wave front at 76 μsec is -19.5 mm when the local explosion occurs. This value is almost the same as the distance between the acrylic plates. From this reason, the local explosion occurred by a portion of the combustion wave reaching the wall. The characteristic time $t_{c2} = \bar{l}_{w2}/\bar{v}$, where $\bar{l}_{w2} = (y_w + z_w)/2$ is the average distance from the ignition point (the origin of the coordinates) to an acrylic plate (y_w) and to the PTFE wall (z_w). Here also $\bar{v}$ and t_e are the average propagation velocity of the combustion wave and the time, respectively, between the ignition time and the time of the local explosion. The ratio

t_e / t_{c2} plotted versus the wall distance is shown in Fig. 11; the result shows $t_e / t_{c2}=2.6\pm1.1$. This value is close to that in the closed-end experiment.

We compared our results with the result of the Test 16 in Reference 14 of Dorofeev et al. in which the combustion wave went into canyon which has 6.3 m×2.5 m of a cross-section area and 10.55 m of length and the detonation initiated there. The ratio between the characteristic time and the time from when the combustion wave went into canyon till when the detonation initiated was 6.5. This is a value of same order though is larger than the results in the present result ($t_i/ t_{c1} =2.0\pm0.1$ and $t_e / t_{c2}=2.6\pm1.1$). In all of our experiments and the experiments by Dorofeev et al. [14], detonation was not initiated before the combustion waves reached the side walls of the tube.

4. Conclusions

In this study, using a high-speed video camera, we conducted visualization experiments to investigate local explosions under various wall conditions. The initiation of detonation was conducted at the closed-tube end. From the result, we considered this necessary for the combustion wave to reach the four walls. (There is no initiation of detonation if the combustion wave does not reach the wall.) The initiation time is $t_i= (2.0\pm0.1)$ t_{c1}; in fact, the initiation time is 2.0 ± 0.1 times the time required for the combustion wave to reach the wall with the velocity it has immediately after ignition.

We observed whether the detonation initiates in the vicinity of the wall. In the experiments, a decrease of the propagation velocities in the wall corner is found. In the condition of the present experiment, we exhibited that the local explosion does not occur in the vicinity of a single wall and of four orthogonal walls. In the experiments with five orthogonal walls, the time of the local explosion is $t_e= (2.6\pm1.1)$ t_{c2}; in fact, the time of local explosion is 2.6 ± 1.1 times the time required for the combustion wave to reach the wall with its average velocity.

(2429 words)

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Figure Captions

Table 1. Experimental condition

Fig. 1. Detonation initiation by local explosion near a closed end.
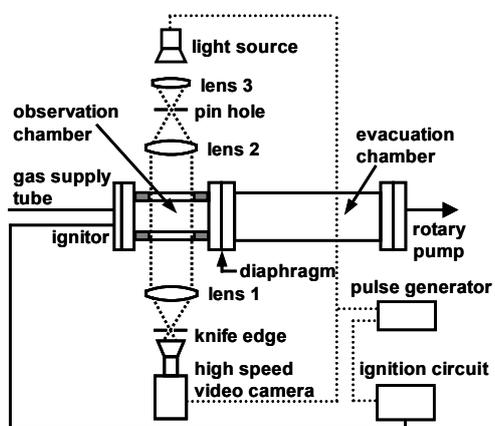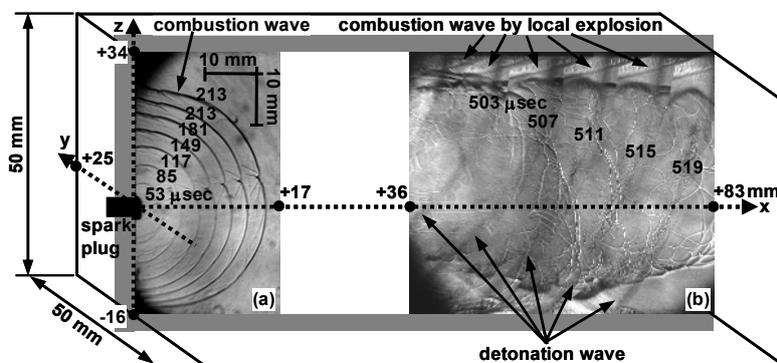
Fig. 2. Experimental setup

Fig. 3. Experimental results of Configuration A. $C_2H_4+3O_2$ mixture, initial pressure of 60 kPa, initial temperature of 294 ± 1 K, left - shot1 (32 msec/flame), right - shot2 (4 msec/flame).

Fig. 4. Trajectories of combustion wave front and detonation wave.

Fig. 5. Configuration B of the observation chamber.

Fig. 6. Experimental results of Configuration B (shot3-5). $C_2H_2+2.5O_2$ mixture, initial pressure of 70 kPa, initial temperature of 283 ± 0 K. Pressure history is shown in (a). Wall distances z_w are 2.25 mm (b), 5.25 mm (c), 10.25 mm (d).

Fig. 7. Configuration C of the observation chamber.

Fig. 8. Experimental results of Configuration C (shot6-8). $C_2H_2+2.5O_2$ mixture, initial pressure of 70 kPa, initial temperature of 282 ± 1 K. Pressure history is shown in (a). Wall distances z_w and x_w are 2.25 mm (b), 5.25 mm (c), 10.25 mm (d).

Fig. 9. Configuration D of the observation chamber.

Fig. 10. Shot16, explosion in closed end. $C_2H_2+2.5O_2$ mixture, initial pressure of 70 kPa, initial temperature of 285 K, wall distance of 5 mm.

Fig. 11. Experimental results of Configuration D (shot9-20). $C_2H_2+2.5O_2$ mixture, initial temperature of 284 ± 1 K. Wall distance versus t_e/t_{c2}.

Table 1

Experimental condition

(single column - 198 words)

shot number	observation chamber configuration	wall distance	mixture	initial pressure
		[mm]		[kPa]
1	A	50×50	$C_2H_4+3O_2$	60±1
2	A	50×50	$C_2H_4+3O_2$	60±1
3	B	2.25	$C_2H_2+2.5O_2$	70±1
4	B	5.25	$C_2H_2+2.5O_2$	70±1
5	B	10.25	$C_2H_2+2.5O_2$	70±1
6	C	2.25	$C_2H_2+2.5O_2$	70±1
7	C	5.25	$C_2H_2+2.5O_2$	70±1
8	C	10.25	$C_2H_2+2.5O_2$	70±1
9	D	3	$C_2H_2+2.5O_2$	40±1
10	D	3	$C_2H_2+2.5O_2$	50±1
11	D	3	$C_2H_2+2.5O_2$	60±1
12	D	3	$C_2H_2+2.5O_2$	70±1
13	D	5	$C_2H_2+2.5O_2$	40±1
14	D	5	$C_2H_2+2.5O_2$	50±1
15	D	5	$C_2H_2+2.5O_2$	60±1
16	D	5	$C_2H_2+2.5O_2$	70±1
17	D	10	$C_2H_2+2.5O_2$	40±1
18	D	10	$C_2H_2+2.5O_2$	50±1
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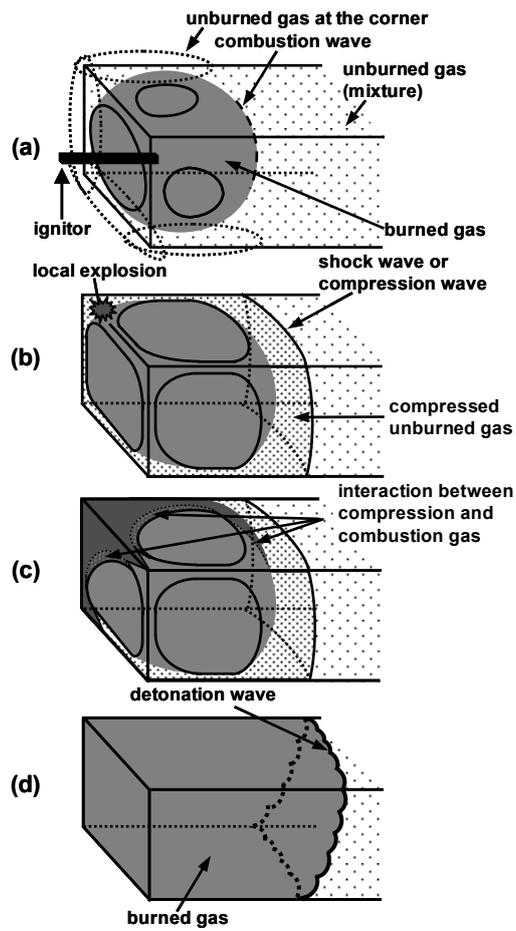
Fig. 1. Detonation initiation by local explosion near a closed end.

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Fig. 2. Experimental setup

(single column - 148 words)

Fig. 3. Experimental results of Configuration A.

$C_2H_4+3O_2$ mixture, initial pressure of 60 kPa,

initial temperature of 294 ± 1 K, left - shot1 (32 msec/flame),

right - shot2 (4 msec/flame).
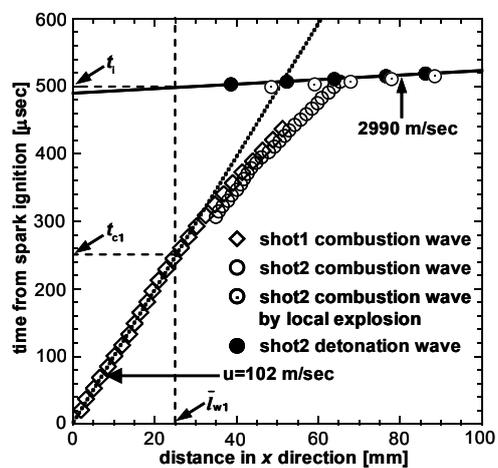
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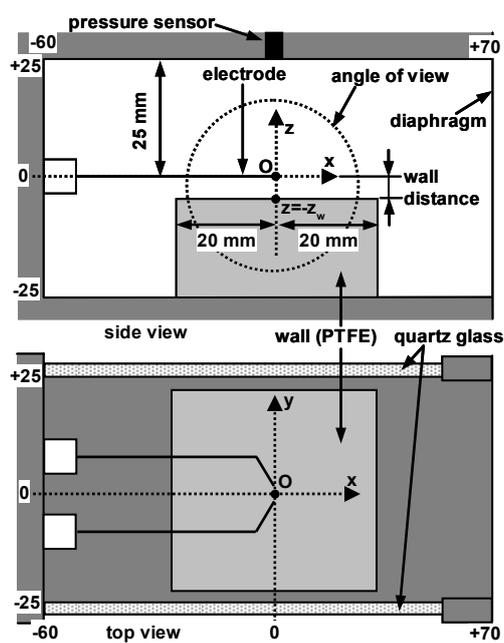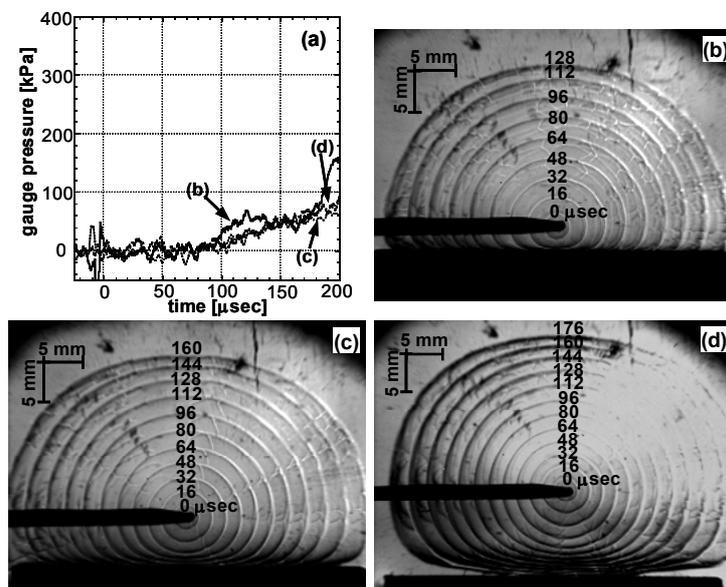Fig. 4. Trajectories of combustion wave front and detonation wave.

(single column - 167 words)

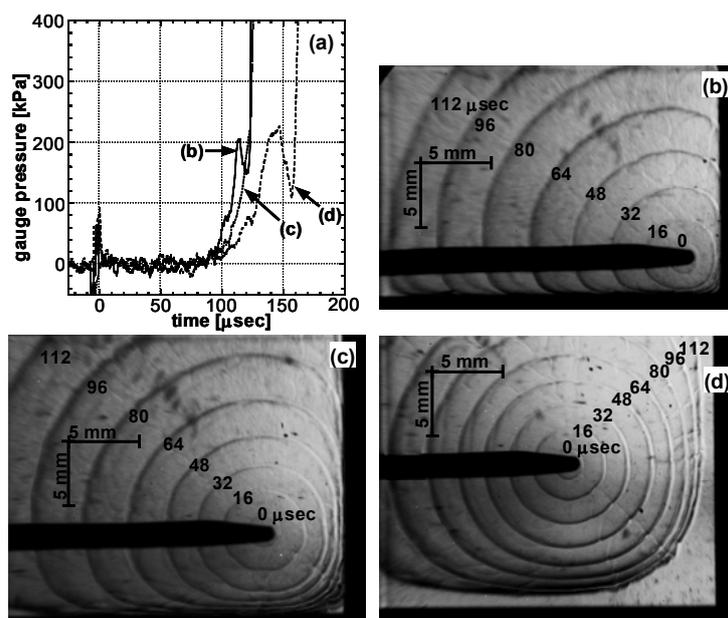Fig. 5. Configuration B of the observation chamber.

(single column - 215 words)

Fig. 6. Experimental results of Configuration B (shot3-5).$C_2H_2 + 2.5O_2$ mixture, initial pressure of 70 kPa, initial temperature of 283 ± 0 K. Pressure history is shown in (a).Wall distances z_w are 2.25 mm (b), 5.25 mm (c), 10.25 mm (d).

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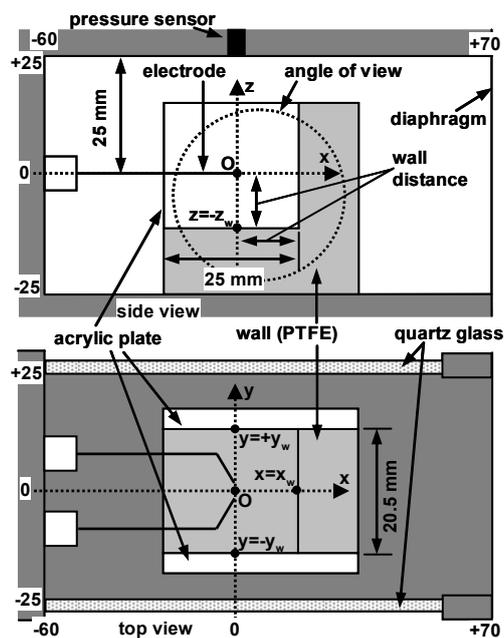
Fig. 7. Configuration C of the observation chamber.

(single column - 215 words)

Fig. 8. Experimental results of Configuration C (shot6-8). $C_2H_2+2.5O_2$ mixture, initial pressure of 70 kPa, initial temperature of 282 ± 1 K. Pressure history is shown in (a). Wall distances z_w and x_w are 2.25 mm (b), 5.25 mm (c), 10.25 mm (d).
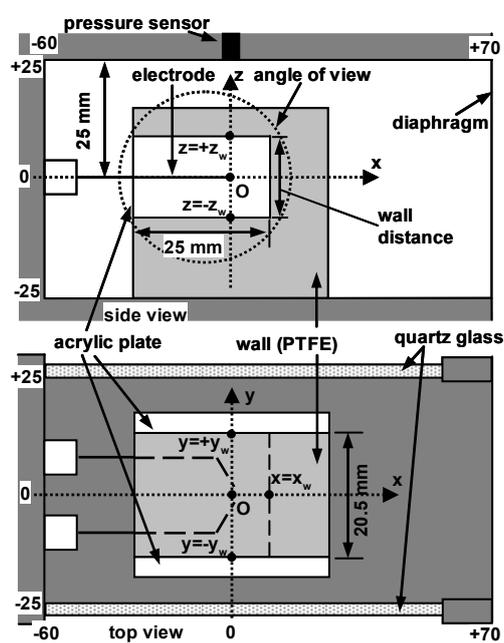
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Fig. 9. Configuration D of the observation chamber.
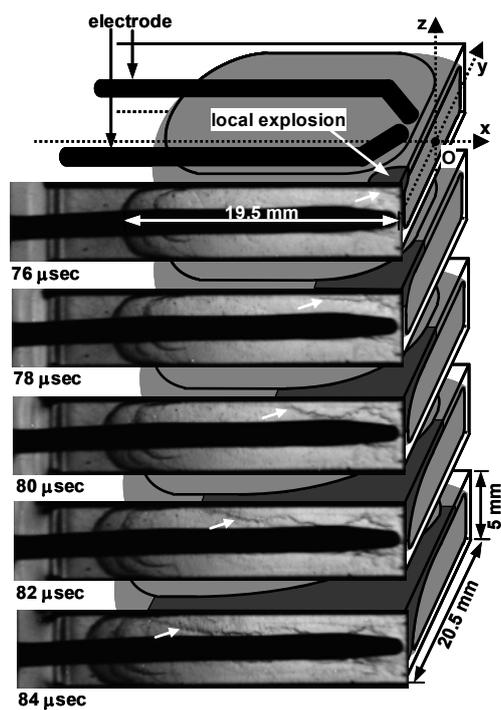
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Fig. 10. Shot16, explosion in closed end.
$C_2H_2+2.5O_2$ mixture, initial pressure of 70 kPa,
initial temperature of 285 K, wall distance of 5 mm.
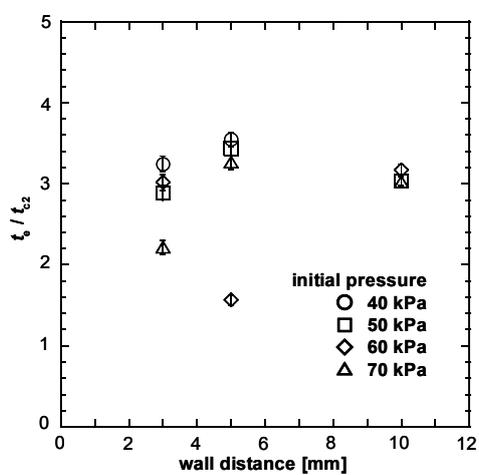(single column - 252 words)

Fig. 11. Experimental result of Configuration D (shot9-20).

$C_2H_2+2.5O_2$ mixture, initial temperature of 284 ± 1 K.

Wall distance versus t_e/t_{c2}.

(single column - 180 words)