

Behavior of Imploding Detonation Waves in A Cylindrical Chamber

K. Ishii, H. Ueo
Yokohama National University
Yokohama, Kanagawa-ken, Japan

1 Introduction

It is well known that by converging gas-phase detonation to a single point, a high-temperature and high-pressure condition can be obtained at the center of convergence. Terao et al. converged detonation using a cylindrical or semi-spherical chamber and reported that the pressure at the implosion center reached 10,000 times the initial pressure [1-4]. Because conventional pressure transducers fixed at the imploding center were severely damaged owing to extremely high pressure, Ishii et al. adopted a piezofilm stress gauge to measure the implosion center pressure through a metal rod [5]. Gelfand et al. studied the initiation of detonation by shock focusing using a semi-cylindrical or a parabola reflector set at the end of a shock tube [6]. Recently asymmetry of imploding detonation was experimentally studied using a thin cylindrical chamber equipped with a device controlling the degree of symmetry of the converging detonation wave [7].

Although a spherical imploding detonation wave, which converges in three dimensions, is ideal to achieve the highest pressure, it is difficult to provide a spherical detonation surface propagating toward the center. An alternative way is simultaneous injection of detonation waves at multiple points from outside of the spherical chamber. In this case, there arises the critical diameter issue of whether the propagation is maintained or not when a detonation wave propagating through a tube is released into unconfined space [8]. The success or failure of the propagation is governed by the ratio of the tube diameter to the cell size, which is a characteristic length of detonation. To form cylindrical converging detonations without introducing gaseous detonation through holes, condensed-phase explosives placed around the outer periphery of the chamber were adopted to cause direct multipoint initiation [9, 10]. This method avoids the critical diameter problem and makes it theoretically possible to generate a spherical detonation front by covering the whole chamber surface with explosives. However, the experimental setup becomes complicated and needs a longer time for preparation for the simultaneous explosion of all the explosives.

In the present work, detonation waves were injected from eight points around the periphery of a cylindrical implosion chamber and the detonation implosion process was experimentally studied for various initial pressures to study the effects of the success or failure of propagation in guiding the detonation wave to the chamber on the implosion manner.

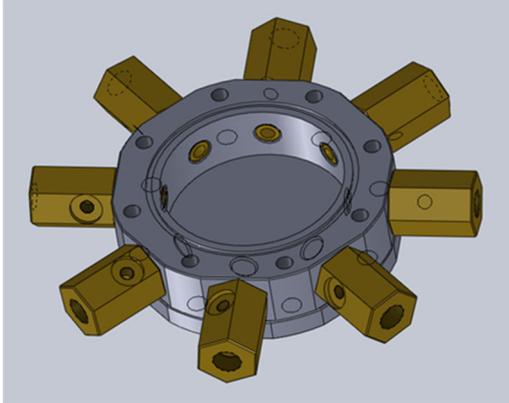


Figure 1: Schematic of imploding detonation chamber.

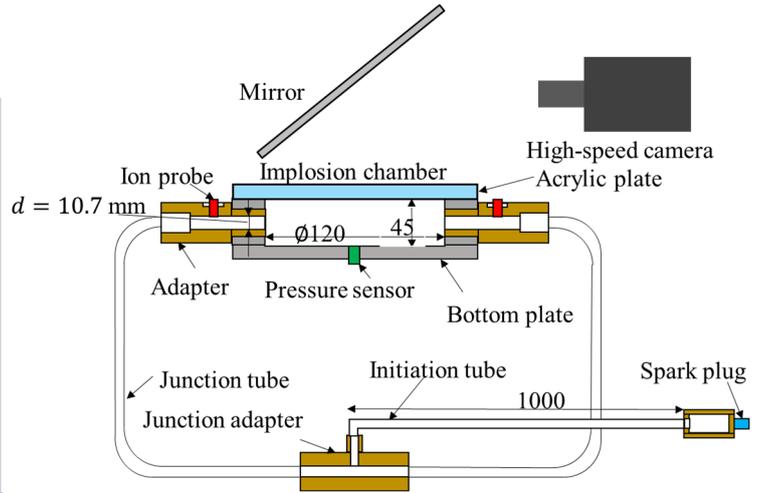


Figure 2: Experimental setup.

2 Experimental Apparatus

The imploding detonation chamber used in the present experiment was cylindrical as shown in Fig. 1, with an inner diameter of 120 mm and a height of 45 mm. Eight adapters for detonation injection, with a hole diameter of 10.7 mm, were fixed to the chamber periphery. A schematic of the experimental setup is shown in Fig. 2. A spark plug for automobile use was placed at the end of the 1000 mm long detonation initiation tube filled with a combustible mixture. A transition from deflagration to detonation occurred in the initiation tube and then the generated detonation wave was branched in eight directions by the junction adapter connecting to the implosion chamber. The eight junction tubes to the imploding chamber had the same length, ensuring simultaneity of the detonation injection. Ion probes were placed on the injection adapter to detect the arrival of the detonation waves for confirmation of their simultaneity at the eight locations. A conventional pressure transducer (Kistler 6229A) was installed at the center of the bottom plate of the implosion chamber and the whole implosion process was recorded by a high-speed camera through an acrylic top plate.

The test gas was a stoichiometric ethylene-oxygen mixture with an initial temperature of 295 K and an initial pressure P_0 varying from 30 kPa to 100 kPa. The frame speed of the high-speed camera was set to 3×10^5 fps or 7×10^5 fps and the exposure time was 0.6 μ s.

3 Results and Discussion

The convergence process of the imploding detonation for two different initial pressures is shown in Fig. 3. The view field of the high-speed camera was 130 mm (W) x 20 mm (H), with the center of the view field being the geometric center of the chamber. The self-emission from the burned gas in Fig. 3 (a) is too weak to detect the combustion wave front at $t = 1090.0 \mu$ s as compared to Fig. 3(b). This indicates that the injected detonation failed to propagate, resulting in decoupling the detonation wave into a shock and reaction front. Weak self-emission from the deflagration front was hardly recorded by the high-speed camera. However, a strong emission can be observed at the chamber center at $t = 1093.3 \mu$ s, indicating initiation of a cylindrical divergent detonation, which is generated by convergence of the decoupled shock waves. In addition, there are also emissions at the outer periphery of the chamber at t

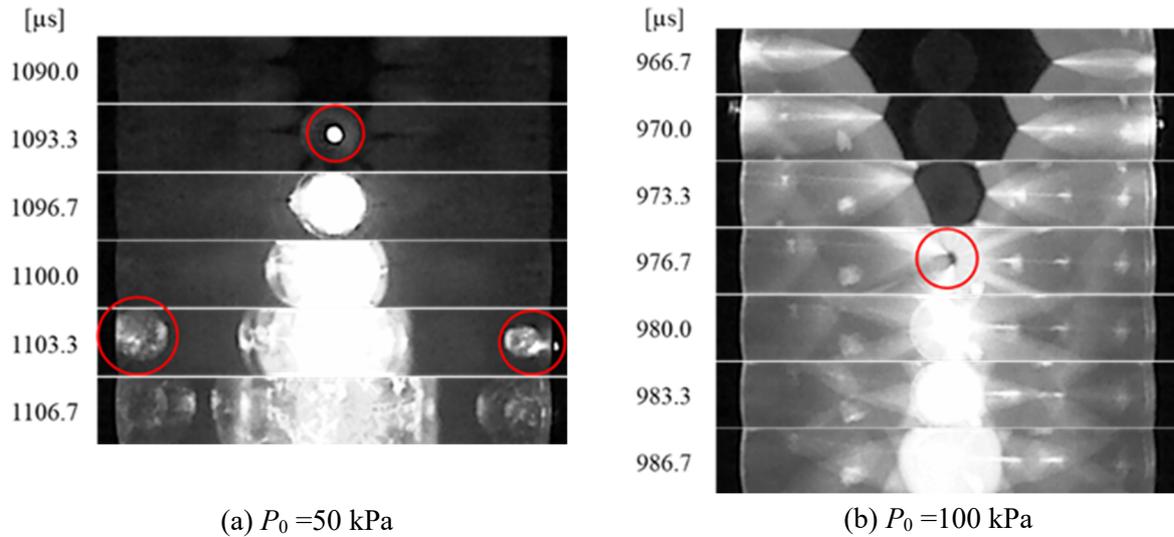
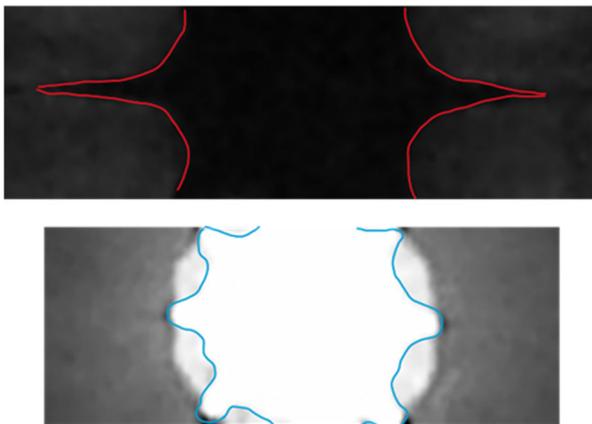


Figure 3: Self-emission images in the wave converging process.

Figure 4: Enlarged images around explosion at the implosion center for $P_0 = 50$ kPa. The red line in the upper image indicates a deflagration front. The blue line in the lower image corresponds to a front with strong emission intensity.Figure 5: Soot track record on the bottom plate for $P_0 = 30$ kPa.

= 1103.3 μs , which is due to explosions of unburnt mixture pockets that have not been burnt by the deflagration.

In Fig. 3(b) for $P_0 = 100$ kPa, the detonation is successfully propagating into the implosion chamber and is accompanied by emission on the wavefront and behind it. From the image at $t = 976.7$ μs , which is just before the convergence, it can be seen that the detonation is converged near the chamber center, although it is not perfectly symmetrical. There is no explosion of the unburnt gas pocket as seen in Fig. 3(a), indicating that the convergence manner varies greatly depending on the initial pressure.

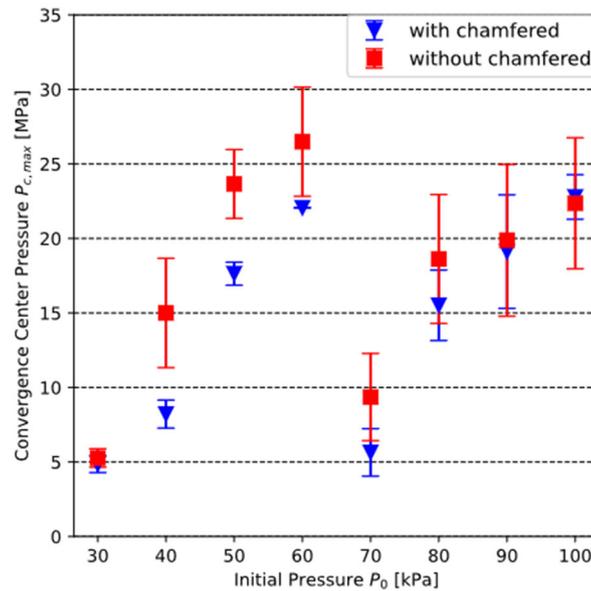


Figure 6: Maximum pressure at the implosion chamber center.

A magnified view of the self-emission image before and after convergence for $P_0 = 50$ kPa is shown in Fig. 4. As mentioned above, the self-emission from the burned gas before convergence is weak and the wavefront is concave to the propagation direction, as indicated by the red line. After convergence, there is strong emission at the chamber center, and the wavefront with particularly strong emission has a star shape with eight legs, as shown in the lower image of Fig. 4. Such a kind of convergence corresponds to the soot track record shown in Fig. 5, where the soot is stripped in an octagonal shape surrounding a star shape with eight legs. By analogy with this smoked record, the injected detonation is decoupled into a shock and a reaction front, with the shock front converging first at the chamber center. A high-temperature and high-pressure condition is then formed by the shock focusing, resulting in direct initiation of detonation. The detonation generated at the chamber center then propagates radially outwards while consuming the unburnt parts and is expected to collide with the deflagration wave at the octagonal position in Fig. 5. Although the smoked track record for $P_0 = 100$ kPa is not shown here, the soot was uniformly removed and no characteristic pattern without fine cellular structure was observed.

Figure 6 shows the maximum pressure measured at the chamber center. For $P_0 = 30$ kPa to 60 kPa, the chamber center pressure increases with the initial pressure, however, at $P_0 = 70$ kPa it is significantly reduced by about one-third compared to $P_0 = 60$ kPa. The chamber center pressure at $P_0 = 100$ kPa does not reach that for $P_0 = 60$ kPa, although it increases with the increase in the initial pressure for $P_0 = 70$ kPa to 100 kPa.

This two-stage increase in the chamber center pressure associated with the initial pressure increase is due to the success or failure of propagation of the detonation injected into the implosion chamber. The case for $P_0 = 30$ kPa to 60 kPa corresponds to the failure of detonation propagation as shown in Fig. 5. In this case, the shock wave decoupled from the detonation front acts as a kind of leading shock wave to pre-compress the unburnt gas. Because the detonation at the chamber center is caused in an elevated initial pressure by shock focusing, the generated pressure is much higher than the case for the detonation implosion with successful propagation in the chamber.

In Fig. 6, the plots with chamfered, which denote the results when the pressure transducer holder is chamfered, the chamber center pressure is lower than the case without chamfered. This is because the shock or detonation wave front is disturbed by concavity caused by the chamfer. Note that Figs. 3 to 5 are all results for the without chamfered.

4 Summary

The convergence of gaseous detonation was experimentally studied using a cylindrical chamber. The results show that at low initial pressures, the maximum pressure at the chamber center was higher than at high initial pressures for which the injected detonation successfully propagates, although the propagation of the injected detonation fails, resulting in the decoupling of the detonation front into a shock and reaction front. This decoupled shock wave converges, causing direct initiation of detonation at the chamber center in an elevated pressure, which is due to pre-compression of the unburnt gas by the shock focusing. The present results suggest that higher pressure can be obtained by intentional failure of detonation propagation than by successful propagation.

References

- [1] Terao K. (1983) Experimental study on cylindrical and spherical implosions. *Jpn. J. Appl. Phys.* 22: 446.
- [2] Terao K. (1984) Temperatures in imploding detonation waves. *Jpn. J. Appl. Phys.* 23: 27.
- [3] Terao K, Wagner HG. (1991) Experimental study on spherically imploding detonation waves. *Shock Waves* 1: 27.
- [4] Terao K, Akaba H, Shiraishi H. (1995) Spherically imploding detonation waves initiated by two-step divergent detonation. *Shock Waves* 4: 187.
- [5] Ishii K, Tsuboi T, Takada H, Torikai Y, Nishizuka S. (1998) Direct Pressure Measurement of Imploding Detonation Waves. *Rev. High Pressure Sci. Technol.* 7: 903.
- [6] Gelfand BE, Khomik SV, Bartenev AM, Medvedev SP, Grönig H, Olivier H. (2000) Detonation and deflagration initiation at the focusing of shock waves in combustible gaseous mixture. *Shock Waves* 10: 187.
- [7] Rodriguez RS, Loiseau J, Higgins AJ. (2024) Asymmetry of imploding detonations in thin channels. *Shock Waves* 34: 413.
- [8] Knystautas R, Lee JH, Guirao CM. (1982) The critical tube diameter for detonation failure in hydrocarbon-air mixtures. *Combust. Flame* 48: 63.
- [9] Dudin SV, Sosikov VA, Torunov SI. Experimental investigation of cylindrical detonation wave. (2016) *J. Phys. Conf. Ser.*: 774 012074.
- [10] Sosikov VA, Torunov SI, Dudin SV. (2019) Smoothing the front of the detonation wave in experiments with multipoint initiation. *J. Phys. Conf. Ser.*: 1147 012027.