Visualization of Detonation Initiation by a Spherical Projectile Launched into The Soap Bubble Filled with a Combustible Mixture

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1 Introduction

When a projectile enters a combustible mixture at hypersonic speed, the shock wave formed around the projectile adiabatically compresses the combustible mixture, induces combustion, and the combustion wave is sustained around the projectile. This phenomenon is called shock-induced combustion. Detonation waves can be initiated by the projectile if the reactivity of the mixture is sufficiently high in response to the energy input to the mixture by the projectile. Furthermore, if the speed of the projectile exceeds the Chapman-Jouguet (C-J) detonation velocity, oblique detonation waves are formed, in which the detonation initiated directly by the projectile is sustained around the projectile. These combustion phenomena have been proposed for application to the combustion process of future hypersonic propulsion systems, which are called as shock-induced combustion ramjet [1] and oblique detonation engine [2]. While these applications are the final engineering goal, there have been many fundamental studies focusing on the interesting feature that various combustion modes can be observed despite the very simple configuration of launching the spherical projectile into the combustible mixture. Shock-induced combustion with oscillation of the reaction front has attracted attention in the past [3-7], and studies have been conducted on direct initiation of detonation [8-10] and stabilization of oblique detonation [11-14] by the projectiles. In many studies, single-frame or multi-frame visualization of the combustion regimes have been made, but there are few optical observations of the detonation initiation process by the projectile. Although detailed experimental studies [8] conducted on the direct initiation of detonation by the spherical projectile under conditions where the projectile Mach number was lower than the C-J detonation Mach number, detailed information on the initiation process was not available because the detonation initiation was detected only by the pressure measurements. In general, in the direct initiation of detonation, the strong blast wave exceeding the C-J detonation Mach number is generated in a combustible mixture using a powerful energy source, and coupling between the shock wave and the reaction front with cellular instability develops as the blast wave decays to the C-J detonation Mach number [15]. On the other hand, it is interesting to see how the detonation occurs when the projectile Mach number (i.e., the shock wave Mach number formed around the projectile) is lower than the C-J detonation Mach number. However, it is difficult to observe the initiation process under such conditions because the initiated detonation propagates quickly overtaking the projectile.

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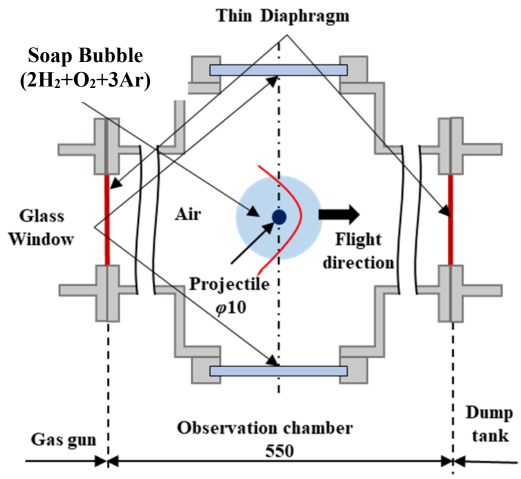
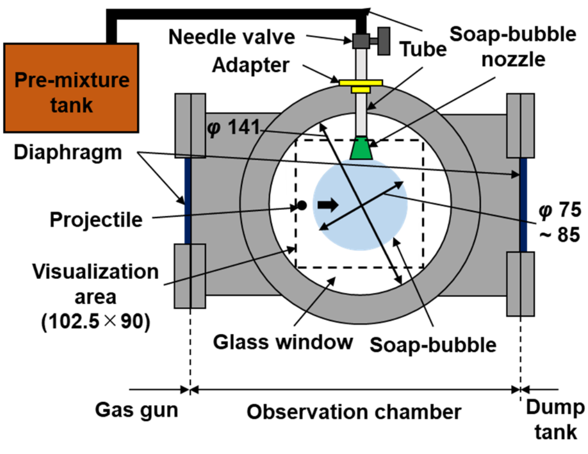
Therefore, we attempted the technique to place the soap bubble filled with the combustible mixture in the visualization area and launching the spherical projectile into the soap bubble. In this study, we visualized the initiation process of detonation by the projectile and discussed the critical condition for the initiation.

2 Experimental apparatus and conditions

Figure 1 shows a schematic of the experimental apparatus. It consisted of the high-speed gas gun and the observation chamber connected to the gas gun, which had optical windows for visualizing the combustion regimes around the projectile. As shown in Fig. 1 (a), the spherical projectile was launched by the gas gun into the soap bubble filled with the combustible mixture, which was created in the observation chamber. As shown in Fig. 1 (b), the tank filled with the combustible mixture was connected to the top of the observation chamber through the gas piping and the needle valve, and the end of the tubing was connected to the soap bubble nozzle for commercial use, which was inserted inside the observation chamber. After the tip of the soap bubble nozzle was dipped in the soap bubble solution, the needle valve was slowly opened to generate soap bubbles filled with the combustible mixture. The size of the soap bubble was set to be approximately 75 mm to 85 mm in diameter to place within the field of view of the optical system, which consisted of the high-speed camera (nac Image Technology Inc., ULTRA Cam HS-106E) and shadowgraph optical system. The size of the field of view was about 103 mm high and 90 mm wide, in which the soap bubble was approximately placed in the center. To minimize the possibility of the soap bubbles breaking before the launching projectile, we launched the projectile as soon as possible, around 20 seconds, after the filling of the combustible mixture in the soap bubble. The combustible mixture was $2H_2 + O_2 + 3Ar$ mixture, and the initial pressure inside the soap bubble was varied from 50 kPa to 120 kPa, which was equal to the pressure of surrounding air in the observation chamber. The projectile was the 4.76 mm or 10 mm diameter sphere and was launched at the velocity in the range of 920~2700 m/s.



(a) Top view



(b) Side view

Figure 1: Schematic of experimental setup (unit of length: mm).

3 Results and discussion

Typical shadowgraph images of the combustion regimes observed in this study are shown in Fig. 2. For clearly showing the combustion regime, each image was processed in the background to eliminate the soap bubble and the soap bubble nozzle. Careful observation of each image allows us to faintly see the circular outline of the soap bubble and the soap bubble nozzle above it. Figure 2 (a) shows the shock-induced combustion, in which the reaction front was accompanied by the oscillational instability. The oscillational instability is known to occur under conditions in the vicinity of the critical condition for detonation initiation. Figure 2 (b) shows the conditions under which the detonation initiation was observed, especially when the projectile Mach number was lower than the C-J detonation Mach number (about 5.1 for the mixture used in this study). Figure 2 (c) is another condition in which the detonation was initiated by the projectile, but the projectile Mach number was higher than the C-J detonation Mach number, so the oblique detonation wave was sustained around the projectile.

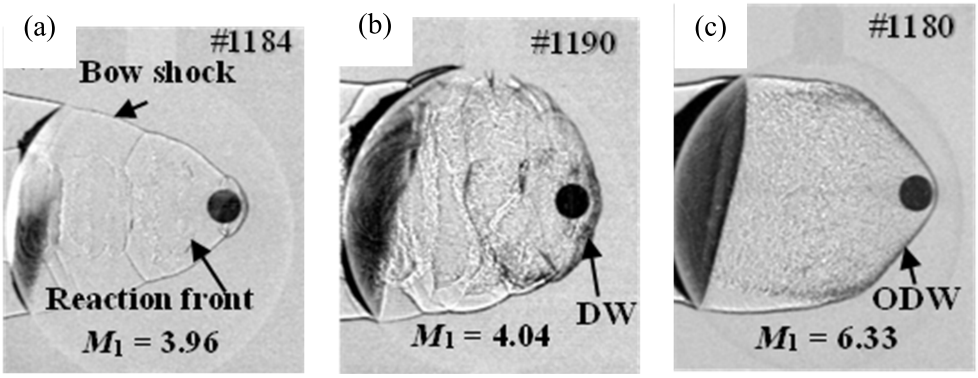


Figure 2: Observed combustion regimes; (a) Shock-induced combustion, (b) Detonation initiation, (c) Oblique detonation wave (M_1: projectile Mach number, projectile diameter: 10 mm)

In this study, the experiments using the soap bubbles enabled to give the optical observation of the detonation initiation process from the instant when the projectile entered the combustible mixture in the soap bubble, and the characteristic initiation process was observed. Figure 3 shows the time sequential pictures of the detonation initiation process in Fig. 2 (b). The time of each image is the elapsed time when the projectile entered the soap bubble. The reaction front formed behind the projectile originally showed the characteristic of the large disturbance regime (LDR) [4], in which the large amplitude oscillations of the reaction front occur with the longer period than the ignition delay time behind the shock wave. In the front of the projectile, the multiple detonation initiations occurred at the positions indicated by (1) and (2) at 18 μs and 26 μs, respectively, in accordance with the oscillatory instability of the reaction front. The detonation waves generated by these initiations eventually develop around the projectile (Fig. 2 (b) was taken a little later than 26 μs in Fig. 3), and the detonation wave spread into the combustible mixture. The numerical simulation by Matsuo and Fujii [6] suggested that the detonation can be generated locally in front of the projectile in the LDR. The results of this study indicates that under conditions where the projectile Mach number is lower than the C-J detonation Mach number, these locally initiated detonations can develop into the self-sustained detonation that spreads throughout the combustible mixture.

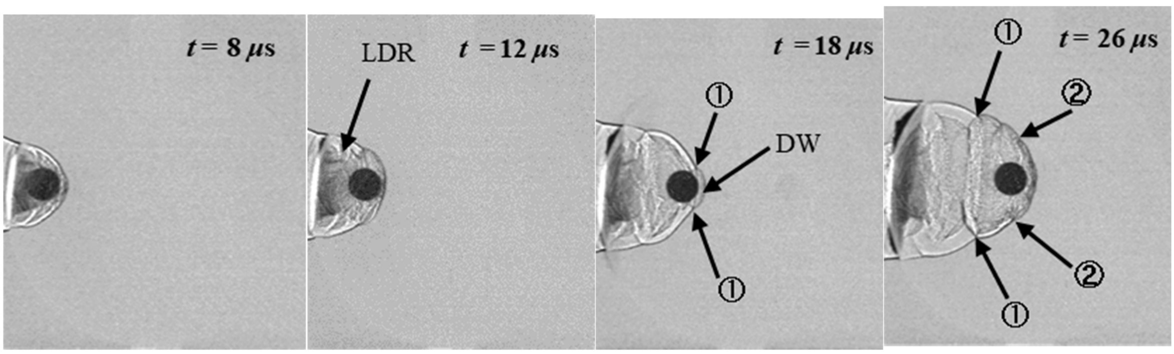


Figure 3: Time sequential shadowgraph pictures of the detonation initiation regime in Fig. 2 (b).

On the other hand, Fig. 4 shows the time sequential pictures of the development process of oblique detonation in Fig. 2 (c). Since the projectile Mach number was sufficiently higher than the C-J detonation Mach number, the overdriven detonation was initiated directly to the front of the projectile at the instant the projectile entered the combustible mixture. As this overdriven detonation developed outward from the projectile, it lost the support of the projectile body and eventually decayed into the C-J detonation under the influence of expansion wave, forming the oblique detonation. The area of oblique detonation was observed to expand with the propagation of oblique detonation wave from 8 μs to 34 μs in Fig. 4. This result was very similar to that observed by Maeda et al. [11], when they observed the initiation process immediately after the spherical projectile broke through the thin PET diaphragm and entered the combustible mixture filled in the observation chamber.

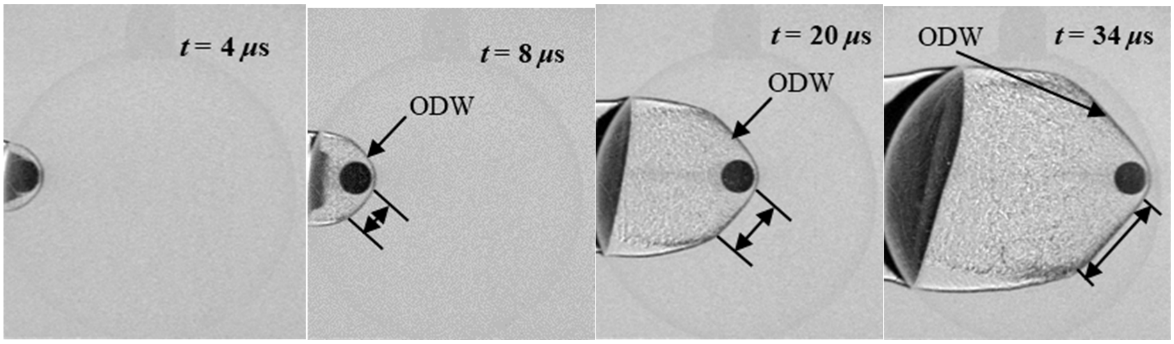


Figure 4: Time sequential shadowgraph pictures of the stabilized oblique detonation regime in Fig. 2 (c).

Then, we discuss the relationship between the experimental conditions of this study and the critical conditions proposed by previous studies. The critical conditions for the detonation initiation [8, 9] and for the stabilization of oblique detonation [11-13] by the spherical projectiles have been expressed by the ratio (d / λ) of projectile diameter, d to detonation cell width, λ. Lee [9] proposed the semi-empirical expression for the critical condition for detonation initiation as $M_p / M_{CJ} = 5.3\ (\lambda / d)$ and it was carefully validated by the experiments of Higgins and Bruckner [8], where, M_p is the projectile Mach number and M_{CJ} is the C-J detonation Mach number. The critical condition for the stabilization of oblique detonation wave [11-13] was also proposed experimentally as $d / \lambda > 3.5$ to 5.5 under the condition $M_p > M_{CJ}$. Figure 5 shows the classification of the combustion regimes observed in this study with the M_p / M_{CJ} on the horizontal axis and the d / λ on the vertical axis. The solid curve in the figure is the semi-empirical equation by Lee [9] described above. The conditions under which the detonation initiation was observed were consistent with the Lee's equation in the region where M_p / M_{CJ} was approximately 0.8 or greater, and the conditions under which the oblique detonation was observed for $M_p > M_{CJ}$ were also approximately consistent with the reported critical condition. The Lee's semi-empirical equation was derived purely from the energetic requirement for detonation initiation. The lack of detonation initiation even for the large d / λ in the region of M_p / M_{CJ} less than 0.8 may be due to the autoignition limit, which was also observed in the experiment of Higgins and Bruckner [8]. The interesting result of this study is that the detonation initiation under $M_p < M_{CJ}$ resulted in the initiation process requiring the finite travel distance in conjunction with the unsteady shock-induced combustion, unlike the instantaneous initiation of overdriven detonation at the front of the projectile under $M_p > M_{CJ}$. The numerical simulation by Matsuo and Fujii [6] indicated that in the large disturbance regime, the detonation could be generated locally in front of the projectile. The result of this study indicates that the detonation initiation regime achieves if the local detonation in the LDR can develop as the self-sustained detonation that extends further into the surrounding mixture. Detailed discussion on the detonation initiation mechanism and the autoignition limit is required for future work. Although it was difficult to identify the detailed mechanism from the experimental results because the visualization was the two-dimensional superposition of the three-dimensional phenomena, the interaction between the flow field behind the shock wave and the chemical reaction in front of the projectile should be considered.

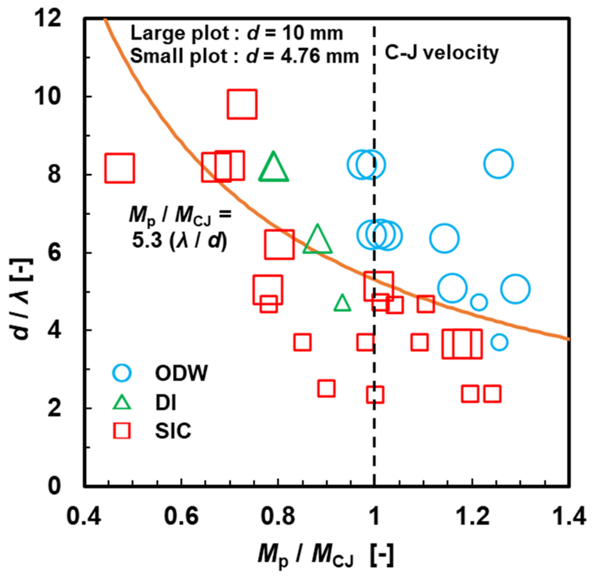


Figure 5: Observed combustion regimes for each condition of M_p / M_{CJ} and d / λ. ODW: oblique detonation wave, DI: detonation initiation, SIC: shock-induced combustion, d: projectile diameter.

4 Conclusions

In this study, the spherical projectile was launched at supersonic to hypersonic speed into the combustible mixture filled in the soap bubble to visualize the combustion phenomena around the projectile. The detonation initiation process was observed when the projectile Mach number was lower than the C-J detonation Mach number, which had not been observed in previous experimental studies. It was observed that the multiple localized detonation initiation occurred at the front of the projectile in accordance with the unsteady combustion of the LDR, which eventually developed into the detonation wave that spread to the entire combustible mixture. When the projectile Mach number was sufficiently higher than the C-J detonation Mach number, it was observed that the area of oblique detonation wave expanded with propagation, starting from the overdriven detonation initiated directly at the front of the projectile. The critical conditions for the detonation initiation and for the oblique detonation stabilization were consistent with the critical conditions proposed in the previous studies.

References

[1] Dudebout, R., Sislian, J.P. and Oppitz, R., Numerical simulation of hypersonic shock-induced combustion ramjets, Journal of Propulsion and Power, Vol.14, No.6 (1998), pp.869-879.

[2] Wolanski, P., Detonative propulsion, Proceedings of the Combustion Institute, Vol.34 (2013), pp.125-158.

[3] McVey, J.B. and Toong, T.Y., Mechanism of instabilities of exothermic hypersonic blunt-body flows, Combustion Science and Technology, Vol.3 (1971), pp.63-76.

[4] Alpert, R.L. and Toong, T.Y., Periodicity in exothermic hypersonic flows about blunt projectiles, Astronautica Acta, Vol.17 (1972), pp.539-560.

[5] Lehr, H.F., Experiments on shock-induced combustion, Astronautica Acta, Vol.17 (1972), pp.589-597.

[6] Matsuo, A. and Fujii, K., Computational study of large-disturbance oscillations in unsteady supersonic combustion around projectiles, AIAA Journal, Vol.33, No.10 (1995), pp.1828-1835.

[7] Matsuo, A. and Fujii, K., Prediction method of unsteady combustion around hypersonic projectile in stoichiometric hydrogen-air, AIAA Journal, Vol.36, No.10 (1998), pp.1834-1841.

[8] Higgins, A.J. and Bruckner, A.P., Experimental investigation of detonation initiation by hypervelocity blunt projectiles., AIAA paper, 96-0342 (1996).

[9] Lee, J.H.S., Initiation of detonation by a hypervelocity projectile, Progress in Astronautics and Aeronautics, Vol.173 (1997), pp.293-310.

[10] Vasiljev, A.A., Initiation of gaseous detonation by a high speed body, Shock Waves, Vol.3, No.4 (1994), pp.321-326.

[11] Kasahara, J., Arai, T., Chiba, S., Takazawa, K., Tanahashi, Y. and Matsuo, A., Criticality for stabilized oblique detonation wave around spherical bodies in acetylene/oxygen/krypton mixtures, Proceedings of the Combustion Institute, Vol.29 (2002), pp.2817-2824.

[12] Maeda, S., Sumiya, S., Kasahara, J. and Matsuo, A., Initiation and sustaining mechanisms of stabilized Oblique Detonation Waves around projectiles, Proceedings of the Combustion Institute, Vol.34 (2013), pp.1973-1980.

[13] Maeda, S., Sumiya, S., Kasahara, J. and Matsuo, A., Scale effect of spherical projectiles for stabilization of oblique detonation waves, Shock Waves, Vol.25, No.2 (2015), pp.141-150.

[14] Kaneshige, M.J. and Shepherd, J.E., Oblique detonation stabilized on a hypervelocity projectile, Symposium (International) on Combustion, Vol.26, No.2 (1996), pp.3015-3022.

[15] Lee, J.H.S., The Detonation Phenomenon. Cambridge University Press, New York (2008)