Unsteady Propagation Process of Oblique Detonation Waves Initiated by Hypersonic Spherical Projectiles

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(Received June 27th, 2011)

A spherical projectile was launched with 110% - 180% of a Chapman-Jouget (C-J) velocity into a detonable mixture, and we investigated the oblique detonation wave (ODW) that stabilized around it. High time-resolution visualizations were conducted using a high-speed camera with 1-μs frame speed to directly confirm the ODW stabilization and to investigate an unsteady phenomenon observed near the stabilizing criticality. In this case, the ODW was a three-dimensional conical wave, and the curvature effect on the conical detonation wave is not negligible near a projectile. We investigated the wave velocity distribution along the wave and revealed that it had a local minimum point at 0.8 – 0.9 times a C-J velocity during the decay process from an overdriven detonation near a projectile to a C-J ODW in the far field. We defined a characteristic wave curvature radius normalized by a cell size on this local minimum point. In this study, the minimum characteristic wave curvature radius of about 18 was needed to stabilize the conical detonation wave around a sphere. Near the stabilizing criticality, we also observed the unsteady ODW stabilization or detonation initiation on a shock-induced combustion. This unsteady regime was characterized by periodical onsets of local explosions that initiate or stabilize an ODW. We investigated the wave velocity distribution along this regime, and our findings revealed that the ODW transition or the detonation initiation following the shock-induced combustion occurred when the wave velocity decayed to 0.5 – 0.6 times a C-J velocity.

Key Words: Hypersonic Projectiles, Detonation Initiation, Oblique Detonation Waves, High-Speed Camera

1. Introduction

An oblique detonation wave engine (ODWE)³ or ram-accelerator (RAMAC)⁴ in which an oblique detonation wave (ODW) is stabilized in a combustor would achieve a continuous, short and almost constant-volume combustion process for a hypersonic propulsion system. One of the important issues for these engines is understanding the critical conditions and mechanism needed to initiate and stabilize the ODW. An experimental visualization of a stabilized ODW around a hypersonic projectile was first reported by Lehr⁵. Lee⁶ and Vasiljev⁷ proposed a criticality equation to initiate a detonation wave by a projectile using the hypersonic blast-wave analogy. Experimental studies to investigate an initiating or a stabilizing criticality have been conducted by Higgins and Bruckner⁸, Kaneshige and Shepherd⁹, Kasahara et al.¹⁰, Verreault and Higgins¹⁰ and Maeda et al.¹¹ by carrying out optical observations or pressure recordings. Although a stabilized ODW is a steady phenomenon, the propagation of an unsteady detonation wave was observed in the vicinity of the criticality¹², and the unsteady propagation process was directly observed by detailed continuous frames using a high-speed camera¹³.

An ODW can be categorized using two configurations. The first is a two-dimensional plane ODW stabilized around a two-dimensional body such as a wedge, and the second is a three-dimensional conical ODW stabilized around a three-dimensional body such as a cone-nosed or blunt-nosed projectile. The conical ODW has a curvature radius on of the wave. A wave curvature radius on a detonation wave decreases the Chapman-Jouget (C-J) velocity and enlarges the cell size, and if it is smaller than a certain critical radius, the detonation wave is quenched. In a conical ODW stabilized around a projectile, the curvature effect on an ODW may not be negligible near the projectile. Therefore, to investigate the criticality for stabilizing an ODW around a projectile, we examined the local curvature radius of the wave.

In this study, we launched a spherical projectile into an acetylene / oxygen mixture highly diluted with krypton, and an ODW was initiated and stabilized around the projectile under a large range of projectile velocities. We conducted high time-resolution visualizations to directly confirm the ODW stabilization and to investigate an unsteady phenomenon observed near the stabilizing criticality. In this paper, we first discuss the characteristic local curvature radius of the ODW needed for stabilizing a steady C-J ODW around a sphere. We then discuss the unsteady ODW stabilization and initiation.

2. Experimental Setup and Conditions

Hypersonic spherical projectiles were launched into detonable mixtures at rest, and Schlieren visualizations were conducted using the HPV-1 high-speed camera (312 × 260 pixels spatial resolution, Shimadzu). The experimental setup¹³ consisted of four devices shown as (1) through (4) in Fig. 1. The projectiles launched by the gas gun broke a very
thin (12-μm thickness) Mylar diaphragm (diaphragm 1 in Fig. 1) and entered an observation chamber filled with a detonable mixture. An optical observation region was circular with a 90-mm diameter, and the center of this region was located 400 mm downstream of the chamber inlet. A spherical projectile was chosen to eliminate any influence of a flight attitude. The projectile had a 4.76-mm diameter and was made of polyethylene. Recording conditions of the high-speed camera were a 1-μs frame speed, a 250-ns exposure time and a maximum of 100 continuous shots in all experiments.

Projectile velocities were always higher than a C-J velocity, and cell widths were several-fold smaller than projectile diameters, to achieve stabilized ODWs around the projectiles. The detonable mixture was a stoichiometric acetylene / oxygen mixture (2C2H2 + 5O2) diluted with krypton (2C2H2 + 5O2 + 21Kr) in a 75% volumetric fraction to lower the C-J velocity of the mixture. This mixture could achieve a substantially lower C-J velocity of about 1300 m/s, and this allowed projectile velocities exceeding the C-J velocity to vary over a wide range (Table 1). The detonability of the mixture was varied by changing the initial filling pressure. The initial temperatures of the mixtures were room temperatures. The projectile velocity condition was expressed as a non-dimensional projectile velocity (the ratio of a projectile velocity to a C-J velocity, \( V_p / D_{CJ} \)), and the detonability of the mixture was expressed as a non-dimensional projectile diameter (the ratio of a projectile diameter and a cell width, \( d / \lambda \)). Experimental results of Desbordes and Desbordes et al.\(^{12, 13}\) for the cell sizes were accessed from the Detonation Database (Kaneshige and Shepherd\(^{14}\)). A fitting equation for these cell sizes (\( \lambda [\text{mm}] \)) as an exponential of filling pressures (\( p_0 [\text{kPa}] \)) gives \( \lambda = 138.4 \times p_0^{-1.206} \), and the cell sizes were interpolated or extrapolated by this equation. In this study, all experimental conditions had cell sizes below 1 mm.

In the following discussion, we treat them as double-digit values, although cell size measurements generally have large errors. Therefore, these values refer to the mixtures’ approximate detonabilities. The C-J velocity was calculated using the chemical equilibrium computation software STANJAN (Reynolds\(^{15}\)). Projectile velocities were determined based on the time histories of projectile locations using observed continuous images. The projectile locations were situated almost linearly over time, and thus the velocity deficits in the observation region were negligible. The large collection of continuous pictures could show many of the projectile locations with good accuracy, and systematic errors of the projectile velocities were within ±0.65%.

3. Results and Discussion

3.1. Steadily stabilized ODWs

Figure 2 shows the visualization results for three cases (Shots No. 2, 8 and 3 in Table 1) cited from Maeda et al.\(^{16}\). Qualitative descriptions\(^{16}\) of these results are provided below; however, the \( d / \lambda \) conditions were almost the same in Fig. 2 (a) and (b), except the projectile velocity of Fig. 2 (b) was higher than that of Fig. 2 (a). Fig. 2 (c) had the intermediate projectile velocity between those of Fig. 2 (a) and (b), and the \( d / \lambda \) condition was close to the stabilizing criticality of the steady ODW. In all cases, an overdriven detonation near a projectile decayed to a C-J ODW in the far field. An ODW around a projectile is a conical wave, and it has a curvature radius. A curvature radius attenuates a detonation wave because of a mass divergence effect behind the wave, and a curved detonation wave has a smaller C-J velocity and a larger cell size than those of a planar detonation wave. Therefore, a small curvature radius near a projectile will affect the propagation velocity of the conical ODW. The wave velocity of a conical wave stabilized around a projectile is related to the geometric wave angle and the...
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projectile velocity, $D_w = V_p \sin \theta_w$. Here, $D_w$ is the wave velocity, $V_p$ is the projectile velocity and $\theta_w$ is the wave angle. From this relationship, the wave angle of a C-J ODW, $\theta_{CJ}$, is represented as $\theta_{CJ} = \sin^{-1}(D_{CJ} / V_p)$, where $D_{CJ}$ is a C-J velocity.

Therefore, a wave velocity deficit arises on the wave angle of an ODW that can be seen in pictures. This curvature effect was visible in three cases in Fig. 2. The overdriven detonation near the projectile didn’t decay asymptotically to the C-J ODW, but it did decay slightly below the C-J velocity near the projectile. This velocity deficit was quite apparent in the small $d / \lambda$ condition of Fig. 2 (c). This case was close to a stabilizing criticality of a steady ODW, and the unstable wave front is visible, that is not found in Fig. 2 (a) and (b) being well above the criticality.

Figure 3 shows these wave propagation velocity distributions. A horizontal axis means the $y$ direction as defined in Fig. 4. These distributions are average values of an upper half and lower half from a projectile flight axis of 5 continuous pictures, for a total of 10 points for each case. All steadily stabilized ODW cases in this study are plotted in Fig. 3, and the conditions ranged from $V_p / D_{CJ} = 1.09 - 1.71$ and from $d / \lambda = 6.0 - 7.0$. Each wave velocity was identical to a projectile velocity ahead of a projectile ($y = 0$). In the far field, it was identical to the C-J velocity of a planar detonation wave, because the curvature effect was vanishingly small. The wave velocity distributions had a local minimum point at 0.8 to 0.9 times the C-J velocity. In this figure, we regard the right side from this point as the self-propagating conical ODW region, and the left side as the bow-wave region where the decay process of an overdriven detonation is subjected to a projectile condition such as a shape and velocity. Arrows point these regions in Fig. 4. In this sense, the local minimum point of a wave velocity is an edge of the self-propagating ODW region. Here we examine the wave curvature radius needed to stabilize a steady ODW on this point. This wave curvature radius is defined as $R_1^*$ in Fig. 4. The $R_1^*$ values were measured from continuous pictures and plotted against projectile velocities in Fig. 5.

Fig. 2. Superposed pictures of steadily stabilized ODW cases. The pictures are cited from Maeda et al.\textsuperscript{16}.

Fig. 3. Wave propagation velocity distributions in the $y$ direction for all steadily stabilized ODW cases.

(a): Shot No. 2, $V_p / D_{CJ} = 1.09$, $d / \lambda = 6.9$, 5-μs intervals
(b): Shot No. 8, $V_p / D_{CJ} = 1.64$, $d / \lambda = 7.0$, 3-μs intervals
(c): Shot No. 3, $V_p / D_{CJ} = 1.49$, $d / \lambda = 6.0$, 3-μs intervals
The $R_1^*$ values are average values of 10 points as well as wave velocities. Under the conditions in this study, $R_1^*$ had an almost constant value, 14 mm, which was independent of the projectile velocity and mixture filling pressure, that is $d / \lambda$. Several parameters may affect the value of $R_1^*$. The $R_1^*$ may depend on the mixture filling pressure (cell size), because if the pressure is high enough (the cell size is small enough) the curvature effect will be vanishingly small even around the projectile. In this study, the pressures were varied within the vicinity of the critical pressure, and therefore $R_1^*$ was independent of the pressure in this pressure range. Additionally, the shape of the bow-wave region (distribution of the wave propagation velocities and the wave curvature radiiues) was less dependent on the projectile Mach number, because it was always hypersonic. The $R_1^*$ will also depend on the projectile diameter, because the larger (smaller) projectile will make a larger (smaller) curvature radius on the shock wave ahead of a projectile, although the projectile diameter was constant in this study.

In Fig. 6, the $R_1^*$ is normalized by cell size $\lambda$, and the horizontal axis is replaced with $d / \lambda$. Larger $d / \lambda$ conditions had larger $R_1^*/\lambda$. This means that it is easy to stabilize an ODW. On the other hand, the ODW was not stabilized below $d / \lambda = 5.9$. Therefore, we revealed that the minimum non-dimensional wave curvature radius was about $R_1^*/\lambda = 18$ in this study. This may show the critical curvature radius for sustaining a C-J oblique detonation wave in this mixture. The critical value will depend on the characteristics of a mixture (such as the activation energy, specific heat ratio and C-J Mach number). Therefore, the value 18 would be valid for the mixture used in this study.

3.2. Unsteady ODW stabilization and detonation initiation following shock-induced combustion

The unsteady ODW stabilization (Fig. 7) or the detonation initiation following shock-induced combustion (Fig. 8) was observed in the vicinity of the stabilizing criticality of an ODW, shown as the shaded portion in Fig. 6.
These results and qualitative explanations of them are cited from Maeda et al.\textsuperscript{16}. In both conditions, $d / \lambda$ values were almost the same, but the projectile velocity of Fig. 8 was higher than that of Fig. 7. In Fig. 7, the bow-wave region near the projectile discontinuously transits into a conical ODW. Although the intersection between the bow-wave and the conical ODW was unsteady, the conical ODW was stabilized with its C-J angle far from the projectile.

This regime was described in our previous study\textsuperscript{11} and called the “Straw Hat type with stabilized ODW”. Figure 8 shows the continuous pictures with 5-$\mu$s intervals, and they are drawn as fixed projectile locations. Opened circles show projectile locations after moving outside the observation region. Times after recording start of the high-speed camera are shown at the upper left on each picture. A shock wave was pushed outward (black arrow) by a local explosion on a shock-induced combustion at $t = 52$ $\mu$s. This explosion kernel grew over time, and it ultimately made a transition into a detonation wave. Almost spherical propagations of the detonation waves are visible on the right side in each picture. These detonation waves can be attributed to the transition from the explosion kernels initiated upstream of the observation region.

Wave propagation velocity distributions for these unsteady cases are shown in Fig. 9. Both axes appear the same as in Fig. 3. Plots connected by dashed lines are the results of Straw Hat type with stabilized ODW cases at two different times. The wave velocity decays from a projectile velocity (at $y = 0$) to 0.5 to 0.6 times a C-J velocity (at $y = 9.5 - 12.5$ mm), and apparently this region was not a detonation wave, but rather a shock-induced combustion. The wave velocity discontinuously jumped into the C-J velocity. Locations of these jumping points fluctuated within $y = 9.5 - 12.5$ mm over time. The plots connected by a solid line are the result of a case in which a local explosion was observed on a shock-induced combustion. The onset point of the local explosion is indicated by an arrow in Fig. 9. The point had almost the same wave velocity as the transition point of the Straw Hat type case. As seen in this figure, we revealed that a characteristic point for the transition to a conical ODW or the detonation initiation on the shock-induced combustion was when a wave velocity decayed to 0.5 to 0.6 times a C-J velocity. In these unsteady cases, the mechanism to stabilize an ODW was apparently different from that of the steadily stabilized ODW cases shown in section 3.1.
4. Conclusions

1) An oblique detonation wave (ODW) was stabilized around spherical projectiles when their velocities ranged from 1.1 to 1.8 times a C-J velocity. We directly confirmed the ODW stabilizations from detailed time histories of the continuous pictures.

2) In steadily stabilized ODW cases, wave propagation velocities along the wave had a local minimum point at 0.8 to 0.9 times a C-J velocity. The minimum non-dimensional wave curvature radius at this point was about $R_{\lambda}^* / \lambda = 18$ in the $2\text{C}_2\text{H}_2 + 5\text{O}_2 + 21\text{Kr}$ mixture.

3) We observed an unsteady ODW stabilization or detonation initiation on a shock-induced combustion near the stabilizing criticality. An ODW transition or a detonation initiation on a shock-induced combustion occurred when the wave velocity decayed to 0.5 to 0.6 times a C-J velocity.

Acknowledgments

This work was subsidized by the Ministry of Education, Culture, Sports, Science and Technology via a Grant-in-Aid for Scientific Research (A), No. 20241040; a Grant-in-Aid for Scientific Research (B), No. 21360411; and the Research Grant Program from the Institute of Space and Astronautical Science, the Japan Aerospace Exploration Agency.

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