Experimental Observation of Non-uniformly Premixed Oblique Detonation

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1 Introduction

Oblique detonation wave (ODW) is defined as detonation stabilized on a solid obstacle in hypersonic flow relative to it (Fig. 1). It has been long since it was first proposed for application to a hypersonic aircraft, and a performance analysis revealed that it especially benefits higher Mach number flight M $\gtrsim$ 15 [1]. Also, due to its relatively steady feature and independence from the confinement, the morphology of ODW will provide important insight into the physical nature of detonation, including those related to the cellular instability. Also, recently, there is an increasing interest in the physics of detonation in non-uniform mixing concerning the application to detonation engines, because fuel and oxidizer must be separately supplied in actual operation. There are not so numerous, but increasing efforts addressing this issue [2-7]. Iwata et al. [2-4], and Fang et al. [5] approached it by numerically studying ODW in hypersonic non-uniform hydrogen-fueled flows. Iwata et al. [2] found in their numerical simulation that Chapman-Jouguet (C-J) theory is still valid in non-uniform mixture with velocity deficit owing to the curvature effect [8]. Moreover, it was indicated that strongly fuel-rich mixture induces quenching of detonation far from the obstacle. In this study, experimental approach was first attempted using a two-stage light gas gun, and an important issue on C-J theory and local quenching in non-uniform mixture is addressed.

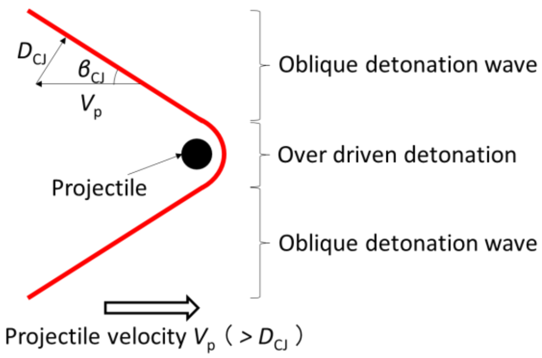

Figure 1: Schematic of oblique detonation.

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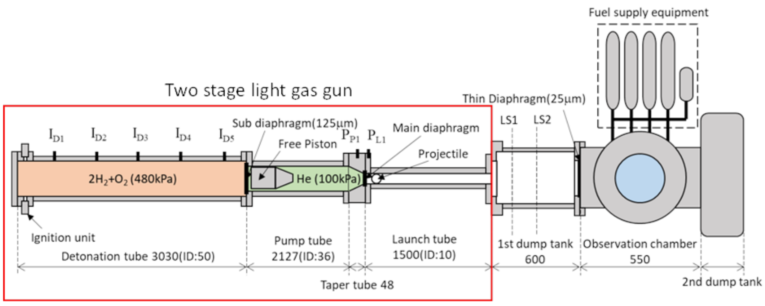
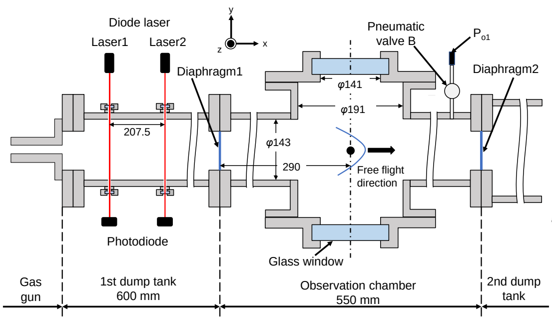
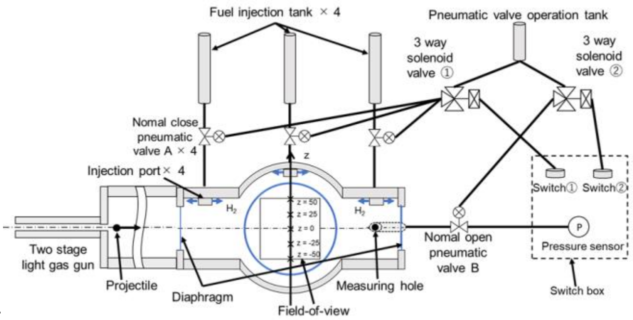


(a) Overview of two-stage light gas gun



(b) Details of observation chamber



(c)Supplying system for non-umiform mixture

Figure 2: Experimental apparatus for observation of sphere-induced oblique detonation in H_2/O_2-3Ar non-uniform mixture

2 Experimental Configuration

Fig. 2(a) is shown as a schematic of the experimental apparatus belonging to Saitama University, whose full details are provided in [9]. The 9.52 mm diameter projectile initially located in the launch tube is accelerated to roughly 1700 – 2200 m/s at the entrance of the observation chamber, depending on the thickness of the diaphragm (25 – 250 μ m) between the pump tube and the launch tube and on the filling pressure in the detonation tube. The observation chamber depicted in Fig. 2(b) is 143 mm in diameter perpendicular to the launching direction. Non-uniform mixture (and uniform mixture for a comparative study) is filled in the chamber composed of hydrogen as fuel and a constant composition oxidizer O_2+3Ar. ODW is formed around the sphere, which is optically accessible in the lateral direction through a couple of BK7 windows for taking Schlieren photography. High-speed camera ULTRA Cam HS-106E (NAC) was used to take high-speed Schlieren photography of ODW in the test chamber through Φ141 mm BK7 windows. Frame rate was set to be 500,000 fps with an exposure time of 300 ns, resolving an area of 103 mm $\times$90mm with 412 pixel $\times$ 360 pixel.

A supplying system of non-uniform mixture was schematically described in Fig. 2(c). Oxidizer mixture O_2+3Ar is supplied to the test chamber in the first place at prescribed partial pressure, and hydrogen is secondly injected through four slit injectors equipped at the top of the chamber, forming buoyantly induced vertical concentration gradient at a final pressure 70.0 ±0.6 kPa. Global mixture composition $2H_2+O_2$+3Ar is thus promised with uncertainty of equivalence ratio Φ=1.00 ±0.03. Strength of the concentration gradient at the moment of the launch was controlled by the time interval from the end of injection to ignition in the detonation tube.

Hot-wire anemometer probe 0251R-T5 amplified by CTA 1011 (Kanomax) was in the present study used for detecting variable heat conductivity dependent on the concentration of hydrogen. The probe was inserted at 5 different vertical positions along the center of the chamber *z*=-50, -25, 0, 25, 50 mm from the height of the projectile flight. Calibrated output voltage is converted to volumetric concentration of hydrogen. Another experiment using only helium did not detect injection velocity ~10 m/s, confirming that the voltage is solely concentration-dependent. Also, an almost identical profile of the concentration was observed at another horizontal position distant by 182.8 mm in the launching direction, which verified the concentration gradient is one-dimensional and vertical to the launching direction. A great reproducibility of temporal/spatial profile ~0.5 % in addition promises the accuracy of the measured volumetric concentration ≲1%. In order to support the measured gradient, three-dimensional numerical simulation applying Fire Dynamic Simulator (FDS) [10] was also conducted.

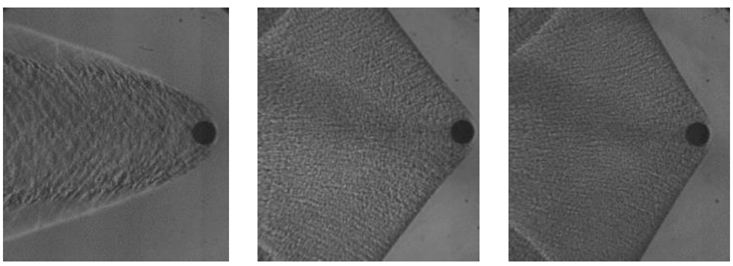
3 Oblique Detonation in uniform mixture

In the first place, ODW was formed in uniform mixture prepared by filling premixed mixture in the observation chamber at 70.0 ±0.6 kPa. Three instantaneous pictures taken by Schlieren photography for Φ=0.60, 0.70 and 1.00 are shown in Fig. 3. ODW is successfully formed for Φ=0.70-1.50, while decoupled shock-induced combustion (SIC) in Large-Disturbance-Regime (LDR) [11] resulted for Φ=0.60 and 2.00. ODW angle is β=52.6 ±0.9° for Φ=0.70 and β=58.9 ±0.9° for Φ=1.00. Detonation velocity is calculated through the relation $\beta=\arcsin(D/V_p)$ as summarized in Fig. 4 for each ODW case. Solid line in this figure denotes C-J theoretical velocity for variable Φ, which was calculated with CEA program [12]. Thus, the experiments reasonably agree with C-J theory, but with slightly lower values. This tendency is attributed to the wave curvature [8].

In order to discuss a threshold for the success of ODW, cell width of uniform mixture was measured in a soot-foil experiment using 25×30 mm^2 rectangular channel, which is summarized in Fig. 5. In the case of ODW around a sphere, scale ratio of the sphere diameter d and cell width λ is known to be a critical parameter [13, 14]. The critical non-dimensional diameter for the present results is then estimated to be d/λ=4.30-4.93, which is reasonable for relatively regular mixture [13].

4 Measured/calculated temporal profile of mixture concentration gradient

Fig. 6 summarizes the measured and calculated distribution of local equivalence ratio at each waiting time t_w=3-30s from the end of injection, as blank symbols. Solid lines denote the numerical results by FDS at a constant tuning for turbulence modeling. Apparently, a good agreement is achieved between both results, which supports the accuracy of the measured temporal/spatial profile. Distribution of local equivalence ratio gradually approached a sinusoidal fashion, which was similarly confirmed by Vollmer et al. [6]. It can be also noted that local equivalence ratio at z=0 mm immediately converged to a final value. It reached Φ=0.67 at 5s with d/λ=4.95, and gradually varied toward Φ=1.00. Therefore, d/λ around the sphere at every waiting time ≥5 s becomes larger than or around the critical value for successful ODW as long as a uniform mixture is primarily concerned.



(a)Φ=0.60 (b)Φ=0.70 (c)Φ=1.00

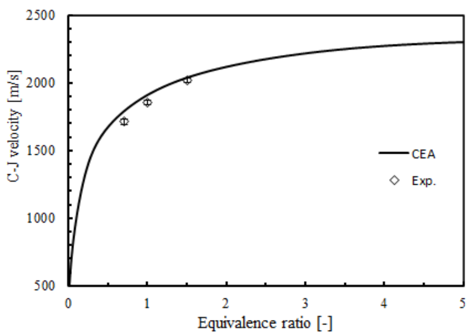


Figure 3 ODW/SICs in uniform H_2/O_2-3Ar mixture V_p=2148±16 m/s Figure 4 C-J velocity versus Φ

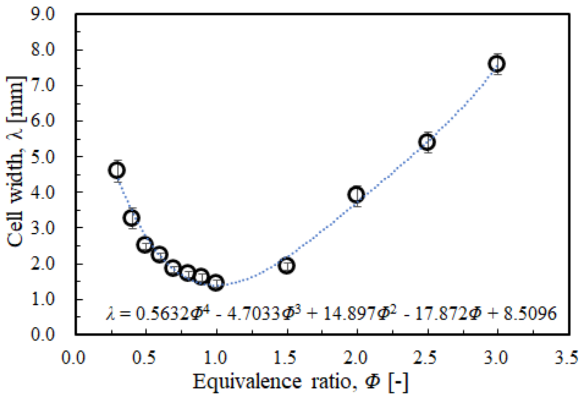


Figure 5 Measured cell width against Φ

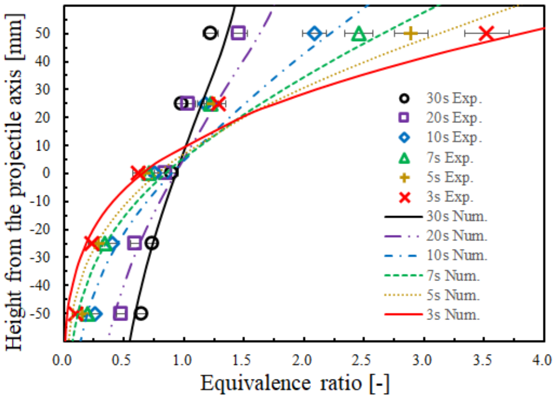
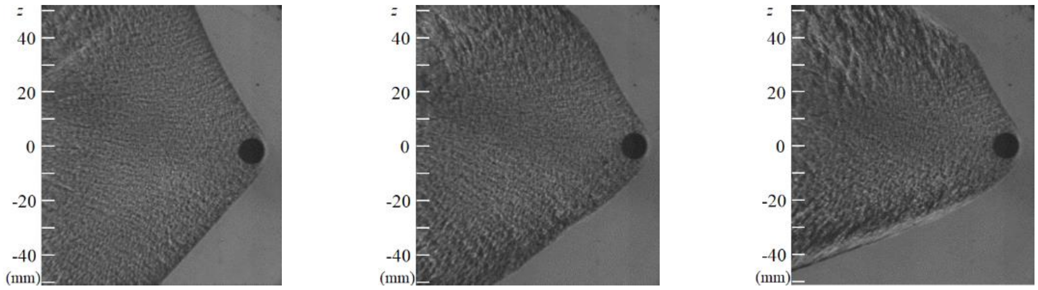


Figure 6 Measured (symbols) /calculated (lines) concentration gradients at each waiting time

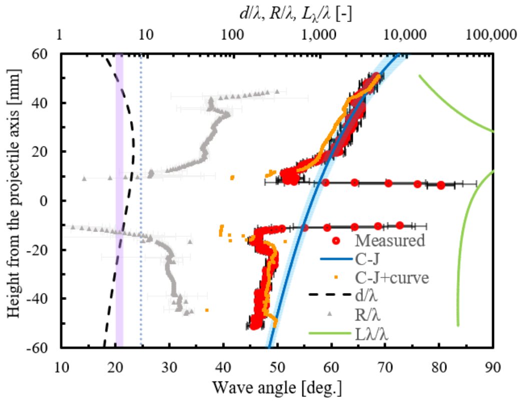
5 Oblique Detonation in Non-Uniform Mixture

Waiting time after the injection was varied to control the concentration gradient according to the measurement shown in Fig. 6, around the launching velocity V_p=2200 m/s. Fig. 7 shows instantaneous wave structures observed at each waiting time t_w=5, 10, 20s. V_p fluctuated roughly ±30-40 m/s during each flight in the visualized area. ODW was successfully formed in the whole visualized area at t_w =20s (Fig. 7a). Weak curvature appeared in this case, as confirmed in several numerical studies on ODW [2-5]. Steeper/shallower angle at the upper/lower side of the projectile agrees with the tendency shown in Fig. 4, which will be analyzed later in detail. At a shorter waiting time t_w =10s, i.e., in a stronger concentration gradient, critical structures were observed on each side of the projectile. Around z=40 mm, there was an inflection point through which the wave angle decreased outwards contrary to the increasing trend closer to the projectile. Also, around z=-30 mm another inflection appeared where the wave angle rather increased outwards. Weak unsteadiness is observed around this point which resembles that of local explosion appearing in Straw-Hat structure [13]. Therefore, it is indicated that transition from bow-shock to ODW occurs here. These two critical features indicates that ODW is now on a marginal state close to quenching. Another thing to note for the case t_w =10s is that the cellular pattern becomes increasingly rougher outwards, which agrees with the trend of local equivalence ratio (Fig. 6) and is thought to have an important role in these critical structures. A stronger concentration gradient at the shortest waiting time t_w=5s (Fig. 7(c)) induced local quenching of ODW on the upper side around z=40 mm. Also, shock and flame are decoupled even closer to the projectile on the lower side without any clear evidence of ODW transition. Cell width variation is also increasingly evident especially where the decoupling occurs, which again implies that scale of cell width plays a key role. Interesting to note is that the quenching on the upper side is accompanied by a sudden reduction of the wave angle, which was qualitatively predicted by the authors' numerical work on sphere-induced ODW [2].

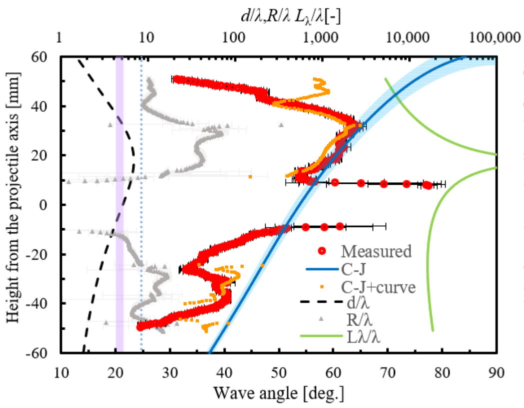


(a)t_w=20s, V_p=2188±27 m/s (b) t_w=10s, V_p=2234±34 m/s (c) t_w=5s, V_p=2163±48 m/s

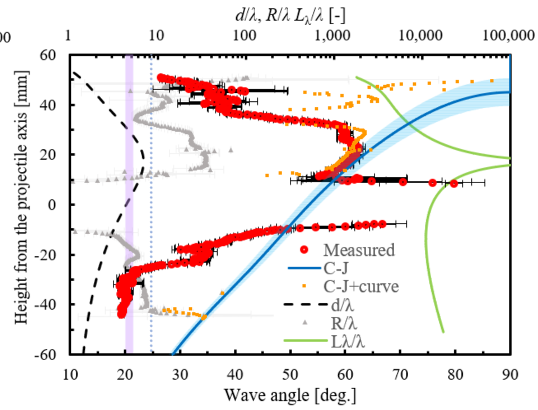
Figure 7 Instantaneous picture of ODWs in non-uniform H_2/O_2-3Ar mixture.



(a) t_w=20s, V_p=2188 m/s



(b) t_w=10s, V_p=2203 m/s



(c) t_w=5s, V_p=2163 m/s

Figure 8 Local wave angles and characteristic length scales of ODWs in non-uniform cases

Local wave angle distribution was evaluated for the three non-uniform cases and compared with theoretical C-J values β_{CJ}=arcsin(D_{CJ}/V_p) for each location, where D_{CJ} is calculated by CEA program for measured local concentration, approximately interpolated with the form H_2 [vol%]=$C\exp(a(z_0-z)^{\gamma})$. Both experimental/theoretical wave angles were shown in Fig. 8 for each case. Experimental wave angles are denoted by red circles with black error bars (roughly within ±1°), and theoretical C-J one is by a blue line with a light-colored uncertainty region considering the fluctuation of V_p. Overdriven area close to the projectile is here omitted. Also, three additional length scales normalized by cell width are introduced: d/λ is non-dimensional diameter with the critical value (4.30-4.93) denoted by a purple colored line, R/λ curvature radius taking into account both in-plane and out-plane curvature, the latter of which is assumed to be $z/\cos\beta$ only true for an axisymmetric wave (but this is a good approximation according to an ongoing 3D geometrical analysis to be presented in the conference and our future paper), and finally L_λ/λ which is the characteristic length of the concentration gradient given by $L_\lambda=\lambda/(d\lambda/dz)$.
Common to all the three cases is that the upper side wave front is close to C-J detonation, whereas notable velocity deficit occurs on the lower side. Quantitative explanation on this is partly given by the effect of the wave curvature R/λ provided by 3rd order polynomial approximation [8]. This well describes the lower side deficit as denoted by orange symbols, while underestimation for the upper side may be due to the uncertainty of curvature and overdriven state of ODW. It is also common that the length scale of the gradient L_λ was always far larger than cell width, which indicates that the concentration gradient in the present study is not strong enough to alter local cellular structure by itself. d/λ is apparently below the critical value even where ODW is formed, as is clear for t_w=20s case. In contrast, transition to ODW and local quenching are almost coincident with the location of the critical curvature radius (denoted by a dotted line). All of these outcomes emphasize the importance of curvature on ODW presently addressed.

6 Conclusion

In the present study, experimental observation of ODW in non-uniform H_2/O_2+3Ar mixture was first conducted using two-stage light gas gun launching Φ9.52 sphere at the velocity around 2200 m/s. Non-uniform concentration gradient was formed by injecting hydrogen into oxidizer O_2+3Ar, and the waiting time before ignition was varied to control the strength of the concentration gradient vertical to the launching direction. Several interesting structures including curved wave fronts, cell width variation and local quenching were observed. One important finding is that ODW is no longer constrained by the requirement of non-dimensional diameter far from the projectile, but dominated by curvature radius. The concentration gradient was not strong in the present study to alter local cellular structure by itself, but future study producing steeper gradients may encounter the situation where the concentration gradient affects greatly and overtakes the effects of curvature radius on velocity deficit and criticality.

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