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Experimental and numerical studies on detonation reflections over cylindrical convex surfaces

Jian Li, Jianguo Ning*

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, 5 South Zhongguancun Street, Beijing 100081, China

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ABSTRACT

The detonation reflection over a cylindrical convex surface was investigated experimentally and numerically by focusing on the length-scale effect on the reflection process, such as the triple-point trajectory and the critical wedge angle at which a transition occurs from regular reflection to Mach reflection. The results show that the critical wall angle plots exhibit significant scatter because of the cellular properties of the detonation front. If the transverse spacing is large as compared to the radius of curvature, the scatter range extends. If the transverse spacing is small as compared to the radius of curvature, the scattering is dramatically reduced. The critical wall angle is found to mainly depend on the scaled length i.e., the radius of curvature (R) over the cell size λ (or the reaction zone thickness Δ). Moreover, the critical wall angle increases with the decrease in the detonation thickness or with the increase in the radius. As R/λ increases to approximately ten, the critical wall angle approaches a value calculated using the non-reactive two-shock theory for pseudo-steady flows. The numerical results reveal that the transition to Mach reflection occurs earlier in the case of a ZND detonation than in the case of an inert shock wave because of the higher sound speed due to the release of chemical heat.

1. Introduction

When a planar incident shock wave encounters a cylindrical convex surface, either regular reflection (RR) or Mach reflection (MR) can occur depending on the initial wall angle and the Mach number (of the incident wave). If the initial reflection is an RR, as the incident shock wave propagates along the cylindrical convex surface, it encounters a decreasing wall angle, which will eventually change the RR to an MR. Ben-Dor presented a comprehensive review on shock wave reflection phenomena [1]. Heilig [2] was probably the first to study the reflection of a planar shock wave over a cylindrical convex wedge. He found that the RR to MR transition over a convex cylinder occurs when the wall angle is significantly smaller than the detachment criterion; this result is consistent with the recent experimental measurements made by Ben-Dor [3] and Geva et al. [4]. Heilig [2] and Itoh et al. [5] numerically calculated the critical wall angle for the transition from RR to MR over a cylindrical convex surface using Whitham's classical theory [6] and its modification by Milton [7]. Takayama and Sasaki [8] and Dewey et al. [9] showed experimentally that the wedge angle for an RR to MR transition depends on the Mach number of the incident shock wave and the radius of curvature of the cylindrical surface. Moreover, the experimental results showed that the critical transition wall angles lie below the RR–MR transition line for pseudo-steady flows. Furthermore, with the increase in the radius of curvature, the transition wall angle increases and approaches the pseudo-steady RR→MR transition line. Later studies revealed the same trend (e.g., Skews and Kleine [10–12], Kleine and Skews [13], Skews and Blitterswijk [14], and Kleine et al. [15]). However, Kleine and Skews [13] suggested that the transition delay reported in literature may have been due to the difficulties in detecting a visible Mach stem.

In 1945, von Neumann [16] proposed the first ever theoretical model to predict the transition from RR to MR, namely the detachment criterion. In the last two decades, much progress has been made in studying the transition from RR to MR, with better understanding of hysteresis phenomena and viscous effects. The most notable transition criteria include the detachment criterion, mechanical-equilibrium criterion, sonic criterion, and length-scale criterion [1]. For a pseudo-steady shock wave reflection over a wedge, it is widely accepted that the transition from RR to MR occurs as soon as the sonic signals generated behind the reflection point overtakes the reflection point corresponding to the so-called sonic criterion. The length-scale concept proposed by Hornung [17] has been successfully used to predict the transition lines in steady and pseudo-steady shock wave reflections as well as in

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* Corresponding author.
E-mail address: jgning@bit.edu.cn (J. Ning).

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the cases of unsteady shock wave reflections over cylindrical concave surfaces. It is believed that the “race” between the corner-generated signals and the incident shock wave is the dominant factor in determining the RR→MR transition process over cylindrical convex surfaces as well. Skew and Kleine [10–12] and Kleine and Skew [13] studied the shock wave interaction with convex circular cylindrical surfaces and found that the “catch-up” condition occurs at wall angles considerably higher than that in the plane wall case. A visible Mach stem was observed only further along the surface at wall angles significantly lower than those of plane walls. The initial wedge angle does not influence the transition process as long as the initial reflection is regular and the corner signal does not cross the reflection point. In this case, the corner signal remains behind the reflection point and therefore does not encounter the initial angle. However, this finding is inconsistent with the recent numerical results obtained by Timofeev et al. [18], Hakkaki-Fard [19], and Hakkaki-Fard and Timofeev [21], wherein they show that the transition in the case of an inviscid flow occurs at the same wall angle as that of a straight wedge. Nevertheless, if the viscous effects are considered in the simulation, a delay in the transition is predicted using computational fluid dynamics (CFD) (Hakkaki-Fard [19]; Hakkaki-Fard and Timofeev [20]); this observation is qualitatively similar to that made in the wedge case [1].

Similarly, a detonation wave can also reflect over a cylindrical convex surface in the form of an RR or an MR. Unlike an inert shock wave, a detonation wave is cellular and exhibits more length scales, such as the reaction zone thickness and cell size, which further increase the complexity of the problem. Akbar [22] tentatively studied the detonation reflection over a convex surface experimentally using Schlieren photography and obtained the triple-point trajectory of MR. However, the critical transition wall angle was not examined in the study. Our previous studies [23–25], on detonation reflection over a wedge, show that the length-scale effect does indeed significantly affect the MR process. The MR of an inert shock wave is self-similar because of the absence of a length scale. However, the detonation thickness makes the MR process non-self-similar. In the present study, as the effect of the radius of curvature is present at the very beginning, the reflection process of neither the inert shock wave nor the detonation is self-similar. Although the detonation reflection over straight wedges has been the subject of numerous experimental and numerical studies, studies on the transition from RR to MR of a detonation over a convex surface are still lacking, with several unanswered questions in this field.

A cylindrical geometry helps better observe the evolution of RR to MR and the subsequent decaying of the MR through diffraction over the cylinder surface. In the present study, experiments and numerical simulations were performed to investigate the length-scale effect on the critical wall angle at which a transition occurs from RR to MR. This should shed more light on the physical phenomena of the unsteady reflection process of detonations.

2. Experimental study

2.1. Setup

The experiments were performed in a narrow detonation channel (1.5 m long, 10 cm tall and 1 cm wide), as shown schematically in Fig. 1. The mixture was detonated by an electrical spark in an ignitor tube, which is vertically aligned with the narrow channel. A Shchelkin spiral was inserted in the ignitor tube to assist the transition to a detonation. For less sensitive mixtures, a small amount of equimolar acetylene–oxygen mixture was injected into the ignitor tube.

The ignitor tube was designed to promote the formation of a planar Chapman–Jouguet (CJ) detonation in the narrow channel by reflection. Figure 2 shows the formation process via a change in the cell pattern. A half cylinder was installed sufficiently far downstream the channel. Hydrogen–oxygen and acetylene–oxygen mixtures with different argon dilutions were used. Argon dilution usually increases the cell size and cellular stability (or equivalently, the regularity of the cell pattern). In this study, five combustible mixtures, namely $2H_2 + O_2$, $2H_2 + O_2 + 2Ar$, $2H_2 + O_2 + 4.5Ar$, $C_2H_2 + 2.5O_2$, and $C_2H_2 + 2.5O_2 +$ 8.16Ar, were used to generate detonations with different cellular instabilities and cell sizes. Detonations with different cellular instabilities have been found to behave differently under perturbations [26–28]. The combustible mixtures were prepared using the method of partial pressures and kept for at least 12 h to mix. Smoked foils were used to register the change in the detonation cellular structure during the reflection process.

The velocity deficit is defined as V/V_{CJ}, where V_{CJ} is the calculated value of the equilibrium (CJ) velocity of the detonation wave, and V is the measured value. The measured velocity was determined across the last two photo probes before the half cylinder. The deficit is calculated for the shots and categorized in terms of the mixture type, as shown in Fig. 3. The tested mixtures consisted of $C_2H_2 + 2.5O_2$, $2H_2 + O_2 + 4.5Ar$ and $2H_2 + O_2 + 2Ar$. It can be observed that a CJ detonation is achieved before intersecting with the half cylinder. Figure 4 shows the cell size comparisons corresponding to the different mixtures with respect to the initial pressure.

2.2. Experimental results and discussions

The propagation modes of the detonations in the stoichiometric combustible mixtures of $2H_2 + O_2 + 4.5Ar$ and $2H_2 + O_2 + 2Ar$ are stable with the presence of a regular cell pattern, as shown in Figs. 5–9. The initial wall angle of the convex cylindrical surface in all cases is 90°. Therefore, an RR first occurs over the surface at the very beginning. As the detonation front travels along the surface, the RR immediately transitions to an MR when the wall angle decreases below a critical value (or equivalently, when the flow behind the reflection point becomes subsonic). Note that the wall angle is defined as the angle between the horizontal and the tangent line to the surface, as shown in Fig. 7. The triple-point trajectory of the MR can be obtained by observing the change in the cell pattern in the smoked foils. The Mach stem is overdriven with the presence of higher pressure, higher velocity, and thinner reaction zone as compared to the incident detonation wave (i.e., a CJ detonation wave). Therefore, in most cases, the cell sizes behind the Mach stem are smaller than that behind the incident detonation wave. The triple-point trajectory is curved because the curved Mach stem undergoes a continuous diffraction process due to the presence of the convex cylindrical surface. The incident detonation wave disappears as the perturbation signal reaches the top boundary along the Mach stem. Subsequently, a fully curved detonation front is formed, resulting in two intersecting sets of logarithmic spirals generated by the triple-point trajectories of the natural transverse waves, similar to the detonation diffraction process when a planar cellular detonation wave propagates into a free space from a tube [29–37] or the propagation mode of cylindrical detonations [29,38–40]. Because of the strong rarefaction effect, the detonation front decays and may decouple into a shock-reaction complex with the presence of an extending induction zone. Under a critical condition, the detonation front either fails locally or is entirely dependent on the instability of the mixtures and the length-scale ratio R/λ, where R is the radius of curvature, and λ is the cell size. As shown in Figs. 5–10, the detonation front is found to easily fail with the decrease in the initial pressure (or equivalently, with the decrease in the cell size).