Length scale effect on Mach reflection of cellular detonations

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ABSTRACT

An experimental study of the Mach reflection of cellular detonations over the wedge is reported in this paper. Throughout the experiments, high-quality smoked foil is obtained to record cell pattern variation. The initial pressures are varied to yield cellular detonations with varied transverse wave spacing (or cell size). This paper focuses on length scales controlling the deviation and recovery of self-similarity in an unsteady Mach reflection process. The results show that the frozen limit and equilibrium limit both exist for all the mixture compositions. The Mach reflection undergoes a frozen condition in the near field, and then goes through a transition process before asymptotically approaching an equilibrium state in the far field. The cell size variation in the Mach stem region also confirms the transient process. Although the final triple-point trajectory angle in the equilibrium state disagrees with classical three-shock theories, it is in agreement with the reactive three-shock theory when the wedge angle is less than 30°. The triple-point trajectory angle asymptotically approaches zero as the wedge angle increases to approximately 50°, indicating the critical wedge angle from Mach to regular reflection. The transition length associated with the equilibrium limit is found to be dependent on the mixture composition and has the same order of a hydrodynamic thickness, which is approximately a few cell lengths. This means that the hydrodynamic thickness is the characteristic length scale that most significantly dominates the Mach reflection process of cellular detonations.

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1. Introduction

The Mach reflection of an inert shock wave on the wedge is self-similar because of the absence of a characteristic length scale [1–3]. As a result, the classical three-shock theory [1–2], as well as the Chester–Chisnell–Whitham (CCW) [4–6] theory, can be used to describe the pseudo-steady state of the Mach reflection process and predict the critical wedge angle for the transition from regular to Mach reflection. Similarly, Mach reflection of a detonation assumed to be a discontinuity of negligible thickness is also self-similar and can be predicted by a modified reactive three-shock theory [7–10] or reactive CCW theory [8,11]. However, for a strong shock or a detonation wave of finite thickness, the existence of a characteristic length scale inhibits self-similarity of the Mach reflection process. Thus, all the theories based on a simple assumption of self-similarity and a pseudo-steady state cannot be applied to solve the non-self-similar Mach reflection process. The studies on shock waves in the dissociating gases [12,13] have identified two limiting regimes for self-similarity: (1) the frozen limit in which the reflection process is controlled by nonreactive

or "frozen" dynamics of the leading shock front in the near field, and (2) the equilibrium limit in which the reflection process is controlled by fully reacted or "equilibrium" dynamics of a reaction front in the far field [14]. Shepherd et al. [15] extend these classifications to detonations. Fortin et al. [16], Li et al. [17], and Li and Lee [18] confirmed the existence of frozen and equilibrium limits in Mach reflection of detonations via experiments and numerical simulations. Li and Lee [18] also suggest that the asymptotical approach to local self-similarity in the far field, when the reaction length is sufficiently small as compared to the travels of the Mach stem, can be explained by the decay of an overdriven detonation (i.e., the Mach stem). Here, two length scales exist to guarantee that the Mach reflection maintains localized self-similarity the frozen limit and is able to recover self-similarity the equilibrium limit. However, there are currently no reported studies on the quantitative measurement of the two length scales; the reason for this likely stems from the difficulties in measurement that result from the cellular properties of detonation fronts.

As shown in Fig. 1, for the Mach reflection of an inert shock wave, a triple-point exists to partition an incident shock wave, a reflected shock wave, and a Mach stem that is perpendicular to the wedge surface. For Mach reflection of a ZND detonation, a chemical reaction occurs behind both the incident wave and the Mach stem, which yields a more complex triple-wave structure. In
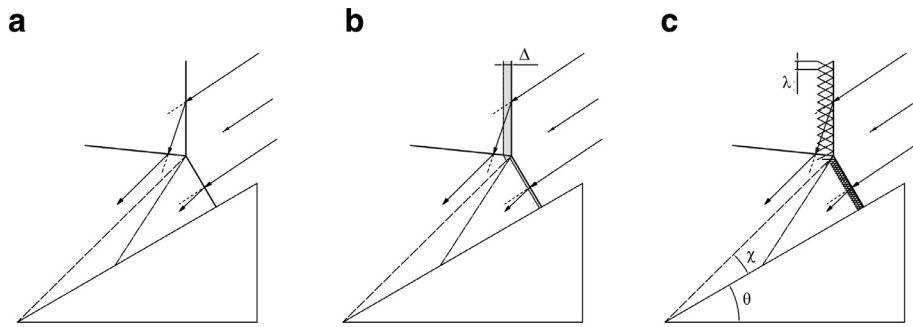
Fig. 1. Schematic illustrations of Mach reflection of (a) an inert shock, (b) a ZND detonation, and (c) a cellular detonation.
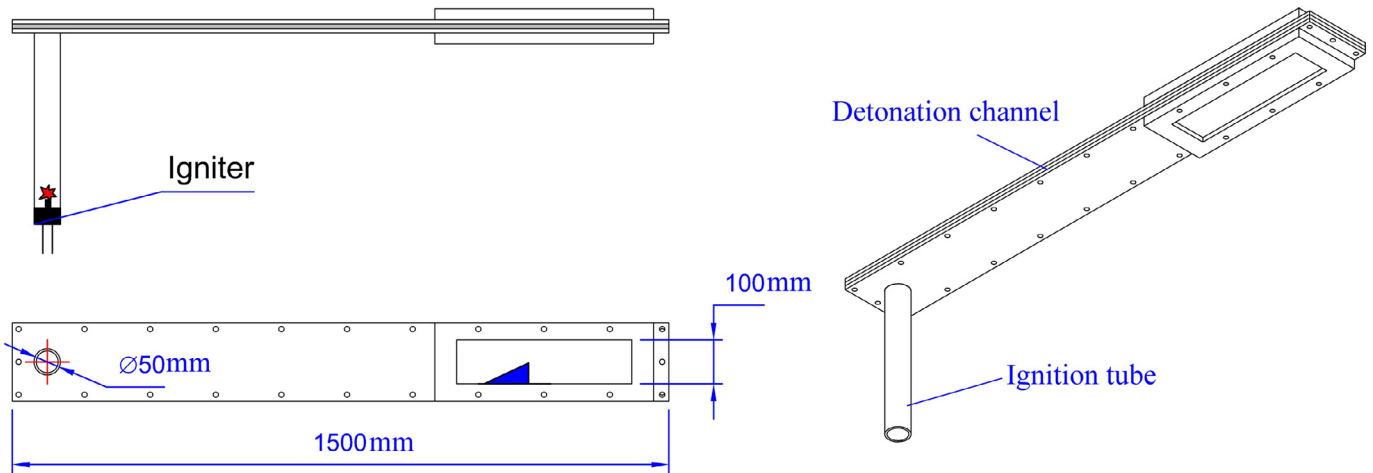

Fig. 2. Schematic of the experimental apparatus.

spite of this, the triple-point of the Mach reflection is still visible, as is observed in the case of an inert shock. However, for Mach reflection of a cellular detonation, the reflected wave of a Mach reflection is periodically disturbed by the vertically moving transverse waves. As such, differentiating the incident detonation from the Mach stem remains difficult. Thus, a clear triple-point trajectory of the Mach reflection cannot be easily obtained. Instead, a region with width on the order of a cell size can be used to demonstrate the transient process of the Mach reflection of cellular detonations. In general, self-sustained detonations are unstable and have a three-dimensional cellular frontal structure formed by the intersection of a system of transverse waves and the leading shock. Thus, the Mach reaction of a cellular detonation differs from that of a planar ZND detonation without cellular instabilities. If the cell size is small or the transverse waves are weak, the triple-point trajectory of a Mach reaction of a cellular detonation is similar to that of a planar ZND detonation. The cellular instability can be considered as small perturbations in the Mach reaction of a ZND detonation. In contrast, if the cell size is large as compared to the Mach stem height, or if the transverse waves are strong, the Mach reflection becomes considerably complex. Consequently, the effects of the wedge can be considered as a perturbation on the characteristic cellular instability of cellular detonations.

The Mach reaction of a cellular detonation over a wedge has been investigated both experimentally and numerically by a number of researchers [7–26]. Previous experimental studies have mainly focused on the triple-point trajectory and critical wedge angle for the transition from Mach to a regular reaction. In most cases, the observations are limited to a short travel distance of the Mach stem; this results in the fitting of a straight line to the triple-point trajectory. Depending on the specific conditions of the

experiments (e.g., cell size), agreement with the self-similar theories has been inconsistent. As an example, in the early study of Ong [7] on Mach reflection in a mixture of $H_2 + O_2$ with a small cell size, the detonation front is essentially a planar discontinuity. Thus, Ong found the results to agree with the self-similar reactive three-shock theory. Conversely, other investigators [9,19,20] have reported that the triple-point trajectory is curved, indicating that the Mach reaction is not self-similar. Despite the curved trajectory, these investigators still attempted to fit a straight line to it to obtain a triple-point trajectory angle to compare with the self-similar three-shock theory. Most previous numerical studies implementing a relatively regular cellular detonation structure were carried out over relatively short travel distances of the Mach stem. In the study by Trotsyuk [19], the numerical computations were carried out in a long Mach stem travel of approximately 60 times the cell size. Thus, Trotsyuk was able to observe the triple-point trajectory as an asymptote in the far field. For cellular detonations, the angle of incidence of the frontal wedge surface changes throughout a cell cycle. Thus, at the wedge surface, a localized reflection that alternates between occurring as a Mach reflection and a regular reflection may occur. Consequently, it may not be meaningful to define a critical angle of the wedge for the transition between Mach and regular reflections [21]. Wang et al. [22] reported that alternating regular and Mach reflections of cellular detonation occurs over a 50° wedge.

In order to understand the physics of the Mach reflection of cellular detonations, it is essential to identify a unique length scale to characterize the self-similarity. In the case of cellular detonations, three intrinsic length scales are presented: (1) the reaction length Δ (or the induction length Δ_I) based on a steady ZND structure, (2) the cell size λ that results from the nonlinear-coupling between the reactions and the hydrodynamics, and (3) the hydrody-