Combustion and Flame 162 (2015) 819–824

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Mach reflection of cellular detonations

Yannick Fortin *, Jie Liu [1], John H.S. Lee [1]

Department of Mechanical Engineering, McGill University, Montreal, Quebec H3A 0G4, Canada

A R T I C L E I N F O

Article history:
Received 31 May 2014
Received in revised form 9 August 2014
Accepted 7 September 2014
Available online 16 October 2014

Keywords:
Cellular detonation
Mach reflection

A B S T R A C T

The present paper reports the results of an experimental study of the Mach reflection of cellular detonations. Mixtures representing regular smoked foil pattern ($C_2H_2 + 2.5O_2 + 70\%Ar$) and irregular pattern ($C_2H_2 + 2.5O_2$, $C_3H_8 + 5O_2$) are used in the experiments. The range of the initial pressures used is 3 kPa < Po < 20 kPa which provide a range of cell sizes of the detonation front. Schlieren photographs as well as smoked foils are used to observe the phenomenon. Wedges of angles ranging from $10^\circ < \theta < 40^\circ$ are used. Measurement of the Mach stem height with distance traveled from schlieren photographs and smoked foils indicate that the triple point lies on a curved trajectory instead of a straight line from the wedge apex as obtained from self-similar three shock theory. This is due to the finite thickness of the detonation front presenting a characteristic length scale that renders the self-similar three shock theory invalid. Following the work of Hornung and Shepherd et al., the present results are analyzed according to the so called frozen and equilibrium limits. The results do seem to agree with the frozen limit for the initial propagation of the Mach stem near the apex of the wedge when the distance traveled by the Mach stem is small compared to the characteristic length of the detonation front (e.g. cell size "λ", hydrodynamic thickness, etc.). In the asymptotic far field region when the distance traveled is large compared to the effective detonation thickness, the present results appear to approach the prediction using three shock theory based on a discontinuous detonation front. Thus in spite of the transient three dimensional structure of a cellular detonation front, the frozen and equilibrium limit concept based on a global quasi-steady reaction zone thickness of the detonation front appears to provide a useful scheme to interpret the results. Examination of the smoked foils indicate that the interaction of the transverse waves of cellular instability with the reflected shock and shear layer of the Mach reflection play an important role in the description of the triple point region.

1. Introduction

Mach reflection of detonation waves by a wedge has been studied by various researchers: Ong [1], Gvozderva and Predvoditeleva [2], Gavrilenko et al. [3,4], Gavrilenko and Prokhorov [5], Edwards et al. [6] and Nettleton [7]. Among the more recent ones are Meltzer et al. [8], Li et al. [9], Akbar [10], Shepherd et al. [11], Hoshi et al. [12], Ohyagi et al. [13,14], Guo et al. [15], Hu and Jiang [16], Qing et al. [17], Wang and Guo [18] and Ziegler et al. [19]. In general the well established von Neumann [20] three shock theory is used to determine the trajectory of the triple point and the critical angle for the transition from regular to Mach reflection. The use of the three shock theory implied the absence of a characteristic length which renders the phenomenon self-similar. Unlike shock waves, the thickness of gaseous detonations is not negligible. Thus comparison between theory and experiments have been inconclusive. Where agreement was reported the experimental conditions may be such that self-similarity is indeed obtained. Perhaps the first to draw attention to the failure of self-similarity due to the finite thickness of the detonation front was Shepherd et al. [11]. They followed the work of Hornung [21] who studied the Mach reflection of strong dissociating shock waves. Two limiting regimes were defined, frozen and equilibrium, where self-similarity may be possible. Choosing the detonation cell size "λ" as the characteristic length scale of the detonation front and the distance of propagation $L \sim Ut$ of the Mach stem as the representative geometrical length scale of the problem, the frozen limit corresponds to $\lambda/l \gg 1$ while the equilibrium limit corresponds to $\lambda/L \ll 1$. Hence in the frozen limit $\lambda \gg$ L the Mach reflection is essentially that of a shock wave with frozen state behind it. In the equilibrium limit where $\lambda \ll$ l, the thickness of the detonation front becomes negligible compared to "L" and hence the problem essentially has

* Corresponding author at: Department of Mechanical Engineering, McGill University, 845 Sherbrooke St W, Montreal H3A 0G4, Canada. Fax: +1 514 398 7365.

E-mail addresses: yannick.fortin2@mail.mcgill.ca (Y. Fortin), jie.liu5@mail.mcgill.ca (J. Liu), john.lee@mcgill.ca (J.H.S. Lee).

[1] Fax: +1 514 398 7365.

http://dx.doi.org/10.1016/j.combustflame.2014.09.003
0010-2180/

no characteristic length scale. Analysis of experimental results by Akbar [10] indicated that self-similarity is observed for two out of three cases. However the range of shock travel is limited and together with uncertainties in the measurement of the shock shape the conclusion is not definitive. It should be noted that unlike the reaction zone of a dissociating shock wave, the cellular detonation front is unsteady and three dimensional. One may approximate a cellular detonation to have a quasi-steady "hydrodynamic thickness" based on averaged quantities. The typical hydrodynamic thickness is estimated to be a few cell lengths. It should be noted that for a cellular detonation the "effective" characteristic length scale of the detonation may not be the cell size λ. The ZND length $\sim 15\lambda$ and the hydrodynamic thickness $\sim 5\lambda$ maybe the appropriate characteristic length scale. However in this study we shall use the cell size λ. However the transverse waves of cellular instability would interact with the reflected shock of the Mach reflection and "blur" the triple point to be a finite region rendering the quasi-steady property invalid. Mach reflection of cellular detonations is a complicated phenomenon and further studies are required. It is of importance to observe the phenomenon over a long distance of travel covering the initial and the far-field asymptotic regions. It appears that smoked foils are the most convenient method of observation. This will be supplemented by schlieren photography that shows the shock configuration. In the present study detonable mixtures with both regular and irregular cell patterns are used and the initial pressure is varied to obtain a range of cell sizes for the incident detonation.

2. Experimental details

A schematic of the experimental setup is shown in Fig. 1. The rectangular detonation channel is 1.14 m × 0.14 m × 0.025 m and the two side walls are tempered glass plates to permit schlieren photography. Some experiments have been carried out in a channel of different thickness and no observable influence on the Mach reflection phenomenon was observed and thus all the results reported are obtained in one channel width of 2.5 cm. Premixed mixtures of $C_2H_2 + 2.5O_2$ with 70% of argon dilution was used to represent a "stable" mixture with regular cellular pattern, and $C_3H_8 + 5O_2$ is used as the unstable mixture with irregular cell pattern. Experiments with undiluted $C_2H_2 + 2.5O_2$ were also carried out to represent a sensitive mixture with a very small cell size. The initial pressure range of the experiments was between 3 kPa and 20 kPa. The glass window cannot withstand higher initial pressures to obtain detonations with very small cell sizes to permit the assumption of a "discontinuous" detonation front. Also it is difficult to initiate the detonation at low initial pressures to obtain detonations with large cell sizes. In the present investigation initiation of the detonation is via a high voltage capacitor discharge through three spark gaps connected in series. Perforated plates downstream of the sparks create turbulence to assist the formation of a planar detonation front across the width of the channel. Schlieren photographs were taken at various time delays to observe the Mach reflection process at different locations on the wedge. Five wedges (10°, 20°, 30°, 35° and 40°) were used. For each wedge and given mixture, various initial pressures are used to give a range for the magnitude of the detonation cell size ranging from 1 mm to 37.7 mm measured from the smoked foils. Comparison with smoke foils obtained in larger tubes shows that the deficits are negligible. To observe the cellular structure, smoked foils are used which give a record of the transverse waves and permit the boundary between the Mach stem and incident detonation to be defined. Each schlieren photograph represents a single experiment but enough reproducibility was found to allow a chronological reconstruction of the phenomenon.

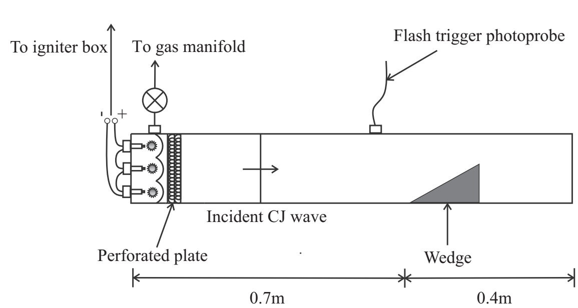

Fig. 1. Schematic of the test section.

3. Results and discussion

Figure 2(a) shows schlieren photographs of regular reflection in $C_2H_2 + 2.5O_2$ mixture at an initial pressure of 20 kPa over a wedge angle of 35°. The cell size is about 1 mm for this case. Using three-shock theory, the critical angle for the transition from regular to Mach reflection is 34°, thus the experiment is close to the critical transition angle. The experiment indicate no discernible Mach stem which is in agreement with the theory. However Fig. 2 show detonations in mixtures of $C_2H_2 + 2.5O_2 + 70\%Ar$ at 20 kPa (cell size of about 2.2 mm) and $C_3H_8 + 5O_2$ at 10 kPa (cell size of about

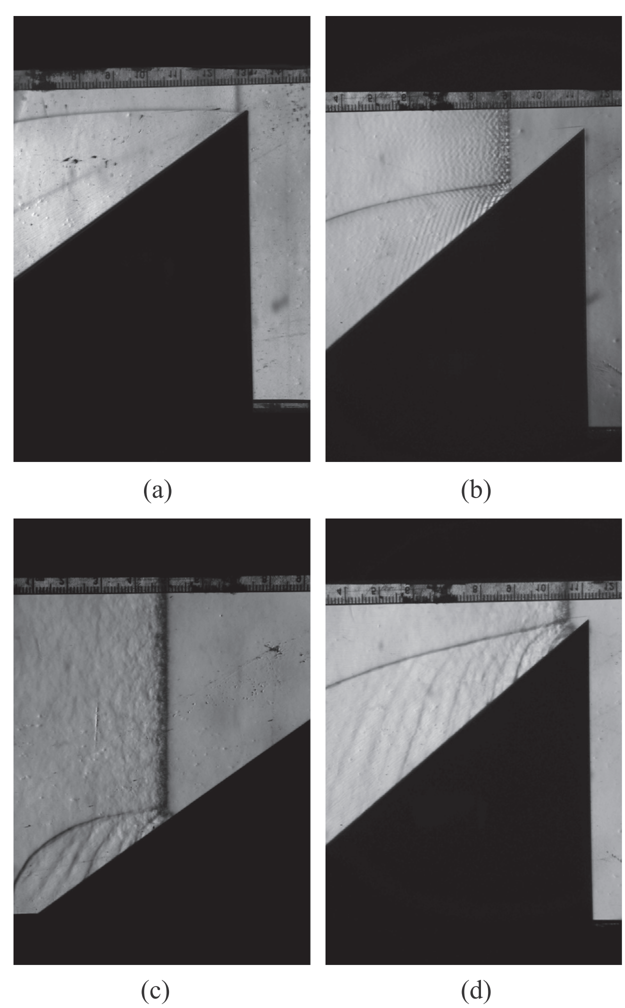

Fig. 2. Detonation wave in (a) $C_2H_2 + 2.5O_2$ 20 kPa over a 35° wedge, (b) $C_2H_2 + 2.5O_2 + 70\%Ar$ 20 kPa over a 40° wedge, and (c and d) $C_3H_8 + 5O_2$ 10 kPa over a 40° wedge.