The critical conditions for the formation of the Mach shock from shock reflections

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1 Introduction

The focus of this study is to establish the critical strength and decay rate of reflecting shocks in a reactive gas that can form a detonation wave. This problem arises within the cellular structure of detonations, where new reactive shocks are intermittently formed from indent Mach reflections [1]. It also addresses the initiation of detonations in engine technology, for example. To the best of our knowledge, this problem has not been previously formulated nor solved. By implementing a technique inspired by White's nozzle method [2], we reliably generate two detracting shock waves. These shocks result from the passage of a detonation wave through a converging-diverging nozzle. In this approach, the cellular instability will be reduced to smaller scales by overdriving the detonation wave in the converging channel. Then by passing through the diverging section, a smooth incident shock followed by a reaction zone will be created, Fig. 1. This simple technique permits us to reproducibly generate Mach reflection and determine the conditions for detonation re-initiation.

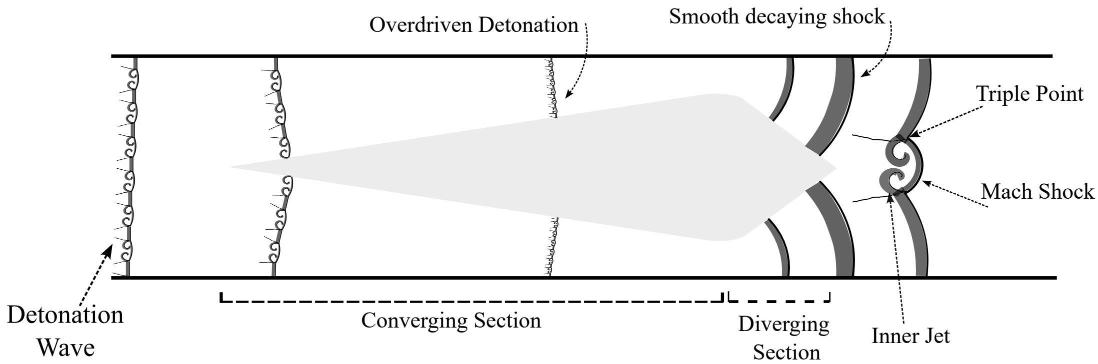

Figure 1: Schematic of the experimental configuration to isolate a reactive Mach reflection.

The controlling parameters that are believed to have an impact are systematically changed to determine the role of the local conditions in the formation of Mach shock [1, 3]. The dynamics of the decaying Mach shock and its reflection will be modelled using standard triple shock theory [4, 5]. The Mach shock velocity will be used to calculate the characteristic ignition delay time and the characteristic scale of the expansion time behind the generated Mach shock [6, 7]. This will allow us to determine the characteristic time scales of Mach shock in the reflection process and its impact on ignition events.

2 Experiment

Experiments are performed in a 3-m-long shock tube, with 0.019-m-thickness and 0.203m-height, detailed in a previous study [8]. The schematic illustrating the experimental set-up is shown in Fig. 2. A 0.708m-long diamond shape object made of aluminum was inserted into the test section to create an inverted converging-diverging nozzle with the top and bottom walls of the shock tube, symmetrically. The angle of the converging section was kept at 15° (7.5° at each side of the channel) to provide a smooth overdriven detonation without any kink on the structure as reported in other studies [9]. In the diverging channel, the detonation is made to recover an idealized quasi-laminar structure of a shock followed by a reaction wave. As sketched in Fig. 1, the two symmetry decaying shocks from the top and bottom channels interact at the apex of the diamond and generate a Mach reflection.

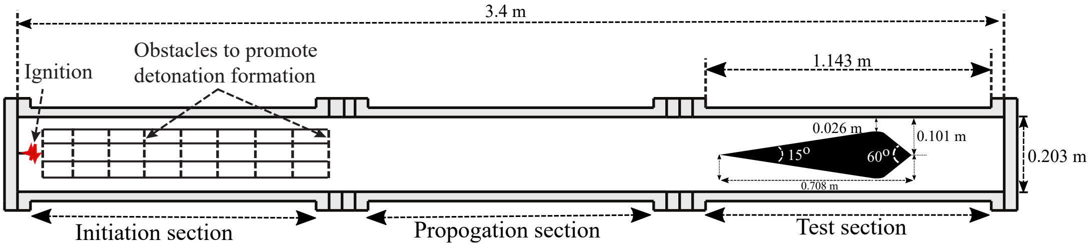

Figure 2: Schematic of the shock tube used in the experiments.

The propagation process is visualized by utilizing Schlieren technique videos with a high-speed Phantom v1210 camera. The time intervals between the frames are 12.9 μs and 13.6 μs for different resolutions (approximately 80,000 frames per second). Table 1 shows the experimental test gases along with their thermo-chemical properties calculated using the San Diego chemical mechanism [10].

Table 1: The experimental test gases and their properties.

Mixture	P_0 [kPa]	γ	Δ_i [mm]	$\frac{t_i}{t_r}$	$\frac{E_a}{RT_s}$	$\chi = \frac{t_i}{t_r}\frac{E_a}{RT_s}$
$CH_4/2O_2$	15	1.17	2.9	44	12	510
$2H_2/O_2/2Ar$	15	1.4	0.38	0.82	4.5	3.7

The two mixtures of interests are the stoichiometric mixture of methane-oxygen ($CH_4/2O_2$) and the stoichiometric mixture of hydrogen-oxygen with two moles of argon ($2H_2/O_2/2Ar$). Between these two mixtures the compressibility factor, γ, and stability parameter, χ, change over a sufficiently wide range. This permits us to study the relevant gas dynamic and thermo-chemical parameters controlling the gas response to local energy release. For each mixture, its sensitivity was controlled by changing the initial pressure of the test gas. The critical pressure of re-ignition in each mixture was determined. In the following, some of the experimental results of the methane mixture are presented.

Fig. 3 (a, b and c) shows the propagation of the detonation wave from left to right through the converging channel. Close to the throat, the average velocity of the detonation reaches 2380 $\mathrm{m/s}$ which is above the CJ velocity (2313 $\mathrm{m/s}$). Fig. 3 (d, e and f) shows the transmission of the detonation wave to the diverging channel. By the end of this section, the shock and the reaction front are decoupled and two smooth decaying incident shocks on the top and bottom sides of the channel are created.

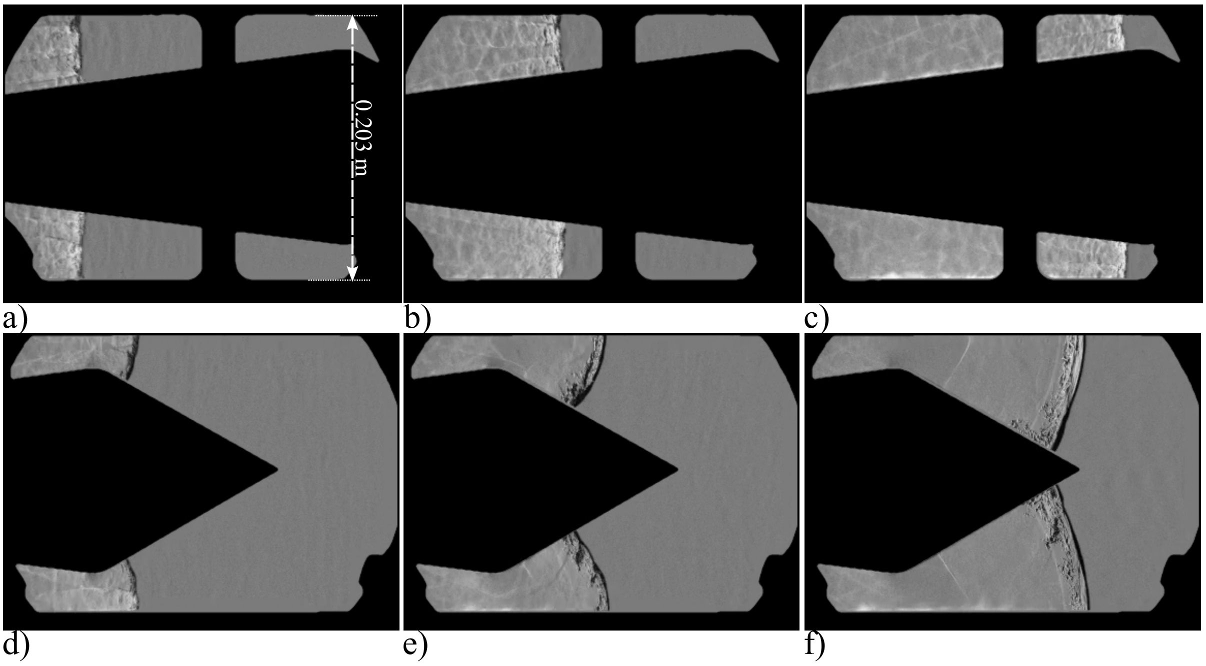

Figure 3: The formation of the overdriven detonation through converging channel (a, b, c) and the decay of the shocks in the diverging channel (d, e, f) in $CH_4/2O_2$ mixture at the initial temperature of 293 k and the initial pressure of 17 kPa.

In Fig. 4, the two decaying shocks reflect on the plane of symmetry and generate a Mach shock. The Mach shock continues to move forward while its speed reduces. The amount of unburned gas behind the decaying shock increases over time. As opposed to the previous case, a successful transmission of detonation wave after the reflection of the two incident shocks is shown in Fig. 5. The initial pressure of this experiment is the same as the earlier reported failed case, P_0= 17 kPa. The repeated experiments at this pressure showed that this pressure is a critical pressure in which either of successful or failed cases might happen.

Fig. 6 (right) illustrates the change in wave velocity profile (relative to the CJ velocity) on the top wall (dashed lines), the bottom wall (dotted lines), and the center line (solid lines) along the x-axis. The graph's origin is located at the object's apex. The black and blue lines in the figure represent two unsuccessful scenarios (as shown in Fig. 4), where the velocity of the Mach shock decreases and does not reach the CJ velocity. In contrast, the red and green lines depict two successful scenarios of detonation reinitiation, with the Mach shock velocity immediately exceeding the CJ speed and eventually propagating at around the CJ velocity. In all cases, the two incident shocks propagate at 60% of the CJ speed before reflecting off the walls.

Fig. 6 (left), is the velocity profiles on the converging section as shown in Fig. 3. In all three different pressures, an overdriven detonation is formed and velocity continues to increase while the area of the channel is decreasing.

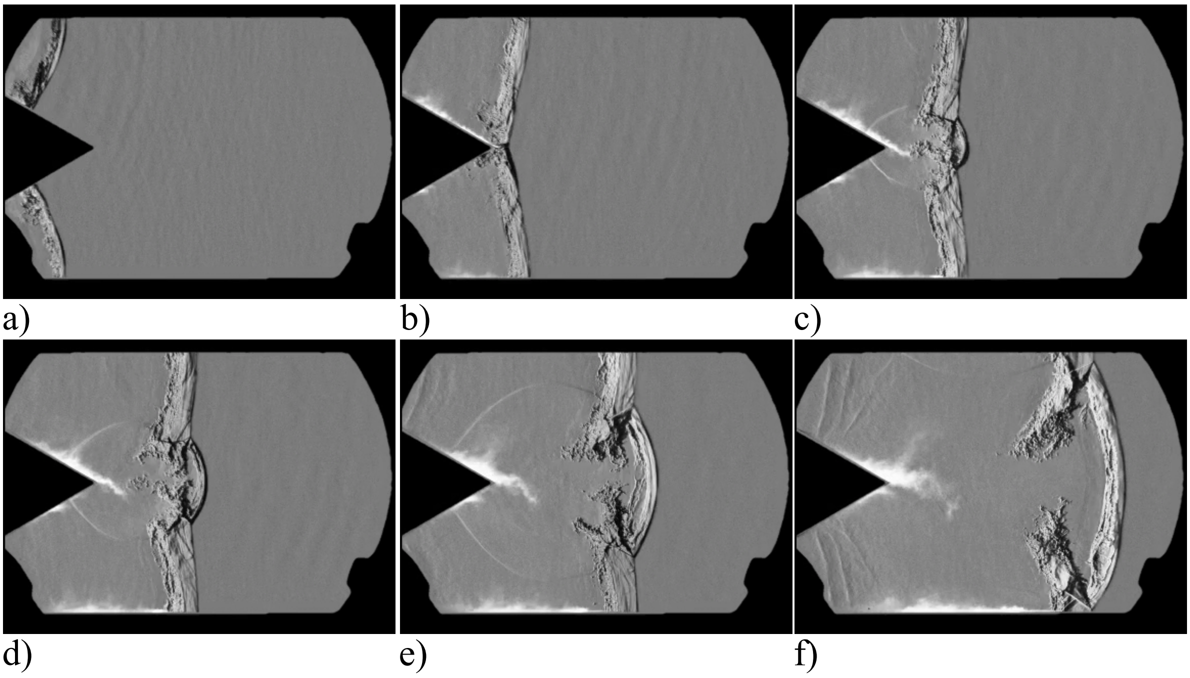

Figure 4: The formation of a decaying Mach shock in $CH_4/2O_2$ mixture at an initial temperature and pressure of 293K and 17 kPa, repectively.

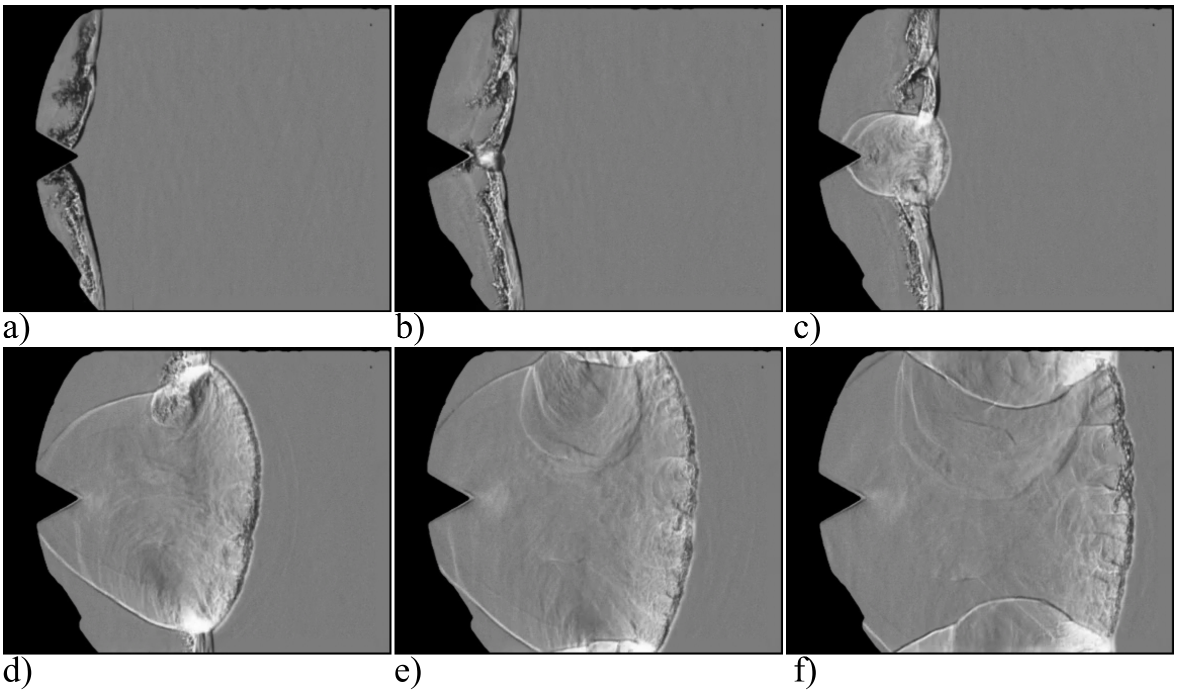

Figure 5: The formation of a detonative Mach shock in $CH_4/2O_2$ mixture at an initial temperature and pressure of 293K and 17 kPa.

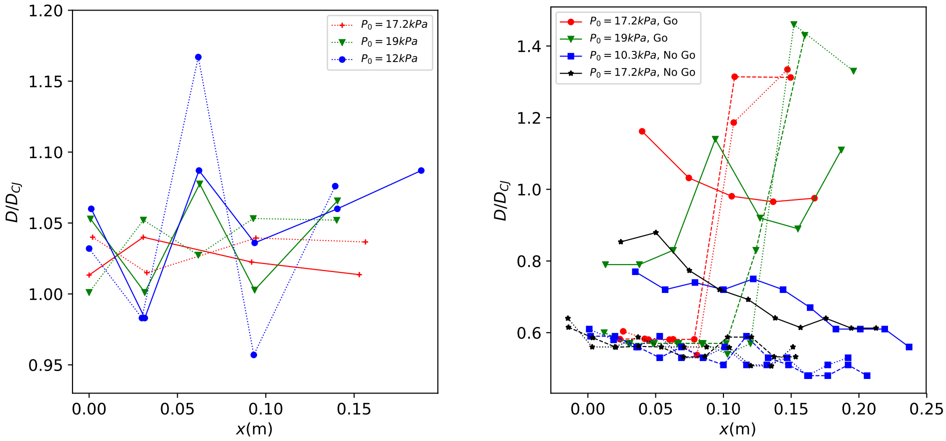

Figure 6: (Right) The velocity profile of the two incident shocks on the top (the dashed line) and bottom walls of the shock tube (the dotted line) and Mach reflection on the centerline (the solid line) after reflection. (Left) The velocity profile of the overdriven detonation in the converging section. The solid lines are along the top wall and the dotted lines are along the bottom wall. All the velocities are nondimensional with the CJ velocity. The visualized distance is approximately 240 mm on each wall. The test gas is $CH_4/2O_2$ at T_0=293 K.

3 Results and disscusion

Fig. 7 (left) shows the velocity of the incident shocks over time on the top and bottom walls in the diverging section at three different pressures (19 kPa, 17 kPa, 7 kPa). The slope of each line represents the deceleration rate, $\dot{D}$, of the incident shocks. The time zero is when the two incident shocks collide. Fig. 7 (right) depicts the distance versus time in which the slope of the lines is the velocity of the incoming shocks for each experiment.

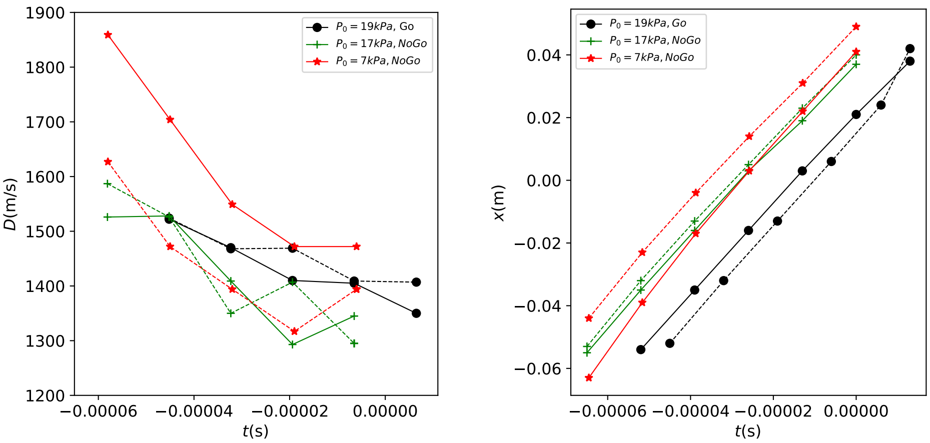

Figure 7: The evolution of the velocity of the shock (left) and the travelled distance by shock over time (right) in the mixture $CH_4/2O_2$ at T_0=293 K. In all cases, the solid lines are along the top wall and the dashed lines are along the bottom wall of the shock tube.

The experimental results of the Mach shock reflection in inert gases showed that the ratio of deceleration to velocity, $\frac{\dot{D}}{D}$, is similar for both the incident shock and its derived Mach shock. By knowing $\frac{\dot{D}_I}{D_I}$, the volumetric expansion [6] time behind the Mach shock is calculated, Table 2. The ignition delay time behind the Mach shock was estimated using constant volume homogeneous reactor calculations from Cantera [11]. The Mach shock velocity is estimated from the triple point theory.

Table 2: The charactersitic times of the Mach shock in the mixture of $CH_4/2O_2$ in three different scenarios.

P_0 [kPa]	result	Expansion time [s]	ignition delay time [s]
19	reinitiation	0.0002	0.0003
17	quenching	0.0001	0.0003
7	quenching	0.00009	0.0006

These results indicate that reinitiation occurs when the expansion time is comparable to the ignition time behind the decaying shock. Further experiments and analysis on different mixtures and geometries will be conducted to develop a model for predicting the initiation conditions.

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