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Shock Wave–Boundary Layer Interaction from Reflecting Detonations

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1 Introduction

The present work is concerned with the differences in how shock and detonation waves inside pipes or ducts reflect from closed ends. One of the motivations for the present study is that the large pressure rise associated with a detonation poses a hazard to pipes that contain flammable mixtures [1]. A detonation impinging normally on a planar wall creates a reflected shock wave to bring the flow at the wall to rest [2] and produces pressures 2.4 times that of an incident Chapman-Jouguet (CJ) detonation [3]. In examining the material deformation produced by reflected detonation loading [4] an inconsistency was discovered between the measured pressure jump across the reflected shock wave and the measured speed of the shock, with the measured pressure being as much as 25% below that predicted by the shock jump relations for the given shock speed. This was theorized to be due to bifurcation of the reflected shock wave associated with shock-wave boundary layer interaction.

Previous researchers have observed shock wave bifurcation in experiments pertaining to shock tube performance [5, 6, 7, 8, 9]. Shock bifurcation is the splitting of a reflected shock near the wall into an oblique and a normal wave due to interaction with the fluid in the boundary layer created by the incident shock. This results in a foot extending from the wall to the primary reflected shock as sketched in Fig. 1. Mark [5] developed a theory describing reflected shock wave bifurcation and created a model for predicting the conditions under which bifurcation will occur. However, the differences between shock and detonation waves prevent this theory from being directly applied to the reflected detonation case. Previous computational work [10] has suggested reflected detonations do bifurcate, but these simulations did not consider the three-dimensional flow behind a detonation nor heat loss to the wall, both of which may affect bifurcation behavior. The goal of the present study is to experimentally investigate the influence of the boundary layer in detonation reflection.

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2 Theory

A sketch illustrating archetypical shock wave bifurcation is shown in Fig. 1 with velocities given in the shock-fixed frame. A reflected shock wave of speed U_R is passing into fluid set in motion by the incident wave to speed u and has developed a boundary layer at the bottom wall due to the no-slip condition. The fluid velocity will be a function of space and time due to the boundary layer and the presence of the Taylor wave behind a detonation [11]. The primary reflected shock wave propagates into the fluid outside the boundary layer in a one-dimensional fashion and determines the shock speed. In the boundary layer the combination of low-speed fluid and the prescribed pressure rise across the shock wave may cause the fluid to detach and form a separated bubble that, due to insufficient static pressure [5], will travel with the reflected shock wave and cause the bifurcated region to grow.

A simple theory has been developed by Mark [5] and refined by Davies and Wilson [7] to predict if bifurcation will occur for a given mixture and Mach number. This theory uses a simplified flow field where the fluid inside the boundary layer has zero velocity and is at the initial temperature and the fluid outside the boundary layer is unaffected by the wall. Bifurcation, Mark argues, will then occur if the stagnation pressure of the fluid inside the boundary layer relative to a frame stationary with respect to the reflected shock is less than the pressure behind the reflected shock wave. In the detonation case the assumption of a cold boundary layer is questionable due to the large temperature variations within the boundary layer. Furthermore, the flow field behind the detonation is three-dimensional with transverse waves and shear layers complicating theoretical predictions. The absence of an applicable theory for the reflected detonation case has led us to pursue experimental work examining reflecting detonation waves and how they compare to reflecting shock waves of similar molecular composition and initial pressure.

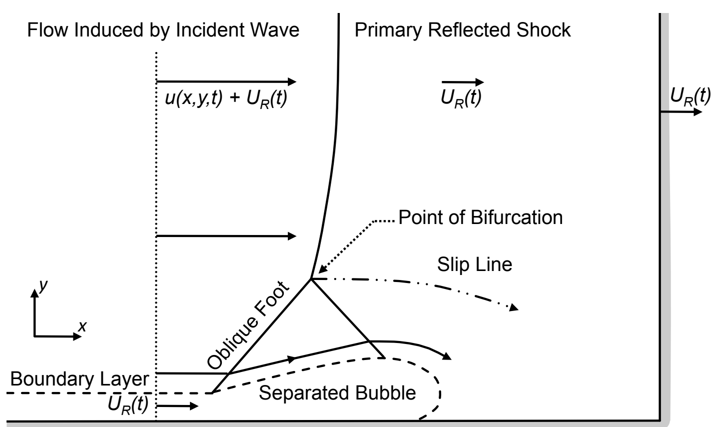


Fig. 1 Sketch of reflected shock wave bifurcation with velocities shown in the shock-fixed frame

3 Experimental Setup

All experiments were performed in the GALCIT Detonation Tube (GDT). (For a description of the facility, see [12].) The GDT is a 7.6 m long detonation tube of inner diameter 280 mm equipped with a test section of 150 mm wide square cross section and two quartz windows to provide optical access. The tube is initially evacuated and then filled via the method of partial pressures to the desired composition; a circulation pump is then employed to ensure proper mixing. After the mixing period, a sequence of events is initiated that begins the experiment: 1) A mixture of acetylene and oxygen is injected into the ignition end of the GDT for a duration of 4.5 s. 2) The mixture is allowed to settle for a period of 1 s. 3) A 2 μF capacitor charged to 9 kV is discharged through an 80 μm diameter 30 mm long copper wire located in the ignition end of the GDT. This discharge vaporizes the copper wire and detonates the acetylene-oxygen buffer. The strong shock wave generated from this detonation then propagates into the test mixture. This shock wave will either detonate the test mixture or, in the case of a non-reacting test mixture, begin to decay. In the results presented herein the test mixture is either air, pure nitrous oxide, or a mixture of nitrous oxide and hydrogen as given in Table 1. Nitrous oxide is chosen for the ease with which it has been observed to bifurcate in reflected shock wave experiments [6]. Four PCB 113B26 pressure transducers mounted in the GDT and test section are used to monitor the wave speeds. Table 1 shows large deviations from the theoretical CJ speed with the pure nitrous oxide mixture implying a detonation is only observed in the hydrogen-nitrous oxide mixture as expected from previous tests [13].

After the ignition sequence occurs, there will either be a decaying shock wave or a detonation wave entering the test section shown in Fig. 2. Two aluminum plates are mounted so that the boundary layer behavior may be seen through the windows. A Z-type schlieren setup consisting of a 400 ns duration spark light source, two 1600 mm focusing mirrors, and a Nikon D200 CCD camera is used to visualize the fluid mechanics. The camera is operated with an open shutter and the timing is controlled via the spark light source. This setup is not capable of obtaining multiple images of a single experiment. In cases where multiple images of the same mixture are shown (as in Fig. 3), the experiment is repeated and the spark timing is altered to create a sequence of events.

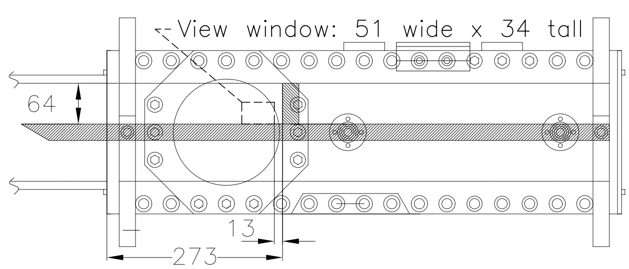


Fig. 2 Detail view of the test section for the GDT; dimensions in mm

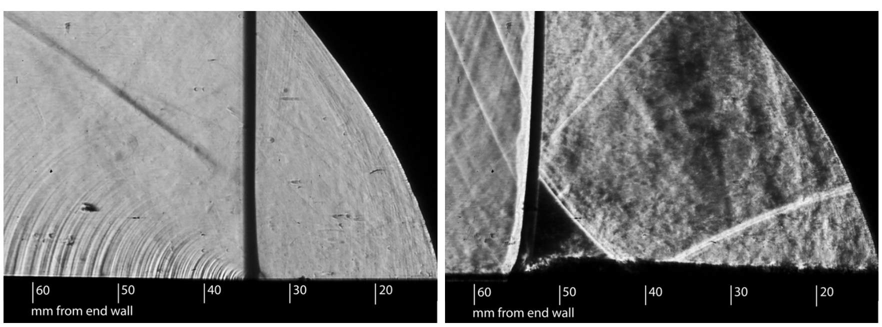
Table 1 Run conditions with incident shock speed U_I, theoretical CJ detonation speed U_{CJ}, incident shock Mach number M_I, reflected shock Mach number M_R, temperature behind the incident wave T_2, and ratio of specific heats γ behind the incident wave

Mixture	Initial Pressure (kPa)	U_I [a] (m/s)	U_{CJ} [b] (m/s)	M_I [a]	M_R [a]	T_2 [b] (K)	γ [b]
79% N_2, 21% O_2	25	770	N/A	2.2	1.6	557	1.4
100% N_2O	15	730	1690	2.7	1.6	578	1.28
90% N_2O, 10% H_2	15	1670	1804	5.9	1.6	2827	1.27

[a] Calculated using the shock jump relations with the pressure rise across the shock as measured by the pressure transducer located in the test section.
[b] Computed using Cantera 1.8 and the Shock and Detonation Toolbox [3].

4 Discussion

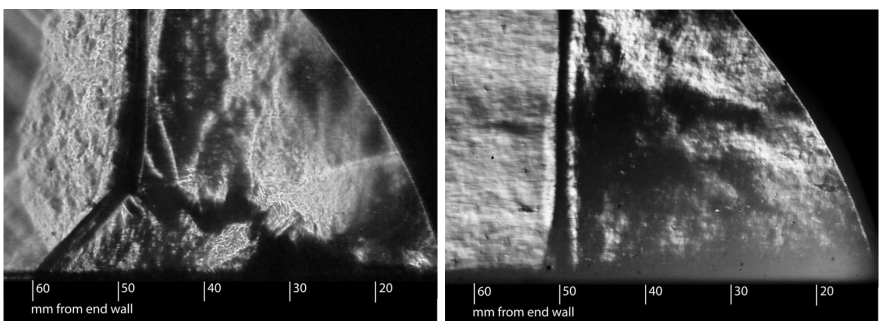
The case of a shock wave propagating in air is shown in Fig. 3. Fig. 3a shows the incident shock propagating to the right of the figure. Fig. 3b is taken 200 μs later than 3a and shows the reflected shock propagating to the left. Visible at the wall is the bifurcated foot propagating ahead of the primary shock wave and a turbulent boundary layer behind the reflected shock. This test serves as a point of comparison as we examine the nitrous oxide mixtures.



(a) (b)

Fig. 3 (**a**) Incident shock wave of Mach number 2.2 in 25 kPa initial pressure air propagating to the right. (**b**) Reflected shock wave in the same mixture propagating to the left and interacting with the boundary layer created by the incident wave

Fig. 4a shows the reflected shock wave in the pure nitrous oxide mixture. Complicating the image is the boundary layer interaction and bifurcation on the side wall formed by the windows, but it is readily observed that the bifurcated region is substantially larger than that observed in the higher pressure air mixture and qualitatively similar to the images obtained in carbon dioxide by Taylor and Hornung [8]. This enhanced effect is due [6] to the lower ratio of specific heats, γ, in nitrous oxide (see Table 1). Comparing Fig. 4a to the reflected detonation shown in Fig. 4b reveals that, although bifurcation is still present, the height of the bifurcated foot at similar distance from the end-wall is substantially reduced by the detonation despite a similar computed specific heat ratio. The observed reduction in bifurcation height is explained by considering the bifurcation theory developed by Mark [5]. As given in Table 1, the temperature behind the incident shock wave is 578 K for the pure N_2O mixture and 2827 K for the N_2O–H_2 detonation. If, like Mark, we assume that the temperature of the fluid in the boundary layer behind the incident wave equals the initial wall temperature then the Mach number of the reflected shock traveling in the boundary layer will be affected much more by the cold boundary layer in the case of an incident detonation than an incident shock wave. Specifically, the reduction in sound speed due to the cold boundary layer will result in a substantially larger Mach number than would be computed using the sound speed in the center of the vessel. This has the effect of hindering bifurcation by increasing the stagnation pressure in the boundary layer. In other words, although the Mach numbers in the free stream are comparable, the reflected shock Mach number in the boundary layer is much higher for an incident detonation than an incident shock wave and thus the potential rise in the boundary layer stagnation pressure is larger in the detonation case. Further investigation is required to better understand the behavior of the boundary layer behind detonations and properly interpret these results.



(a) (b)

Fig. 4 (**a**) Reflected shock wave in pure N_2O and (**b**) reflected detonation wave in 90% N_2O, 10% H_2. Both tests had initial pressure 15 kPa and the waves are propagating to the left

5 Conclusion

Bifurcation of a reflecting shock wave is readily observed in a pure nitrous oxide mixture of initial pressure 15 kPa. However, adding a small amount of hydrogen to the mixture thereby creating a detonation wave drastically reduces the degree of bifurcation observed. The present work is preliminary and further study is in progress to generalize this to other mixtures and obtain a clear explanation for this effect.

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