The Structure of Convective-Diffusive Fast Flames and their Transition to Detonation

Logan Maley, Rohit Bhattacharjee, Matei Radulescu
Department of Mechanical Engineering, University of Ottawa
Ottawa, Canada

1 Introduction

The last stage of the deflagration to detonation transition is the so-called fast flame, or choking regime, where a deflagration and shock wave complex propagate quasi-steadily at approximately half the CJ velocity. This regime is presently very poorly understood, sometimes even labeled as a "strange wave" [1]. Burning velocities of a few hundred meters per second are required behind the leading shock in order to explain such waves. It is difficult to account for such high deflagration speeds based on turbulent deflagration velocities; experiments in fan-stirred bombs show that turbulent velocities eventually saturate as the turbulent intensity is increased. Based on indirect experimental observations, it is believed that these fast deflagration velocities are maintained via the action of pressure waves within this deflagration complex (see [2] and references therein). These transverse pressure waves are believed to contribute to the increase of the level of turbulent mixing by the Richtmyer-Meshkov instability, similar to the action of transverse waves in highly unstable cellular detonations. Chao investigated the fast deflagration waves established downstream of a porous plate [3]. She observed a complex gas-dynamic system, which accelerated slowly towards the CJ detonation regime. Ciccarelli et al. also observed such a high intensity burning regime in a more complex set-up [2]. Fast deflagration waves were established in a porous medium with an adjacent open channel; the fast deflagration waves in the open channel were driven by the transverse waves emanating from the porous layer. Radulescu and Maxwell [4] also investigated the re-initiation of detonation waves downstream of a porous medium, which comprised a two-dimensional array of staggered cylinders. They reported in their numerical simulations that such high-speed deflagrations require auto-ignition spots via shock compressions to drive strong pressure wave activity. This suggests that high speed deflagrations and unstable detonations share the same propagation mechanism. Open shutter photographs supported this scenario as shown in Fig. 1.

The present study attempts to experimentally isolate the structure of high-speed deflagrations established after a detonation has interacted with a porous plate or series of cylindrical obstacles. This study focuses on the flow field established following the interaction with a single obstacle, as this effectively represents the unit cell of the turbulent deflagration structure. Detailed flow visualization was implemented in order to clarify the propagation mechanism of this wave.

Correspondence to: LMaley@uottawa.ca

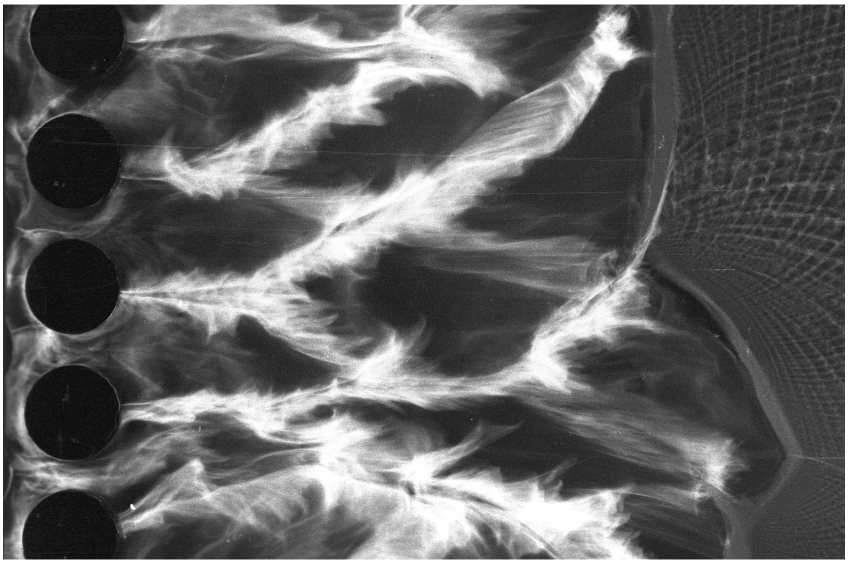

Figure 1: Open shutter photograph illustrating the fast deflagration wave propagation through active transverse waves and the eventual onset of detonation in acetylene-oxygen, adapted from [4]

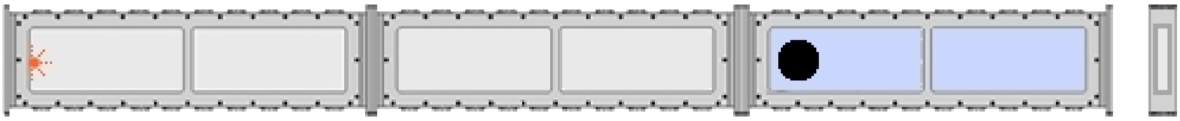

Figure 2: Schematic of the experimental channel used to investigate the structure of the fast flame established after a detonation interacts with a cylindrical obstacle. The channel is 3.1 m long, 203.2 mm tall, and 19.1 mm wide

2 Experimental Method

The experiments were performed in a 3.1m long rectangular channel with a thin aspect ratio, 19.1 mm by 203.2 mm, seen in Fig. 2. The thin aspect ration allows for the observation of quasi two-dimensional phenomena. The final section of the channel has glass walls allowing for optical access of the phenomenon. In order to visualize the phenomenon, a Z-type Schlieren photographic system has been implemented allowing for a visual field of 317.5 mm diameter. The photographs are taken with a Phantom v1210 high speed camera which records frames at a rate of 77108 frames per second and a high intensity LED light source. The Schlieren system is designed to capture horizontal density gradients using a vertical knife edge. Direct chemi-luminous photographs were also captured with the same Phantom camera with frame rates up to 140000 frames per second.

The test mixture used was stoichiometric oxy-methane mixed using the method of partial pressures and left to diffuse for a minimum of 24 hours before testing. The channel was evacuated to a pressure below 70 Pa before being filled with the gas to be tested.

The initial detonation waves were ignited using a capacitor discharge at one end of the tube opposite the view field. The detonations reached the CJ velocity before interacting with the obstacle. The experiments consisted of passing this self-sustained detonation around a cylindrical obstacle, 152.4 mm in diameter. For sufficiently low initial pressure, the diffraction of the wave around the downstream side

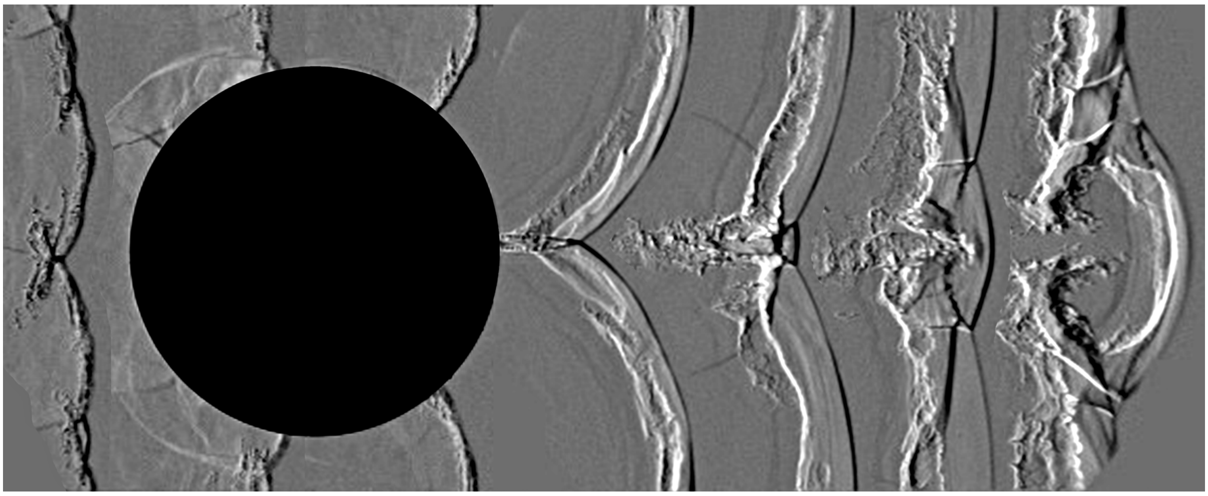

Figure 3: Composite of Schlieren frames illustrating the diffraction of a detonation wave around the cylindrical obstacle and the local re-ignition after shock reflections due to jet behind the Mach stem obtained at 8.2 kPa initial pressure.

of the cylinder causes the detonation to fail, decoupling the shock wave and reaction zone. The resulting dynamics of the fast flame structure were monitored with time-resolved Schlieren photography and chemi-luminescence photographs.

3 Results

Fast flames were observed in the pressure range of 5 kPa to approximately 20 kPa. Above this pressure range, the detonations transmitted directly over the obstacle. Below this range, a decoupled shock-flame system was observed. Further details can be found in Bhattacharjee's thesis [5]. Fig. 3 shows a typical example obtained at 8.2 kPa, illustrating the diffraction of a detonation wave around the cylindrical obstacle and the local re-ignition into a fast flame.

Figure 4 shows an example of the completely decoupled shock reaction zone structure obtained at 3.5 kPa. The sequence of photographs show the details of shock reflections, while the reaction zone remains relatively smooth.

In vivid contrast with Fig. 4, the re-ignited case of Fig. 3 shows re-ignition. After the detonation diffracts around the cylinder, the reaction zone decouples from the decaying shocks. The subsequent Mach reflection, however, permits local re-ignition, seen as a kernel of reacted gases violently expanding behind the front, marked by a system of new shock waves within the reaction front. Inspection of the photographs reveals that the re-ignition is greatly enhanced by the jetting action accompanying strong Mach reflections [6, 7]. As the hot combustion products enter the region behind the Mach stem, these products increase the local burning rate. The increased burning rate drives a series of transverse waves into the un-burnt gas which promotes turbulent mixing with the hot products. This mixing is via the Richtmyer-Meshkov instability on the tongue of un-burnt gas. As the burning rates increase, the energy release provides more support to the leading shock which assists in the propagation of the fast flame.

Interestingly, the re-ignition spot observed in Fig. 3 does not lead to a detonation, although it participates in the reaction of significant amount of gas. The Mach stem strength is found to be approximatively 5, while the CJ detonation Mach number for this mixture is 6.4.

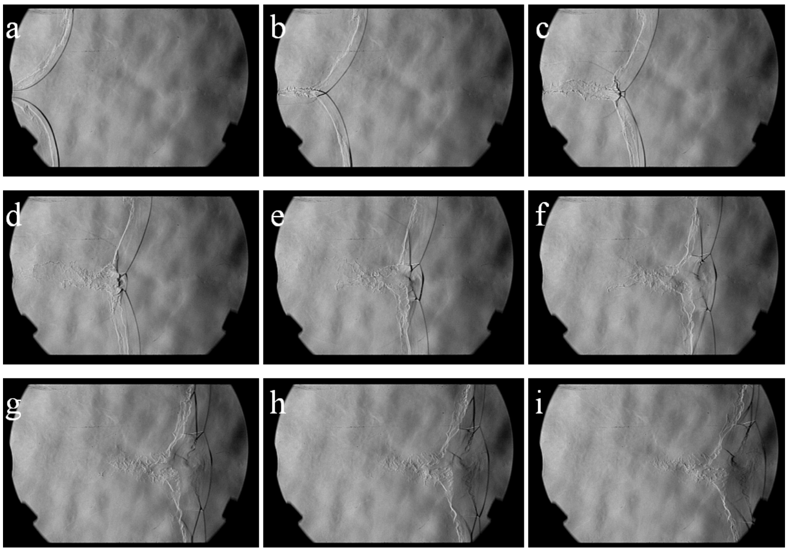

Figure 4: Schlieren frames illustrating the decoupled reaction zone from the leading shocks at 3.5 kPa initial pressure.

Figure 5 shows the subsequent dynamics obtained from a different experiment using the self-luminosity. The sequence of photographs illustrates the same transient as Fig. 3 in the first three frames. By the fifth frame, the reflection of the triple points with the walls gives rise to the second generation of hot spots. This again causes local amplification of the shock, and drives a next generation of wall reflections. By the ninth frame, a third generation hotspot is created near the bottom wall, which finally transits to a detonation. The mechanism of propagation of these fast flames is thus a sequence of localized explosion kernels behind shock reflections which release enough energy to maintain propagation. This confirms the view drawn by Radulescu and Maxwell [4] from their numerical simulations and experiments, such as Fig. 1. Taken from a different experiment, Fig. 6 shows the typical acceleration profile of the fast flame propagating at approximately 60% CJ rising to approximately 80% after each reflection. The acceleration of the fast flame is shown to be derived from the spike in velocity caused by each local explosion. This is followed by a period of decay which is unable to stabilize the velocity before the next reflection occurs, resulting in the global acceleration of the wave.

The amplification of the leading front through these series of explosions eventually gives rise to the onset of detonation. Fig. 7 shows how a detonation kernel finally forms when one of these Mach reflections becomes strong enough.

4 Conclusions

The present experiments thus clarify the nature of fast flames observed in previous experiments as a pre-cursor to the detonation formation. The experiments revealed that the fast burning rates, which are required to sustain these waves, are due to shock reflections which generate hot spots, as well as the further interaction of the transverse waves, which are driven by these explosion kernels with the broken up reaction zones. The wave interactions are thus very similar to those in self-sustained detonations, but have much slower dynamics and propagation speeds. Nevertheless, the interactions are eventually capable of amplifying the fast flame to the point where one Mach reflection is able to couple the shock and reaction zone and form a detonation wave.

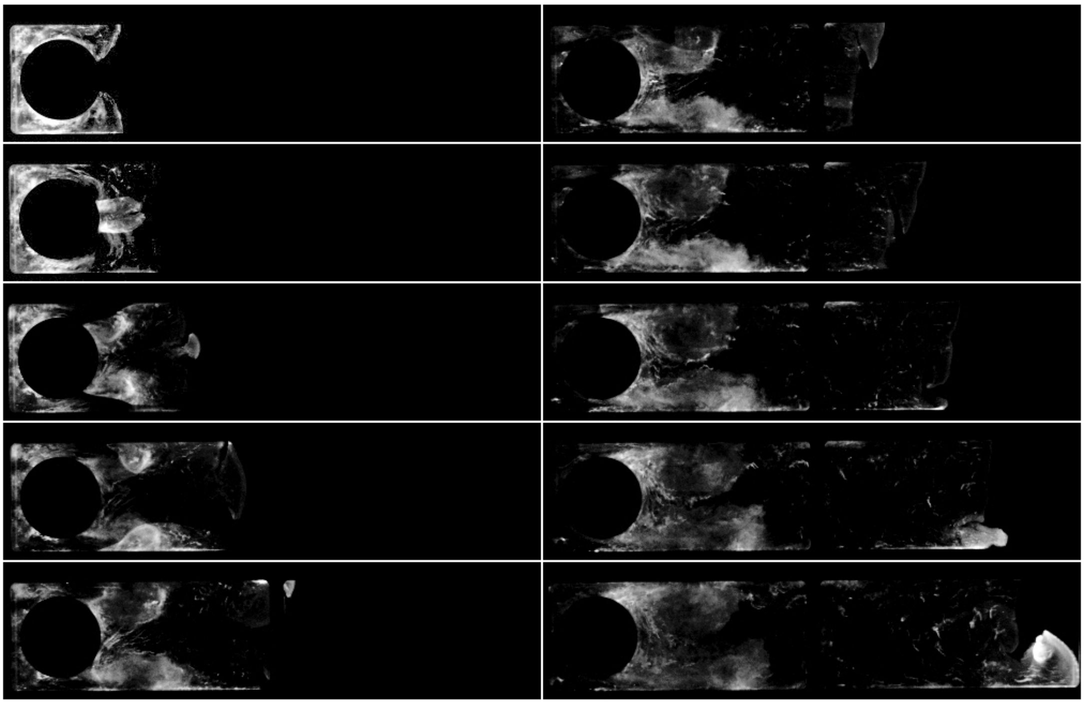

Figure 5: A series of direct chemi-luminescence photographs of stoichiometric methane-oxygen at 6.89 kPa initial pressure showing the overall structure of a fast flame eventually transitioning to a detonation, using a $1\mu s$ exposure, the inter-frames time is 57.1 microseconds.

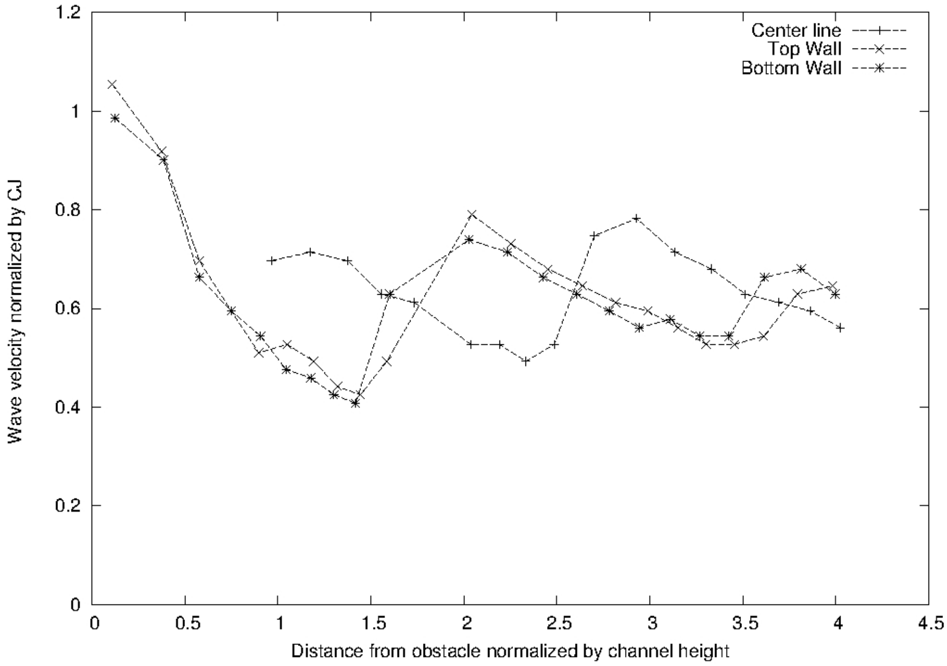

Figure 6: Velocity profile of a fast flame in methane oxygen at an initial pressure of 8.48 kPa using the same experimental set up as Fig. 5

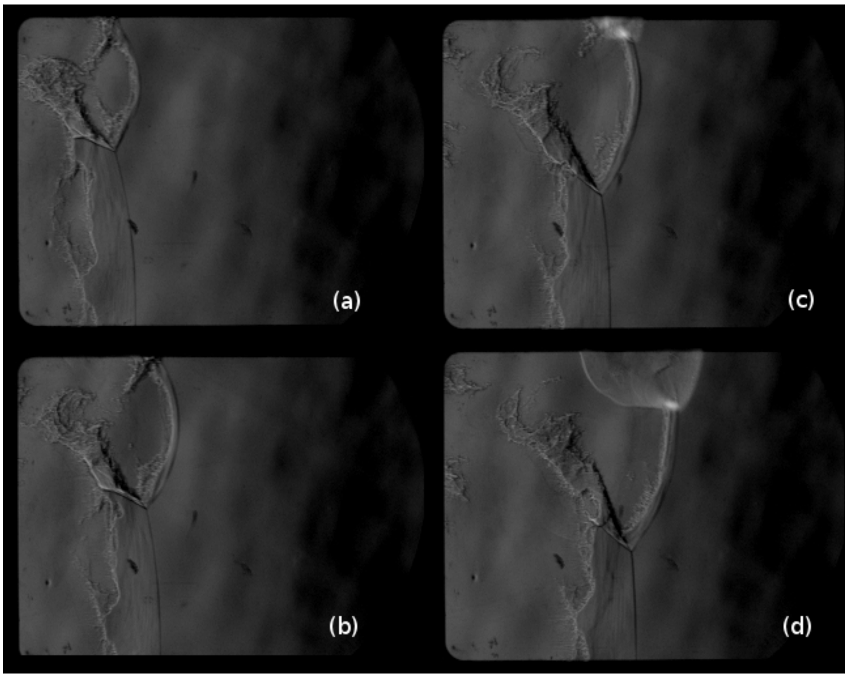

Figure 7: Schlieren composite of the wave interaction with the cylindrical obstacle and the local ignition event occurring after the reflection. Exposure time of $0.97\mu s$ and an inter-frame time of 12.97 μs at an initial pressure of 8.41 kPa

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