Experimental Study of the Head-On Interaction of a Shock Wave with a Cellular Flame

Maxime La Flèche[a], Qiang Xiao[a], Yongjia Wang[b], Matei Radulescu[a]
[a] Department of Mechanical Engineering, University of Ottawa, Ottawa, Ontario, Canada
[b] School of Power and Energy, Northwestern Polytechnical University, Xian, China

1 Introduction

Since the pioneering work of Markstein [1], the problem of the interaction of shocks with flames has been recognized to be of prime importance in most reactive compressible flows. Since the interaction generally generates vorticity through the baroclinic torque mechanism, it generally enhances turbulent mixing and can amplify combustion rates. It is central to practical problems ranging from deflagration to detonation transition and supersonic propulsion applications. In spite of its fundamental importance, previous experimental studies could not isolate the interaction in a canonical configuration devoid of secondary effects. For example, Markstein [1] studied the distortion of stoichiometric butane-air flames after the interaction with shock waves of different pressure ratios in a combustion chambers and tubes. Thomas et al. [2] examined the macroscale deformation of a spherical flame bubble with a side-on incident shock wave, leading to flame folding and the transition to detonation. In these studies, the interaction generally lead complex flow that was difficult to study due to the large deformations of the flame bubble. Numerical studies have mostly dealt with a shock-bubble configuration [3] and the chemically reacting Richtmyer-Meshkov instabilities on the flame cusps [4–7]. It is thus of interest to isolate experimentally the problem of shock flame interaction where both the shock and flame are flat and parallel, and the interaction is along the normal direction, i.e., head-on.

In practice, flames are almost always subjected to hydrodynamic instabilities and take on a cellular structure. We thus focus on the interaction of shocks with a cellular flame, where the cell perturbations provide the seeds for the Richtmyer-Meshkov instability. In order to visualize the cellular structure of the flames, we adopt the Hele-Shaw geometry consisting of a thin channel. The Hele-Shaw apparatus has proven to be efficient for studying cellular flame evolution in the past. Sharif et al. [8] analyzed the thermal expansion and the buoyancy effects of a flame propagating in a Hele-Shaw cell. Almarcha et al. [9] studied the transition of a flat to a wrinkled flame propagation in a vertically-oriented Hele-Shaw cell. This technique allows for the study of the cellular instabilities on the flame front in a quasi-bidimensional fashion.

In the present study, we propose two novel Hele-Shaw geometries whereby a cellular flame interacts with a shock wave head-on. We study the passage of the shock wave in both directions: from the burned to the

Correspondence to: mlafl042@uottawa.ca

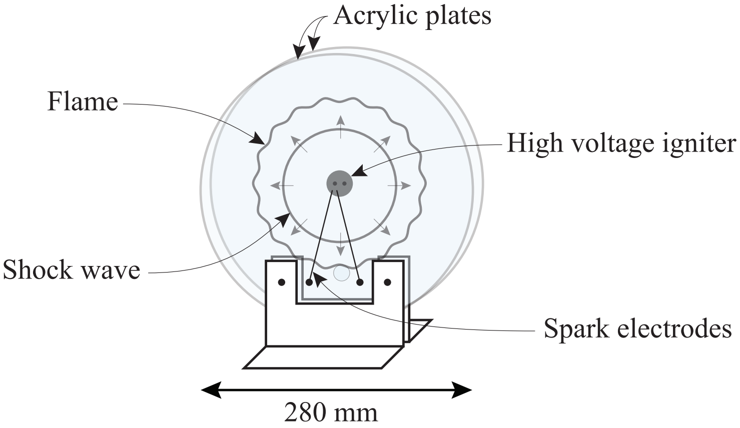


Figure 1: Schematic of the Hele-Shaw apparatus.

unburned side, and vice-versa. The goal of our study is to monitor the flame deformation subsequent to the interaction on acoustic time scales and the ensuing lengthening of the flame sheet.

2 Experimental procedure

The experiments were conducted according to two different configurations: in a Hele-Shaw cell at ambient pressure and in a thin shock tube at low pressure. Fig. 1 shows the Hele-Shaw cell composed of two acrylic parallel plates separated by a 5-mm gap. The thin gap width insures that the propagation is quasi-bidimensional. The reactive mixture was first filled in the cell at ambient pressure. Then, the spark electrodes ignited the mixture at the center point and a shock wave was initiated subsequently using the high-voltage igniter (HVI). Both the flame and the shock propagated in the same outward direction. The apparatus was equipped with a latex sheet on its circumference to allow for sealing and for a nearly constant-pressure evolution as it deformed with the expansion on the burned gas.

The low pressure shock tube consists of a rectangular channel with a thin aspect ratio outfitted with optical quality glass windows in the final section in order to visualize the phenomenon. The 19.1 mm channel was initially filled with the mixture at the desired pressure. Then, the ignition was triggered leading to a detonation. Before propagating through the test section, the shock was decoupled from the reaction front using a perforated plate. Thus, the reflected shock from the end wall traveled in the opposite direction and encountered the flame front. Fig. 2 illustrates the experimental setup for the shock tube. For all the experiments, the apparatus was first evacuated with a vacuum pump to pressures less than 80 Pa prior to filling with the test mixture.

To visualize the event, a Z-type Schlieren system [10] was implemented to capture the horizontal density gradients and the image sequence was recorded using a high speed camera (Phantom v1210). The frame rate was varied from 59,590 to 77,481 frames per second (fps). The exposure time was set to 0.468 μs and the field of view of the parabolic mirrors was 317.5 mm.

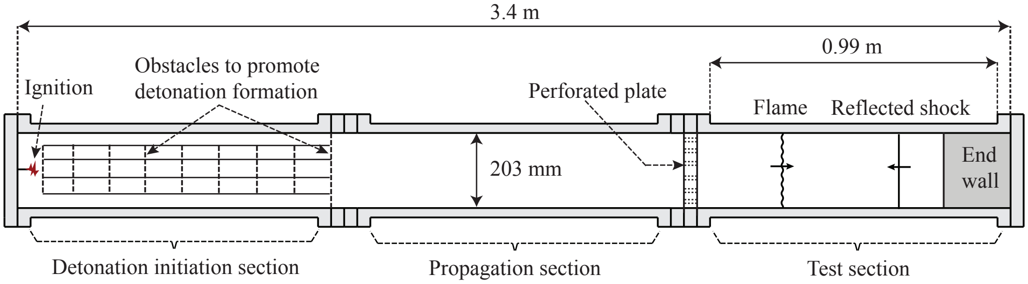


Figure 2: Schematic of the shock tube setup.

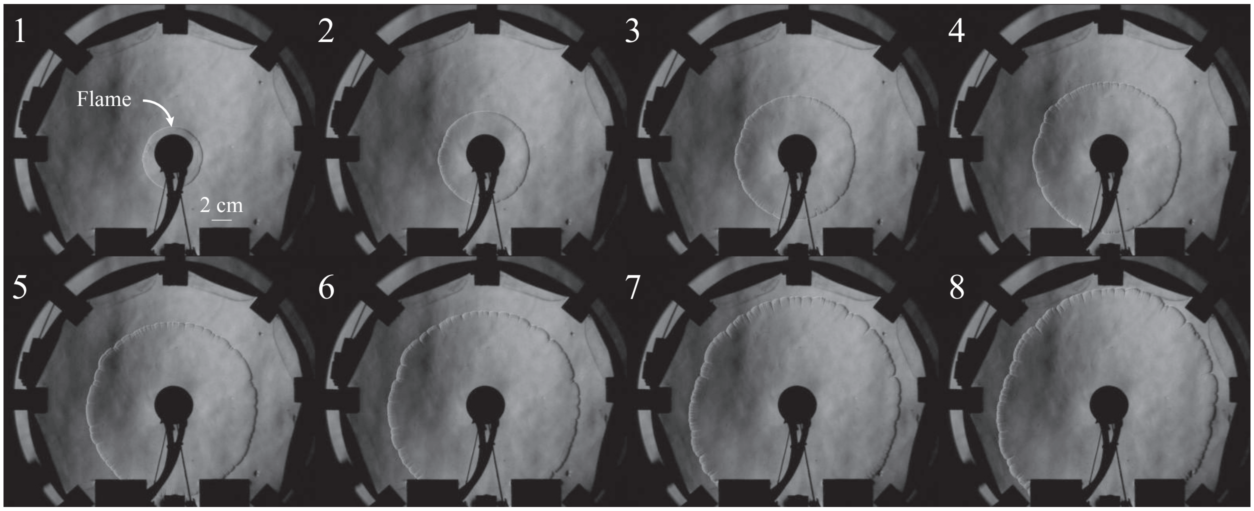


Figure 3: Combustion of a stoichiometric hydrogen-air mixture in the Hele-Shaw cell. Pressure of 1 atm. Recorded at 59,590 fps. The time interval between the frames is 0.67 ms.

3 Results

A combustion study was first used to quantify the laminar flame speed of the flame in the Hele-Shaw cell without a shock wave. Figure 3 depicts the flame dynamics of a stoichiometric hydrogen-air mixture at ambient pressure and temperature conditions. In the early stages (frames 1 and 2), the flame surface remains nearly smooth and circular. Later on, the deflagration wave takes on a cellular structure as it consumes the fresh mixture ahead (frames 3 – 8). When the deflagration reaches the edge of the circular plate, the latex sheet expands. The shape of the flame front is quasi two-dimensional, provided the thin gap between the closely separated plates. The flame speed was found to be constant across the field of view.

Figure 5 shows the interaction of the shock wave with a flame front in the Hele-Shaw cell. Similarly, the flame remains nearly cylindrical with a smooth surface at the initial stages (see frames 1 to 2). In the third frame, flame cusps are distinguished on the surface. After the flame has sufficiently propagated, the HVI is synchronized to be discharged and to create a cylindrical shock wave. In the fourth frame, the shock travels in the combustion products to reach the flame interface. In the fifth frame, one can discern the acceleration of the flame front after the interaction. An increase of the number of cells is also noticeable. Finally, in the eighth and ninth frames, the flame front appears to be inverted. We also varied the mixture in order to better

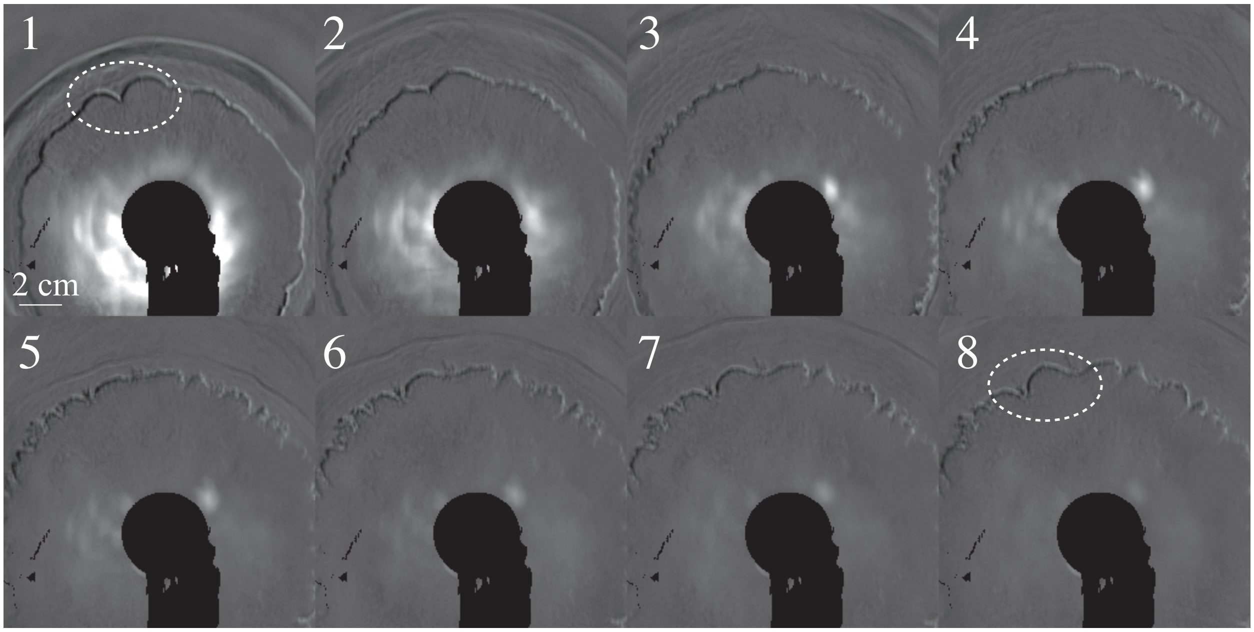


Figure 4: Combustion of a 20% hydrogen-air mixture in the Hele-Shaw cell. Pressure of 1 atm. Recorded at 77,481 fps. The time interval between the frames is 26 μs.

visualize the flame cusp. Figure 4 highlights the reversal of the cellular flame after the interaction between the shock and a 20% hydrogen-air flame with larger cusps size. From the first to the eighth frame, the initial peak from the pair of cusps becomes a bubble.

To further investigate the effect of the direction of the shock on the combustion front, experiments in the shock tube were conducted with a methane-oxygen mixture. In this case, the passage of the shock was in the opposite direction of the flame, i.e., from the unburned to the burned gas. Fig. 6 shows selected frames from the high speed video. In the first frame, the decoupled shock reflects off the end wall and proceeds towards the flame front. Furthermore, the flame surface is wrinkled. From the third image, microscales develop as the surface gets more corrugated until the end of the sequence. In the three last frames, the interaction with the shock wave also reverses the shape.

In order to help in the interpretation of the experimental results, numerical simulations were also performed in 2D for a shock wave incident on a density interface with the shape of a flame cusp. The inert simulations were performed using the MG code developed by Sam Falle at University of Leeds. These simulations are representative of the early deformation of the flame cusps on acoustic time scales. Fig. 7 shows the evolution of the flame cusps after passage of a $M_s = 1.2$ shock across a density interface of density ratio 6.84, either from the light gas side or heavy gas side.

The deformation of the flame cusps observed is an illustration of the Richtmyer-Meshkov instability. The mechanism of deformation is by vorticity generation by the baroclinic torque mechanism of misaligned pressure gradients and density gradients. For the light to heavy case (see Fig 7a), the passage of the shock from the low density side elongates the funnels of the flame, which become shear layers, with nascent finer scale mixing. Thus, the contact area of the flame increases accordingly and could translate to an increase of the burning rate. These funnels of unreacted gas can be observed experimentally in the sixth and seventh

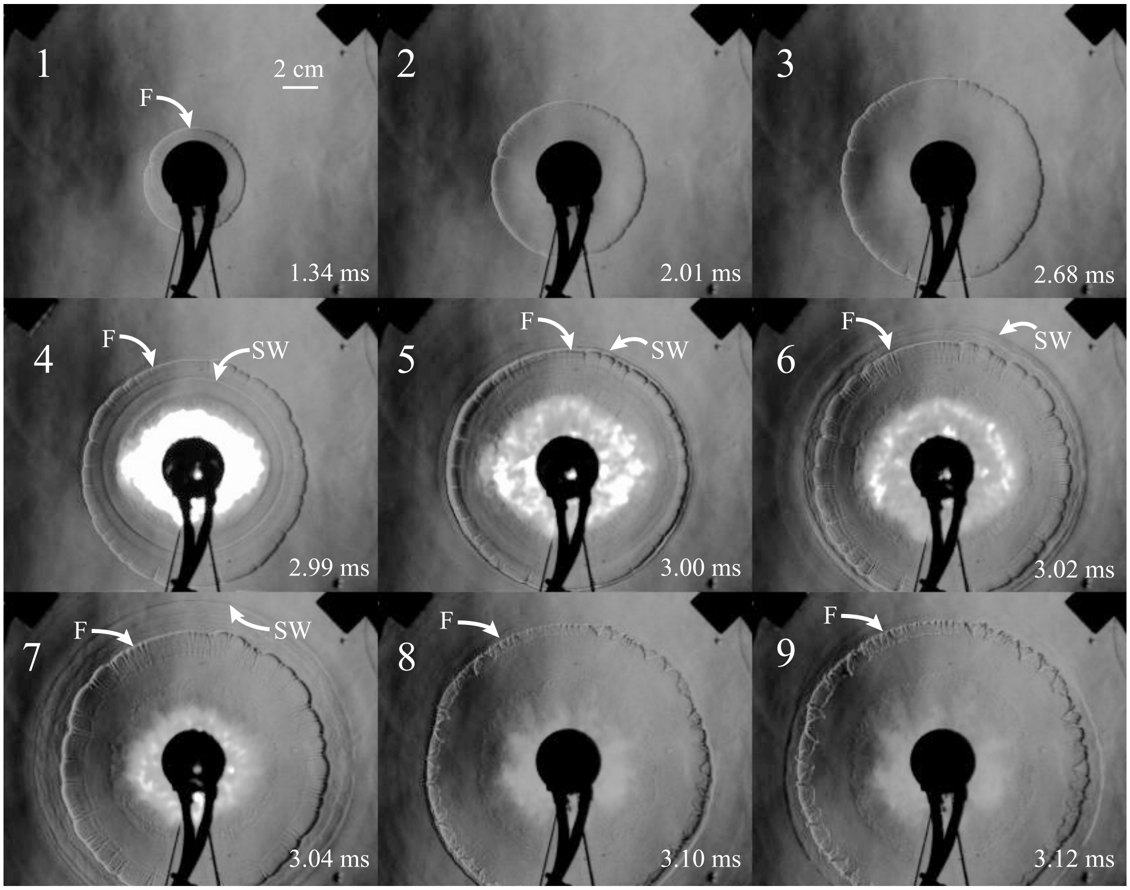


Figure 5: Schlieren images of the interaction of a shock wave (SW) with a cylindrical flame (F) of hydrogen-air mixture at stoichiometry propagating in the Hele-Shaw cell. Initial pressure of 1 atm. Recorded at 59,590 fps.

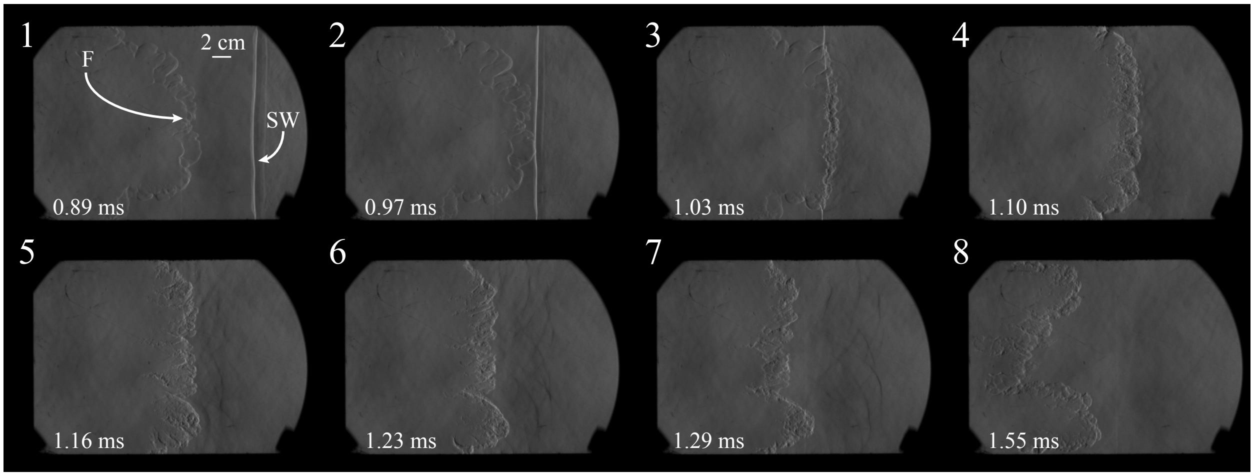
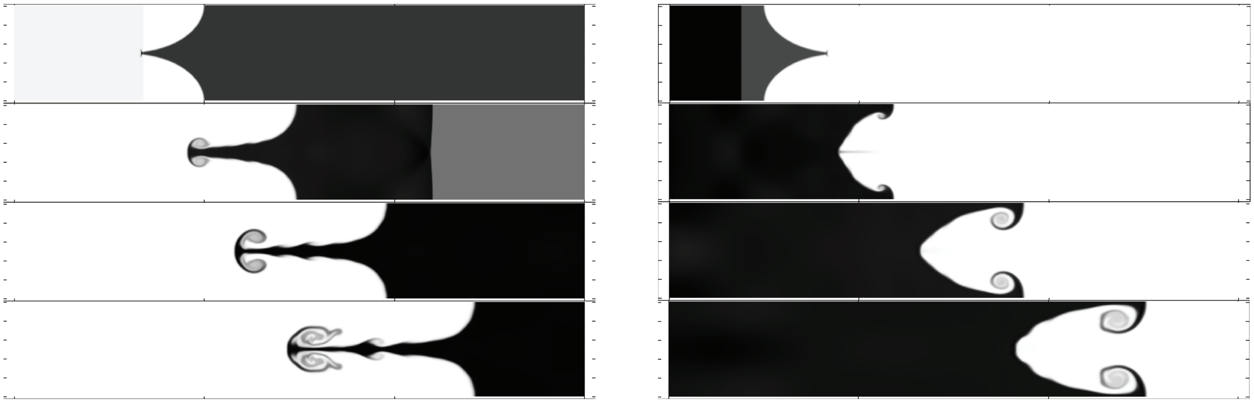


Figure 6: Schlieren images of the interaction of a shock wave (SW) with a flame (F) of CH_4-$2O_2$ mixture propagating in the shock tube. Initial pressure of 7 kPa. Recorded at 77,481 fps.



(a) Light to heavy.

(b) Heavy to light.

Figure 7: Density field for the interaction of the shock coming from the left with a flame cusp.

frames of Fig. 5. Afterwards, the funnels are consumed rapidly in the eighth frame. For the heavy to light case (see Fig 7b) corresponding to a shock originating in the unburned gases, the passage of the shock reverses the flame cusp's shape and smaller scale mixing appears in the material originating in the cusp front. This reversing phenomenon was obtained with the experiments in the shock tube as shown in Fig. 6 and one could relate the appearance of smaller scales within the cellular flame structure from the third to the latest frames.

4 Conclusion

In this study, the implementation of a Hele-Shaw cell technique provided two novel ways to monitor head-on shock-flame interactions. The early transient is characteristic of Richtmyer-Meshkov instabilities on the flame cusps. The experiments of the interaction of a shock wave with a cellular flame showed a good agreement with the preliminary numerical simulations. Future study will quantify the increase of the flame surface due to the instabilities.

References

[1] G.H. Markstein. A shock-tube study of flame front-pressure wave interaction, Symposium (International) on Combustion, Volume 6, Issue 1, Pages 387–398, 1957.

[2] G. Thomas, R. Bambrey, and C. Brown. Experimental observations of flame acceleration and transition to detonation following shock-flame interaction. Combustion Theory and Modelling, Volume 5, no. 4, pp. 573–594, 2001.

[3] Picone, J., & Boris, J. Vorticity generation by shock propagation through bubbles in a gas. Journal of Fluid Mechanics, 189, 23-51, 1988.

[4] Khokhlov, Alexei M., et al. Interaction of a shock with a sinusoidally perturbed flame. Combustion and flame , 117.1, 99-116, 1999.

[5] Massa, L., and P. Jha. Linear analysis of the Richtmyer-Meshkov instability in shock-flame interactions. Physics of Fluids 24, no. 5, 056101, 2012.

[6] Attal, N., and P. Ramaprabhu. Numerical investigation of a single-mode chemically reacting Richtmyer-Meshkov instability. Shock Waves 25, no. 4, 307-328, 2015.

[7] Jiang, H., Dong, G., Chen, X. and Li, B. A parameterization of the RichtmyerMeshkov instability on a premixed flame interface induced by the successive passages of shock waves. Combustion and Flame, 169, pp.229-241, 2016.

[8] Sharif, J., M. Abid, and P. D. Ronney. Premixed-gas flame propagation in Hele-Shaw cells. Technical report, Spring Technical Meeting, joint U. S. Sections, Combustion Institute, Washington D. C. 1999.

[9] C. Almarcha, J. Quinard, B. Denet, E. Al-Sarraf, J. M. Laugier, et al.. Experimental two dimensional cellular flames. Physics of Fluids, American Institute of Physics, 27 (9), pp.091110, 2015.

[10] G. S. Settles. Schlieren and Shadowgraph Techniques. Springer-Verlag, 2001.