An Experimental Investigation of Flame Deflagration Over Single and Multiple Solid Obstacles

S. Jarvis, G. K. Hargrave and S. S. Ibrahim
Faculty of Engineering, Loughborough University, Loughborough, LE11 3TU,UK

Introduction

There is much academic and industrial interest in developing an understanding of flame propagation in premixed combustion. Practical applications include SI-engines, gas turbines and studies of flame propagation in explosions. There have been many recent advances in both optical diagnostic measurement techniques and computer simulation tools for premixed combustion. However, there are still many limitations to both the mathematical prediction of turbulent premixed combustion and the quantity of detailed experimental data. The development of accurate models requires detailed experimental data in order to develop an understanding of the underlying physical processes. A review of the challenges presented by turbulent combustion was presented by Bray [1]. Much work over recent years has concentrated on large-scale explosion studies, including work reported by Moen et al. [2] and Hjertager et al. [3,4]. These experiments were conducted to define the effect of obstructions on flame propagation in explosion chambers. These experiments provided some useful insights into the flame/obstruction effects, but the data was limited to pressure-time histories and flame speeds. More recent studies by the present authors [5] have provided data in small-scale experiments aimed at investigating the interaction between propagating flames and obstacles in semi-confined geometries. High-quality experimental data for small-scale flame propagation studies has been presented by Lindstedt and Saktitharan [6]. This work provided two-component velocity data for premixed flame interaction with wall-type obstacles.

In previous studies [7-10], the present authors have investigated the effect of mixture stoichiometry and obstacle geometry on propagating flame structure during interaction with single obstacles. It is clear from the above work that the acceleration of a propagating flame in a premixed mixture is enhanced by interaction with solid obstacles. The extent of the effect depends on the flow structure developed in the wake of the solid obstacle. In turn, the structure of the turbulent wake depends on the obstacle geometry. In this paper, data is presented for the results from an experimental investigation carried out to understand the interaction between a propagating premixed flame and single/multiple solid obstacles.

Experimental Rig

The experimental rig (Figure 1) consisted of a simple square-section combustion chamber manufactured from polycarbonate to facilitate the application of optical diagnostics. The chamber was 150 mm x 150 mm cross-section and 500 mm long. The chamber was closed at one end and a thin plastic diaphragm was used to seal the open end of the tube and contain the flammable mixture. During the flame propagation, the diaphragm ruptured at low pressure to reduce excessive over-pressure generation in the combustion chamber. For the experiments presented in this paper the flammable mixture was methane-air and the obstacles were rectangular cross-section 75 mm x 10 mm, providing a blockage ratio of 50%. The premixed methane-air gas was purged through the combustion chamber for several minutes to establish a homogeneous mixture. The mixture was then allowed to settle in the chamber before being ignited by a spark source located in the closed end of the tube. In this paper, data for three experimental test cases will be presented: TC1, TC2 and TC3, which incorporate one, two and three obstacles respectively.

Laser Diagnostics

A high-speed, laser-sheet flow visualisation system, incorporating a copper-vapour laser and Kodak 4540 high-speed digital video camera, was used to record the progress of the flame front. The premixed methane-air entering the chamber was seeded with micron-sized droplets of olive oil to act as scattering centres for the laser light. The laser was formed into a laser sheet 150 mm high by 1 mm thick and used to illuminate the region of interest within the combustion chamber. Laser light scattered by the particles and recorded using the high-speed camera at 9000 frames per second. As the flame front propagated down the combustion chamber the oil droplets were consumed, differentiating the burned/unburned mixture.

The velocity field in the vicinity of the obstacles was recorded using Digital Particle Image Velocimetry (DPIV). The laser source for the DPIV was a pair of Nd:YAG lasers providing 150mJ per pulse, with 8ns pulse width and pulse separation variable from 1 to 300 μs. The PIV images were recorded using a Kodak ES1.0 CCD camera, which provided twin frame imaging for cross-correlation PIV with a minimum inter-frame spacing of 1μs. The CCD camera resolution was 1024 x 1024 pixels and was used to image an area of 35 x 35 mm in the vicinity of the obstacles. The aim of these measurements was to describe the flow structure in the wake of the obstacle and characterise the nature of the flame/turbulent flow interaction.

Results and Discussion

Example data for flame propagation around one, two and three rectangular obstacles is presented in figs 3, 4 and 5, respectively. These figures show representative sequences of images extracted from the high-speed laser-sheet videos. Figure 3 presents images for flow around a single rectangular obstacle. With reference to fig. 3, the main features of the propagation are as follows. As the flame front propagates towards the obstacle, the flow ahead of the flame is pushed passed the obstacle and 'jets' downstream close to the containing wall. This flow generates eddies which shedd from the obstacle into the stagnant wake behind the bluff body. A symetrical pair of eddies is formed either side of the obstacle. For the rectangular obstacle of Fig. 3, the first eddies appear at the surface of the obstacle at approximately 10ms after ignition for the stoichiometric mixture. The shedding point for these first eddies is the downstream facing edge of the obstacle.

As the flame approaches the obstacle the eddies grow and convect downstream, moving towards the chamber centre-line behind the obstacle. As the eddies separate from the body further eddies as formed. For the stoichiometic case, by 31 ms as the flame is burning past the obstacle. As the flame reaches the obstacle it accelerates rapidly through the constriction between the obstacle and the wall. On exiting from the constriction the flame decelerates and starts to burn into the obstacle wake. The flame wraps around the wake vortices and flame area increases. As the flame burns into the wake and effectively 'reconnects', it leave a small trapped volume of unburned mixture. The location of the reconnection and the volume of the trapped mixture is dependent on mixture stoichiometry, obstacle shape and blockage ratio.

After the deceleration, where the flame burned into the wake and reconnected, the flame accelerates and burns the remaining mixture

As the number of obstacles increases, Figs 4 and 5, the flame accelerates past each obstacle, propagating with the high velocity unburned mixture pushed between obstacle and wall by the flame. This processes leaves unburned mixture trapped in the space between the obstacles. With increasing flame velocity, the unburned gas flow ahead of the flame is accelerated, generating higher velocity flows across the obstacles. In turn this produces high turbulence levels in the obstacle wakes. For the case of three obstacles the flame velocity past the obstacle is in excess of 100m/s. The wake flow behind the third obstacle is turbulent, generating a turbulent flame in the wake.

The effect of the propagating flame on the overpressure generated within the combustion chamber is presented in Figs 6 for test cases TC1, TC2 and TC3. The higher turbulence level and higher flame speed associated with the three obstacle configuration (TC3) generated a higher overpressure, with the time of peak pressure coinciding with burning of the mixture behind the second obstacle.

In this paper, data will be presented for the time variation of flame speed, flame shape and combustion chamber overpressure for flame propagation around single and multiple obstacles. Data will also be presented for two-dimensional velocity fields in the region of the obstacles in order to define flow structure ahead of the propagating flame. In this work, algorithms are developed for the characterisation of the turbulent flow structure from two-dimensional PIV data. The aim is to provide experimental data for the development and validation of LES models for turbulent premixed flame propagation.

References

(1) Bray, K.N.C., “The challenge of turbulent combustion”, Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp.1-26, (1996).

(2) Moen, I.O., Lee, J.H.S., Hjertager, B.H., Fuhre, K. and Eckhoff, R.K., Comb. Flame, 47 pp31-52, (1982).

(3) Hjertager, B.H., Fuhre, K., Parker, S.J. and Bakke, J.R., Prog. AIAA, 94, pp504-522, (1985)

(4) Hjertager, B.H., Fuhre, Bjorkhaug, M., Comb. Sci. tech., 62, pp239-256, (1988)

(5) Fairweather, M., Ibrahim, S.S., Jaggers, H.and Walker, D.G., 26th Symp. (Int.) on Combustion, pp365-371, (1996)

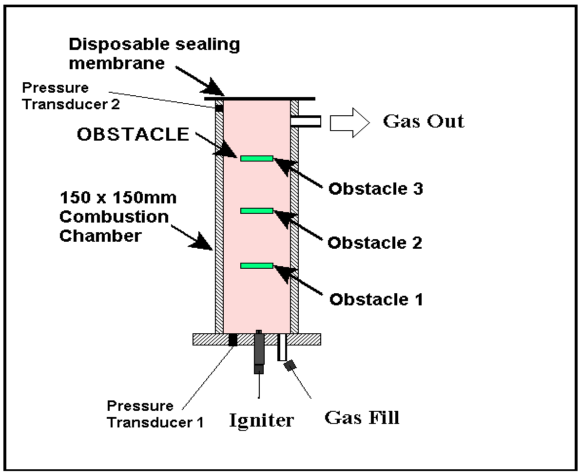
(6) Lindstedt, R.P. and Saktitharan, V., Comb. Flame, 114, pp469-483, (1998).

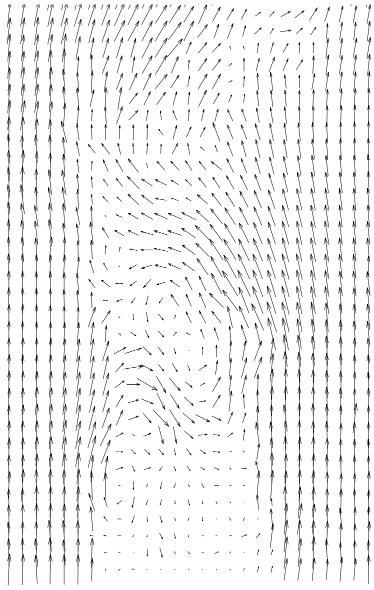
(7) Hargrave, G.K. and Williams, T.C., “High Speed Visualisation of Flame Propagation in Explosions” 9th International Symposium of Flow Visualisation, Edinburgh, 2000.

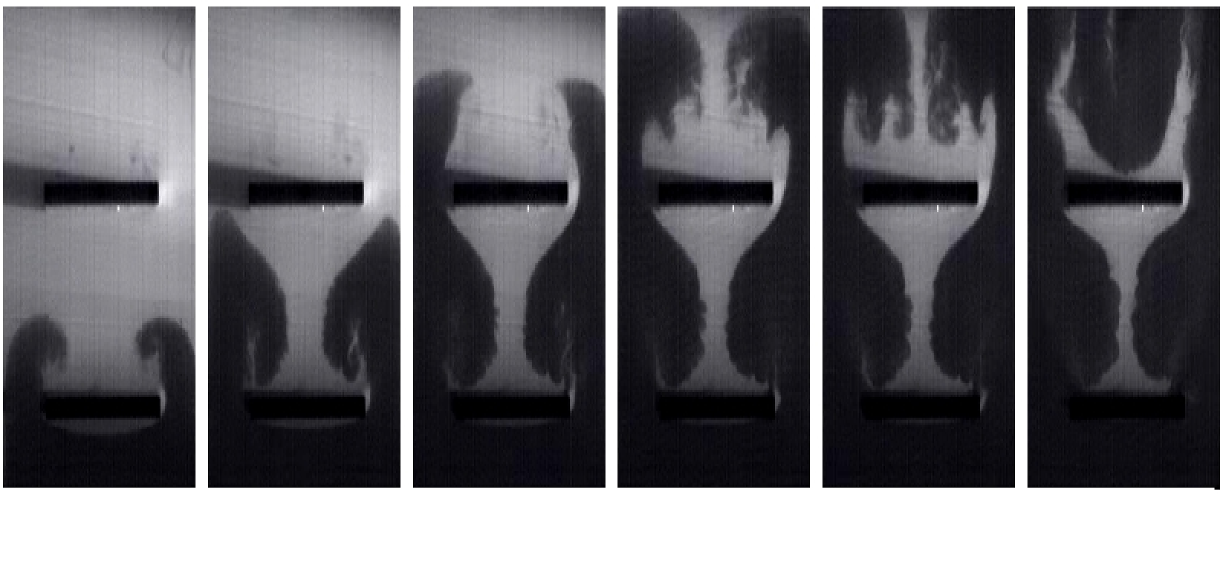
(8) Hargrave, G.K., Ibrahim, S.S. and Williams, T.C., Proc. Third International Symposium on Turbulence, Heat and Mass, Transfer, Nagoya, Japan, April2-6, 2000.

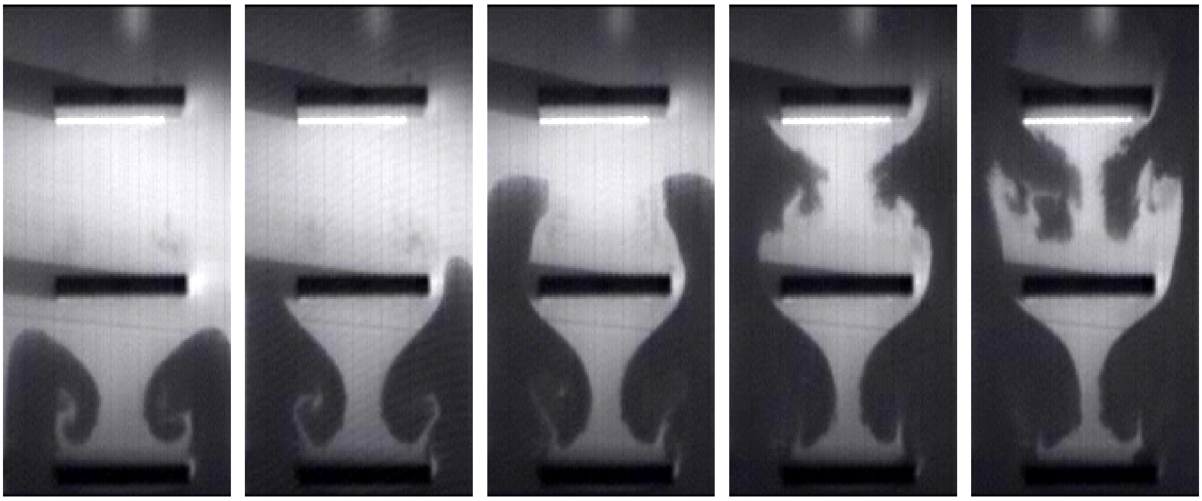
(9) Hargrave, G.K., Ibrahim, S.S., Williams, T.C. and Jarvis, S., “High-Speed Visualisation of Flame Propagation in Explosions”, accepted for publication in Journal of Visualisation, 2001.

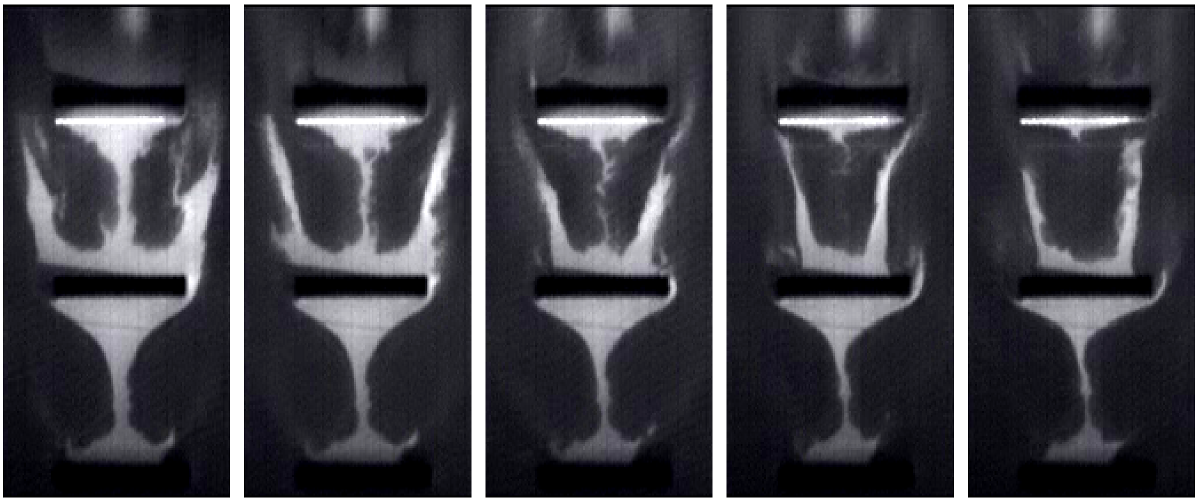
(10) Ibrahim, S.S., Hargrave, G.K.and Williams, T.C., “Experimental Investigation of Flame/Solids Interaction in Turbulent Premixed Combustion”, accepted for publication in Experimental Heat Transfer, Thermodynamics and Fluid Mechanics, 2001.

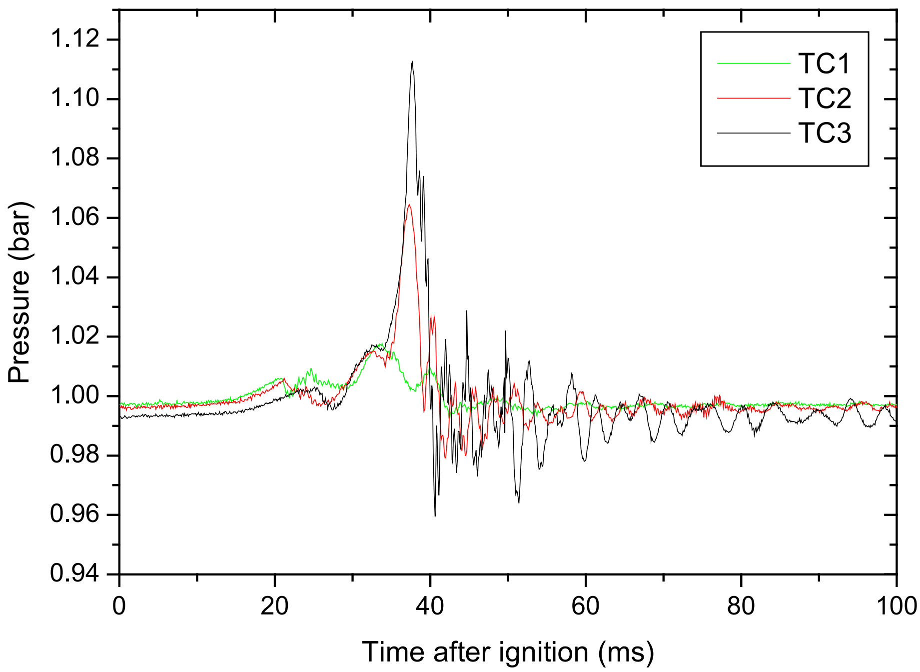

Disposable sealing membrane
Pressure Transducer 2
Gas Out
OBSTACLE
Obstacle 3
150 x 150mm Combustion Chamber
Obstacle 2
Obstacle 1
Pressure Transducer 1
Igniter
Gas Fill










TC1
TC2
TC3
Pressure (bar)
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0
20
40
60
80
100
Time after ignition (ms)