Journal of Visualization, Vol. 4, No. 4 (2001) 357-364

High-speed Visualization of Flame Propagation in Explosions

Hargrave, G. K.*, Williams, T. C.* and Jarvis, S.*

* Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, UK.
e-mail: g.k.hargrave@lboro.ac.uk

Received 21 March 2001.
Revised 27 July 2001.

***Abstract*:** Flow visualization data is presented to describe the structure of flames propagating in methane-air explosions in semi-confined enclosures. The role of turbulence is well established as a mechanism for increasing burning velocity by fragmenting the flame front and increasing the surface area of flames propagating in explosions. This area increase enhances the burning rate and increases the resultant explosion overpressure. In real situations, such as those found in complex process plant areas offshore, the acceleration of a flame front results from a complex interaction between the moving flame front and the local blockage caused by presence of equipment. It is clear that any localised increase in flame burn rate and overpressure would have important implications for any adjacent plant and equipment and may lead to an escalation process internal to the overall event.

To obtain the information required to quantify the role of obstacles, it is necessary to apply a range of sophisticated laser-based, optical diagnostic techniques. This paper describes the application of high-speed, laser-sheet flow visualization and digital imaging to record the temporal development of the flame structure in explosions. Data is presented to describe the interaction of the propagating flame with a range of obstacles for both homogeneous and stratified mixtures. The presented image sequences show the importance of turbulent flow structures in the wake of obstacles for controlling the mixing of a stratified concentration field and the subsequent flame propagation through the wake. The data quantifies the flame speed, shape and area for a range of obstacle shapes.

***Keywords*:** high-speed, laser-sheet, imaging, combustion, explosions.

1. Introduction

If an accidental release of gas in a building, process plant or offshore module results in the build-up of a flammable gas cloud and an ignition occurs then a flame front will propagate through the mixture. The combustion process will generate high temperature combustion products, which expand and, if the gases are confined, the pressure in the volume will rise. In many real scenarios accidental releases occur in confined or semi-confined regions of process plant in which the expansion has a restricted outlet, ie. solid boundaries on all but one or two sides of the confinement. In such semi-confined situations, the rate of pressure rise within the volume is directly dependent on the rate of flame expansion, that is the flame speed. It is well understood that the presence of turbulence can wrinkle a flame front, increasing the flame surface area and hence the burning rate. For flame fronts propagating in explosions, this increase in burn rate can enhance the local explosion overpressure and exacerbate the hazard. In experimental investigations of flame propagation in congested regions, studies by Eyre and Harrison (1987), Mercx (1992) and Bjerkelvedt and Bakke (1993) demonstrated that the presence of repeated obstacles, such as process pipework can produce flames propagating at several hundred metres per second. These studies showed that the congestion generated by pipework has two effects. Firstly, the obstacles generate turbulence in the unburned gas mixture which increases flame speed, and secondly they act as an obstruction to the expansion process, thereby increasing the local pressure.

A range of correlations which allow the turbulence enhancement of burning velocity to be predicted was presented by Abdel-Gayed and Bradley (1981). Fairweather et al. (1996, 1999) provided experimental data, which demonstrated an increase in flame speed and overpressure as propagating flames interacted with baffle-type obstacles in semi-confined, cylindrical vessels. In real situations, such as those found in complex process plants, the acceleration of a flame front results from a complex interaction between the moving flame front and the local blockage caused by the presence of pipes and vessels. This interaction between the propagating flame, the unburned gas movement and the obstacles creates a turbulent flow field in the wake of the obstacles. As the flame propagates through this flow field the flame front area wrinkles and distorts, increasing the surface area available for combustion. The influence of such local events on the overall explosion process and overpressure is not fully understood. Preliminary laboratory-scale studies of flame/solid interactions by Hargrave and Williams (2000), Hargrave et al. (2000) and Ibrahim et al. (2001) have demonstrated the importance of obstacle geometry and blockage ratio on explosion overpressures.

A further area of interest is the nature of the flow at the periphery of the gas cloud. In these regions the character of the mixing field generated in the transient flow/obstacle interactions will have a distinct effect on the flame propagation. In such stratified conditions the turbulence field will control the extent of the mixing and the structure of the flame propagating through this region. The important issue at the focus of this study is to establish the influence and importance of the turbulence field, the mixing field and combustion in the wake of obstacles representative of offshore plant and process equipment.

2. Experimental Rig

Two separate explosion rigs were constructed; one for homogeneous mixtures and one for stratified operation. A schematic of the homogeneous charge rig is presented in Fig. 1. It consisted of two rectangular cross-section combustion chambers separated by a thin plastic diaphragm. The overall dimensions of the rig were 75 mm × 150 mm × 800 mm. The primary chamber was constructed from polycarbonate to allow visualization of the combustion process. The diaphragm allowed a fuel/air mixture, premixed to a known stoichiometry, to be contained within the first chamber. During the flame propagation, the diaphragm ruptured at low pressure to reduce excessive over-pressure generation in the chamber. The fuel and air were metered using mass flow controllers and purged through the chamber for 150 seconds and then allowed to settle for a further 30 seconds prior to being ignited by spark source located in the closed end of the chamber. The obstacles under investigation were placed within the first chamber and the interaction between the propagating flame and the obstacle wake was studied.

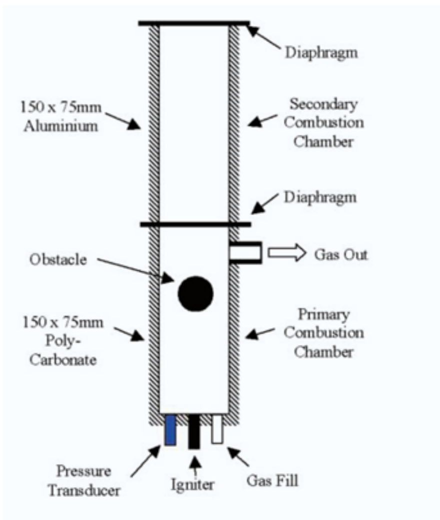

Fig. 1. Homogeneous mixture combustion chamber.

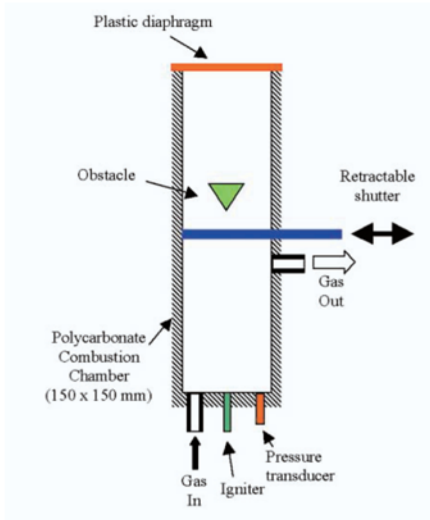

Fig. 2. Stratified mixture combustion chamber.

The stratified combustion chamber (Fig. 2) consisted of a 150 mm square cross-section polycarbonate enclosure with a pneumatically controlled, retractable shutter mechanism placed across the middle of the chamber. A premixed charge of methane and air, of predefined stoichiometry, was introduced into the lower half of the chamber and pure air into the top. As the shutter was retracted at high speed, this produced a two-dimensional interface between combustible and non-combustible material. As the flame propagated down the chamber, the stratification plane interacted with the complex fluid motion generated downstream of the obstacle allowing a characterization of the interaction.

A schematic diagram of the overall layout of the experiment is presented in Fig. 3. The light from a copper vapour laser was formed into a vertical laser sheet 175 mm high and 1 mm thick and was introduced horizontally into the combustion chamber to illuminate the centre of the rig in the wake of the obstacle. The laser produced 2 mJ pulses with a pulse width of 30 ns, which was a sufficiently short illumination pulse to effectively freeze the high-speed fluid motion. To allow visualization of the propagating flame the combustion air was passed through an oil seeder, which introduced a mist of 1 micron diameter droplets of olive oil. A high-speed digital CCD camera, operating at 9000 frames per second, was used to image the light scattered by the oil droplets. The CCD camera was synchronised to the laser to ensure a single laser pulse for each video frame. The propagating flame, as it burned through the combustion chamber, also consumed the olive oil droplets allowing visualization of the location of the flame front. The recorded digital images, together with the synchronously recorded chamber pressure data, were transferred directly to a computer for archiving and analysis. The derived data consisted of flame speed and flame front area together with information about flame shape and scales of flame front wrinkling.

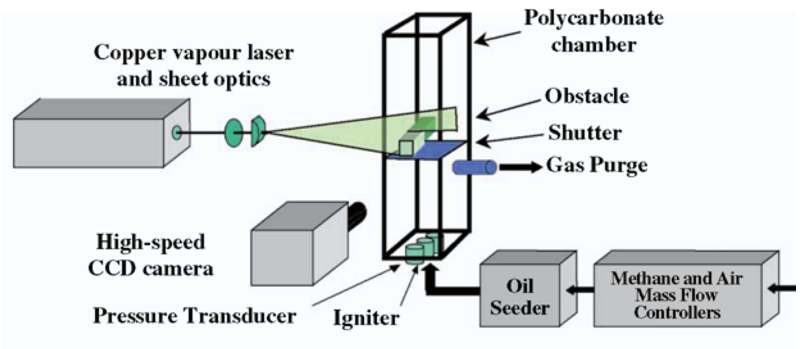

Fig. 3. A schematic of the explosion test rig and optical configuration for laser sheet visualization.

3. Results and Discussion

3.1 Homogeneous Mixture

The effect of variation of mixture equivalence ratio on the flame speed and structure is demonstrated in Fig. 4, which shows sequences of flow visualization images of flames propagating in lean, stoichiometric and rich mixtures. The flames were allowed to interact with a cylindrical obstacle, which provided a blockage ratio of 50%. It can be seen from this data that the flame shape approaching the obstacle is essentially the same, but there is a clear change in flame speed with equivalence ratio. The time to reach obstacle was 45 ms, 32 ms and 42 ms for the F = 0.8, 1.0 and 1.2 respectively. This effect was expected since this early propagation is controlled by the mixture laminar burning velocity, which shows a maximum for stoichiometric mixtures. Another feature of these images is the variation in flame speed as the flame front passes the obstacle. The variation in flame speed with distance downstream is presented in Fig. 5. The flame speed was calculated from the maximum downstream distance reached by the flame.

With reference to Figs. 4 and 5, 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 shed 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 cylindrical obstacle of Fig. 4, the first eddies appear at the surface of the obstacle at approximately 10 ms after ignition for the stoichiometric mixture.

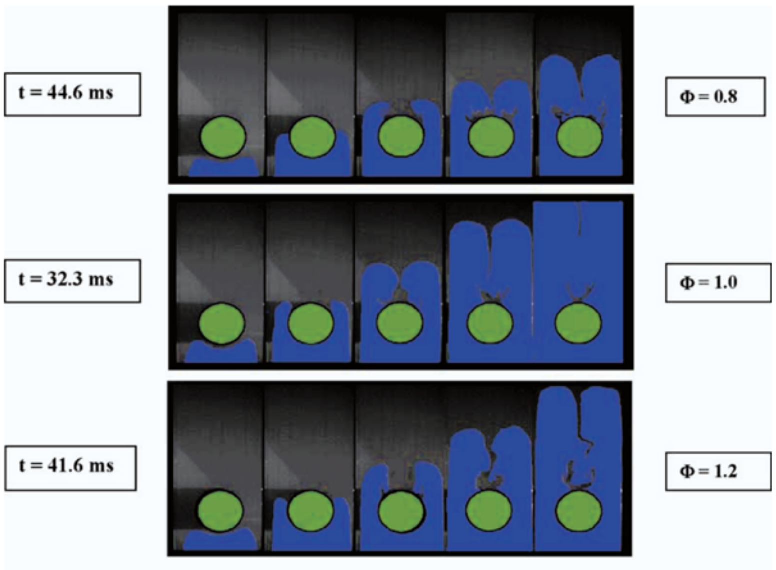

Fig. 4. Visualization of propagating flame for a cylinder: blockage ratio = 50%, *Dt* = 1.1 ms.

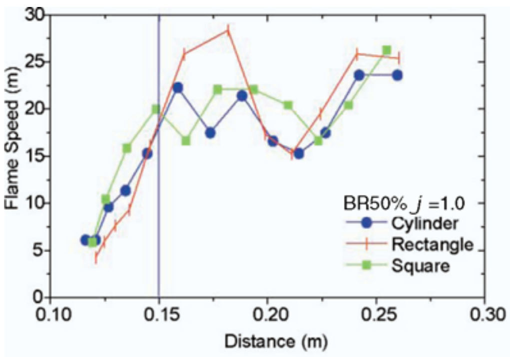

Fig. 5. Variation of flame speed with distance.

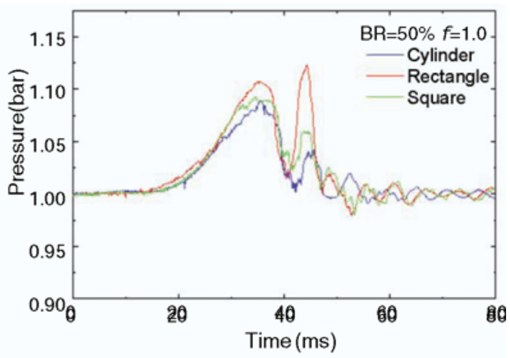

Fig. 6. Pressure-time histories for the three obstacles.

The eddy formation is more clearly seen in the higher resolution images in Fig. 7, where the eddies formed in the wake appear as darker regions in the seeded flow due to centrifugal separation. The shedding point for these first eddies is at a location of 75 degrees from vertical on the downstream side of the cylinder. 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 are formed. For the stoichiometric case, by 33.4 ms as the flame is burning past the obstacle, the first vortices have reached approximately half an obstacle diameter downstream. As the flame reaches the obstacle it accelerates rapidly through the constriction between the

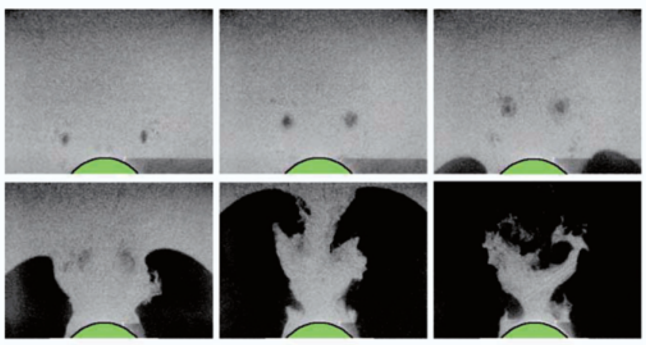

Fig. 7. Turbulent flow structures formed in the wake of the cylindrical obstacle.

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 leaves a small trapped volume of unburned mixture. The location of the reconnection and the volume of the trapped mixture are 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 pushed into the second chamber.

The effect of this flame propagation on the chamber pressure is presented in Fig. 6. The double peak is typical for all the configurations presented here. The first peak represents the bursting of the diaphragm and the second peak coincides with the burning of the mixture behind the obstacle. It is clear from the flame speed data (Fig. 5) and the pressure histories (Fig. 6) that the propagation rate varies strongly with obstacle shape. The temporal development of the propagating flame with stoichiometric mixtures over rectangular, circular and square cross-section obstacles is presented in Fig. 8.

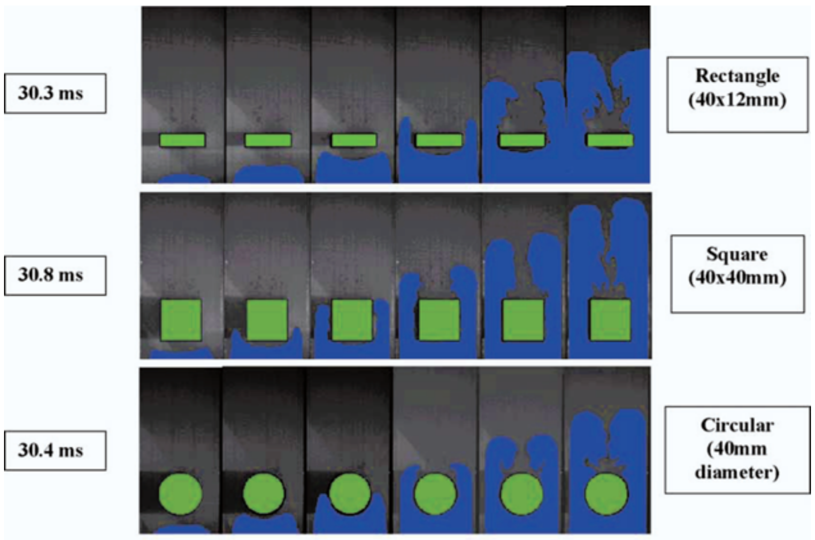

Fig. 8. Visualization of propagating flames for three obstacle shapes: blockage ratio = 50%, Dt = 1.1 ms.

As the flame starts to burn past the obstacle, propagation is faster for the square obstacle. However, the propagation past the rectangular obstacle induces the highest acceleration. Figure 5 shows that the peak pressure is also highest for the rectangular obstacle. This is possibly due to this configuration generating the largest trapped volume and a highly turbulent wake, which burns very rapidly. The detailed video images of the rectangular obstacle flow field suggested that the high flame wrinkling was caused by the generation of many small-scale vortices shed from the sharp edges of the obstacle. To investigate this phenomenon, a triangular obstacle was studied in both the homogeneous and the stratified flow combustion chambers. The results for the homogenous

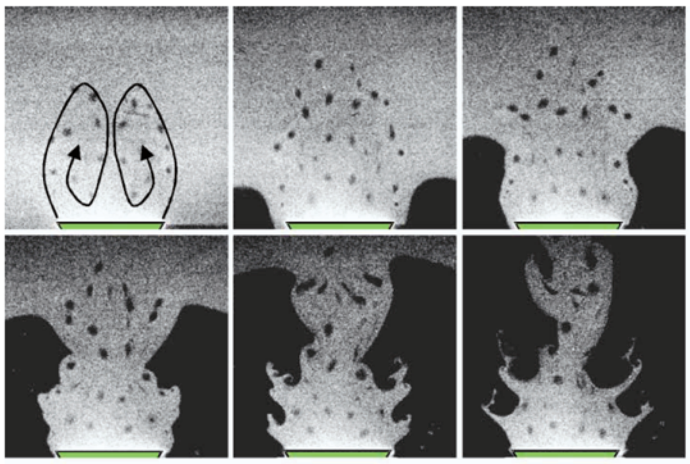

Fig. 9. The formation of turbulent flow structures in the wake of the triangular obstacle: blockage ratio = 50%, Dt = 1.1 ms.

flow are presented in Fig. 9. In the first image, the large scale rotation of the twin vortices has been indicated. Superimposoed on this large eddy is a stream of small-scale, rapidly rotating eddy structures, shedding from the sharp downstream edge of the obstacle and following the main rotation in the wake. As the flame starts to burn into the wake it is these small-scale eddies which distort the flame and cause wrinkling of the flame front.

3.2 Stratified Mixture

The stratified charge experiments provided information about the mixing field generated in the wake of an obstacle. Figure 10 presents a sequence of images of the flow field around a triangular obstacle. The obstacle was placed 70 mm downstream of the shutter in the stratified flow arrangement. The shutter was retracted 50 ms before ignition of the premixed mixture, creating a plane 'wave-front' of flammable gas, which was pushed towards and over the obstacle by the propagating flame. The timing was varied to control the extent of the interaction between the unburned mixture and the air in the wake of the obstacle. In Fig. 10 the unburned premixed fuel/air mixture appears white, the air is black and the flame has been highlighted in blue. The first image (40.4 ms) shows the flame as it starts to burn past the obstacle and the unburned charge is starting to mix into the wake. By 42.8 ms the flammable mixture is rolling into the vortices in the obstacle wake creating 'layers' of flammable gas and pure air. At this time the propagating flame has reached a location approximately an obstacle diameter downstream of the rearward-facing edge of the obstacle – just past the vortex centre. From here the flame turns into the vortex, following the flow streamlines, burning along a trajectory on the inner edge of the vortex layer. It is clear from the image at 42.8 ms that the inner edge contains many small scale turbulent structures compared with the smooth outer edge of the vortex. From the image at 43.7 ms, it appears that the flame burns across the layers, i.e. across concentration gratients. The flame burns into the vortex in preference to burning the stoichiometric mixture pushed past the obstacle. The mixture in the vortex is almost completely combusted before the flame then continues downstream and engulfs the remaining flammable mixture.

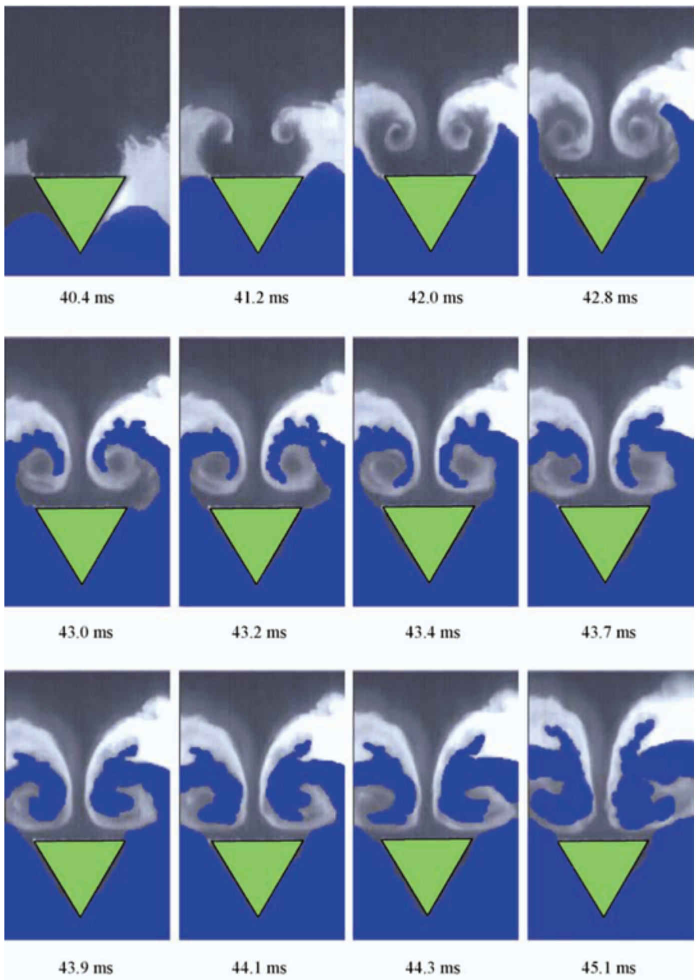

Fig. 10. Flame propagation through stratified charge in the wake of a triangular obstacle.

4. Conclusions

Flow visualization data has been presented for the interaction of a propagating flame with an obstacle in an explosion. High-speed, laser sheet flow visualization images have provided some valuable insights into the nature of the interaction between a propagating flame and the turbulent flow generated in the wake of an obstacle.

In a study of flame propagation in homogeneous mixtures, it was demostrated that:

1. obstacle geometry has a direct effect on the structure of a propagating flame and the overpressure generated in an explosion.
2. propagation was fastest for square-shaped obstacles and the propagation past the rectangular obstacle induced the highest acceleration.
3. the peak pressure generated within a semi-confined chamber was highest for the rectangular obstacle. This was attributed to this configuration generating the largest trapped volume and a highly turbulent wake behind the obstacle.

In a study of flame propagation through stratified flow, it was noted that:

1. the mixing field in the wake of an obstacle formed 'layers' of flammable gas and pure air as the gas rolled into vortices formed in the turbulent wake.
2. the propagating flame followed the flow streamlines and burned into the wake vortices. The flame front propagated across the concentration gradient in preference to combusting the homogeneous mixture outside the wake.

References

Abdel-Gayed, R. G. and Bradley, D., Phil.Trans. Royal Society, 301, (1981), 1.

Bjerkelvedt, D. and Bakke, J. R., Gas Explosions Handbook, Version 1.1, Ref. No CMR-93-A25003, (1993).

Eyre, J. A. and Harrison, A. J., The Effect of Obstacle Arrays on the Combustion of Large Premixed Gas/Air Clouds, Comb. Sci. Tech., 52, (1987).

Fairweather, M., Ibrahim, S. S., Jaggers, H. and Walker, D., 26th Int. Symp. on Combustion, The Combustion Institute, (1996), 365-371.

Fairweather, M., Hargrave, G. K., Ibrahim, S. S. and Walker, D., Comb. Flame, 116, (1999), 504-518.

Hargrave, G. K. and Williams, T. C., High Speed Visualisation of Flame Propagation in Explosions, 9th Int. Symp. of Flow Visualisation (Edinburgh), (2000).

Hargrave, G. K., Ibrahim, S. S. and Williams, T. C., Proc. 3rd Int. Symp. on Turbulence, Heat and Mass Transfer (Nagoya, Japan), (April 2-6, 2000).

Ibrahim, S. S., Hargrave, G. K. and Williams, T. C., Experimental Investigation of Flame/Solids Interaction in Turbulent Premixed Combustion, Experimental Heat Transfer, Thermodynamics and Fluid Mechanics, 24, (2001), 99-106.

Mercx, W. P. M., Large Scale Investigation into Vapour Cloud Explosions, 7th Int. Symp. on Loss Prevention and Safety Promotion in the Process Industry (Italy), (1992).

Author Profile

Graham K. Hargrave: He received his Ph.D. in 1984 from the Department of Fuel and Energy, University of Leeds. His research work included studies of the structure and heat transfer from turbulent, premixed flames and the application of optical diagnostics for flow field characterisation in combustion systems. After his Ph.D. he worked in Research and Development for British Gas plc., where he specialised in the development and application of optical diagnostic techniques. His current position is senior lecturer in Thermofluids in the Department of Mechanical Engineering at Loughborough University. His research interests include Particle Image velocimetry (PIV), Laser Induced Fluorescence (LIF) and High-Speed Imaging, with particular emphasis on their application to SI Engines, fuel injection systems, domestic and industrial burners, medical inhalers and the study of flame propagation in explosions.

Timothy C. Williams: During his B.Eng degree in Mechanical Engineering at Loughborough University he worked for British Gas plc on the development of high intensity, low-NO_x, natural gas burners. In 2000 he received his Ph.D. from Loughborough University for his research work into the oscillatory combustion processes contained within Helmholtz pulse combustors. He is currently a Research Associate within the Optical Engineering Research Laboratory at Loughborough University where he is involved with the application of laser diagnostic techniques to fluid dynamic and combustion problems. His current research work includes the study of turbulent flame interactions occurring in propagating flame fronts and the study of turbulent flow structures in impacting jets. He is particularly interested in the PIV technique and is currently working on a high-speed three-dimensional system.

Simon Jarvis: He is currently undertaking a Ph.D. at Loughborough University. He gained his B.Eng. (honours) degree in Mechanical Engineering from Loughborough University in July 1999 before starting his research work funded by Lotus Engineering UK later the same year. His work involves investigating the fundamentals of turbulent premixed combustion using laser diagnostic techniques. The aim of this research is to provide visualization and physical property data on turbulent flame propagation in idealistic geometry for the development and validation of CFD codes for SI engine applications. Results have also been used for prediction of accidental gaseous release in conjunction with the Health and Safety Executive in the UK. Present research interests are High Speed Laser Diagnostics and Particle Image Velocimetry applied to turbulent premixed flame propagation with plans to move into diagnostics on real SI engines.