Time Resolved Flow Characteristics of Confined Turbulent Gaseous Explosions

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Abstract

The transition of a turbulent flame to a gaseous explosion in a confined pre-existing turbulent flow field is of direct scientific and practical interest. Related topics include the intentional transition to detonation in pulsed detonation engines and industrial hazard assessment. Experimental data sets suitable for the developments of predictive techniques are required in order to advance the basic understanding of such flows. The present paper thus outlines an experimental study into the interactions between baffle accelerated premixed turbulent flames and their self-generated flow in a long closed flame tube. In particular, the effects of a pre-existing velocity field at the ignition point located upstream of the baffle are examined. Flow characteristics, including time-resolved mean and rms profiles in a two-dimensional plane, have been obtained using laser Doppler anemometry for a stoichiometric methane-air flame. Instantaneous spark schlieren photographs have been obtained around the baffle to elucidate the flame behaviour and qualitatively describe the burning process. The present configuration yields over-pressures of around 200 kPa and peak mean velocities around 150 m/s – both significantly higher than those reported by Lindstedt & Sakthitharan (1998) for initially quiescent mixtures.

Introduction

Previous investigations in the field of gaseous explosions (e.g. Moen *et al.* 1980 and Lindstedt & Sakthitharan 1998) have shown that the presence of an obstacle in the path of a flame can significantly affect its mode of propagation and burning rate. In particular, the flame propagation process has been shown to depend strongly on details of the interactions between the flame structure and the flame-induced flow field around the obstacle. This relationship is intrinsic to many premixed flame situations, particularly in the field of gaseous explosions, where the accidental spillage of flammable vapour or gas can lead to extremely damaging over-pressures. The effects of single or multiple obstacles have been shown to increase flame speeds (e.g. Chan *et al.* 1983), potentially leading to quasi-stable strong deflagrations (Lindstedt & Michels 1989) or detonations (e.g. Moen *et al.* 1989). Although the qualitative understanding of such processes is good, a detailed assessment of controlling mechanisms has typically not been possible due to severe experimental difficulties. However, to understand the relevant mechanisms, detailed quantitative velocity measurements in the region around the obstacle are a pre-requisite. It is therefore a striking deficiency that at the present time only one such data set, relating to the development of an initially laminar stoichiometric methane-air flame (Sakthitharan 1995; Lindstedt & Sakthitharan 1998) exists. In a further attempt to address this deficiency the present study is concerned with the behaviour of freely propagating flames ignited in a pre-existing jet induced velocity field upstream of a solid obstacle. The data provides a basis for further development and validation of simple (e.g. Dunn-Rankin & McCann 2000) and Computational Fluid Dynamics based models for compressible turbulent reacting flows.

Experimental Details

The experimental facility used in the present study is similar to that reported by Lindstedt & Sakthitharan (1998). It consists six interchangeable rectangular sections (72 mm x 34 mm) of length 1.825 m and two window sections of length 0.385 m. A round axi-symmetric jet of 5 mm internal diameter is centred in a plate fixed to the flame tube at the obstacle end. Two opposing electrodes are symmetrically placed either side of the jet with a spark gap of approximately 10 mm. The obstacle, made from a 5 mm thick steel plate and with a height of 36 mm, is placed 0.415 m downstream of the jet exit. Sixteen coaxial ionisation probes are used to detect flame arrival times and six piezoelectric pressure transducers (PCB 113A21; PCB Piezotronics, Inc.) are similarly positioned along the vessel to provide information on the pressure development. The method of partial pressures is applied to prepare gas mixtures and the path from the mixing vessel to the flame tube includes a flame arrester, a sonic nozzle, two solenoid valves and an alumina oxide particle seeding arrangement. The flame propagation process is visualised by means of spark schlieren photography featuring a parallel beam of white light. A circular pin hole is used as the schlieren stop. Gas particle velocity measurements are obtained using the standard dual-beam forward scatter laser Doppler anemometer arrangement previously reported by Lindstedt & Sakthitharan (1998). Data reduction follows the method outlined by Lindstedt & Sakthitharan (1998) and the effect of different types of seeding on measurement accuracy has been addressed by Sakthitharan (1995). At least twelve sets of flame arrival times are available at each port. Velocity measurements along the axial (u–velocity) and vertical directions (v–velocity) are presented at 33 points above and downstream of the obstacle for a stoichiometric methane–air flame. The points are separated by 9 mm and 50 mm in the vertical and horizontal directions respectively. All the points lie on the vertical plane passing through the axis of the flame tube. The flame propagation is extremely reproducible over the first 4 m. Although the temporal variations associated with the initial kernel growth are ~ 10 %, the reproducibility of the flame arrival at subsequent ports is excellent with variations ~ 3 %. The latter indicates that the development of the vortex structure downstream of the baffle is highly reproducible and relatively insensitive to variations in initial kernel growth.

Results

Measurements in the isothermal jet flow show that the mean velocity falls to zero at the ignition point at approximately 65 ms after valve closure. The decay time of the turbulence is difficult to determine accurately as the source of seeding particles is removed once the valve has closed. However, measurements indicate that the turbulence field persists up to a minimum of 80 ms. The time-scale of combusting experiments is two to three times shorter and the conditions at the time of ignition appear approximately steady.

Examples of measured velocity magnitudes can be seen in Figures 1 and 2. In Figure 1 the u– and v–velocity profiles at 11 and 13.5 ms after ignition are shown at all the measurement planes. The u–velocity profile above the obstacle is almost flat. The v–velocity profile is fairly steep with velocities decreasing from 48 m/s at 6 mm to 0 m/s at 30 mm above the obstacle. At later times the velocities above the shear layer exceed 100 m/s. Between the 0.465 and 0.515 m planes the v–velocity changes sign, indicating the centre of the re-circulation zone. As the vortex structure moves across the two planes the values of the turbulence velocities in the shear layer increase from 2 m/s to ~ 7 m/s as shown in Figure 2. Higher values are obtained at other locations. The flow is, however, not strongly anisotropic at this point. Around 13.5 ms the flame propagates across the channel leading to a further increase in axial (u”) turbulence velocities to ~ 15 m/s. At other locations above the height of the obstacle a decrease in u” velocities from around 4 m/s to ~ 5 m/s is observed. The result is unlikely to be influenced by non-turbulent broadening effects (Lindstedt & Sakthitharan 1998) as the lowest turbulence levels correspond to the steepest mean velocity gradients. The corresponding v”–velocities also increase at all points below 45 mm as the flame burns across the plane and the turbulence in the vortex is approximately isotropic. The rms velocities accompanying the hot gas expansion as the flame propagates past the obstacle indicate anisotropic effects although the result may arguably be influenced by a non-turbulent broadening effects. The peak pressure is 100 kPa (~ 50 %) higher in the case of ignition in an initial turbulence field and the peak occurs much earlier. This indicates a strong coupling between the compressible flow field and the time of burnout. The increased rate of expansion in the present study drives higher velocities over the baffle, which precipitate higher levels of turbulence in the separated vortex structure. For example, u”~ 12 m/s in the shear layer in the present case compared to u”~ 7 m/s with an initially quiescent flow field. Further comparisons of the u–velocities in the shear layer 0.5 m downstream of the obstacle confirms these effects – the maximum velocity in the shear layer is almost 100 % greater in the present study.

Conclusions

A data set has been obtained that provides sufficient detail to serve as a stringent test for the development of detailed modelling techniques applicable to areas ranging from pulsed detonation engines to industrial hazard assessment. The present data quantifies the effects of turbulence levels at ignition on the nature of the flame propagation and the strength of the gaseous explosion. It is shown that in the present case the peak pressure observed for a stoichiometric methane-air flame ignited in a pre-existing velocity field is 50 % higher than that observed for ignition in an initially quiescent medium (Lindstedt & Sakthitharan 1998). The LDA measurements also show that the time taken for the flame to reach the obstacle in the present study (u”/u ~ 0.21) is about three times shorter than in the quiescent case (u”/u = 0.0). The vortex formed in the present study therefore has less time to develop and occupies less volume than that reported by Lindstedt & Sakthitharan (1998). However, the higher initial turbulence levels precipitate higher levels of turbulence in the separated vortex structure and significant increases in over–pressures.

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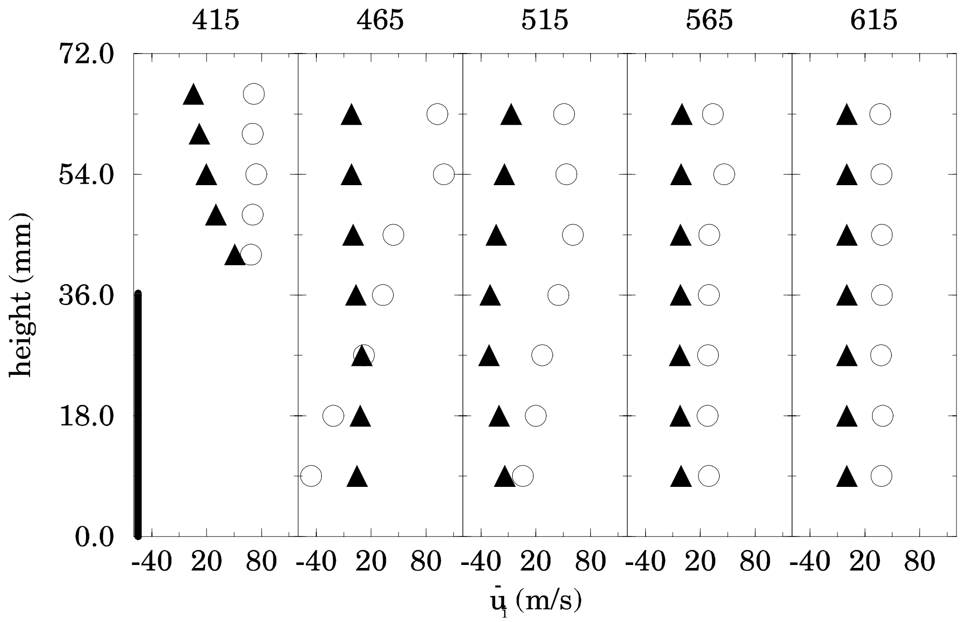

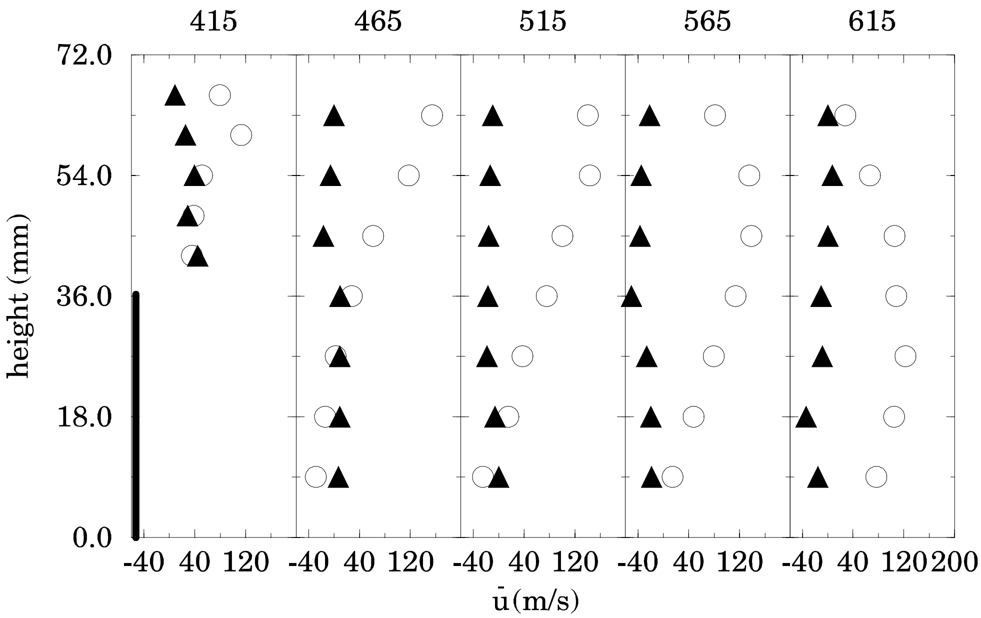

Figure 1. Spatial variations of mean velocities at the 415, 465, 515, 565 and 615 mm planes form the jet exit at (top) 11 ms and (bottom) 13.5 ms. The circles and triangles indicate axial and perpendicular velocity components respectively.

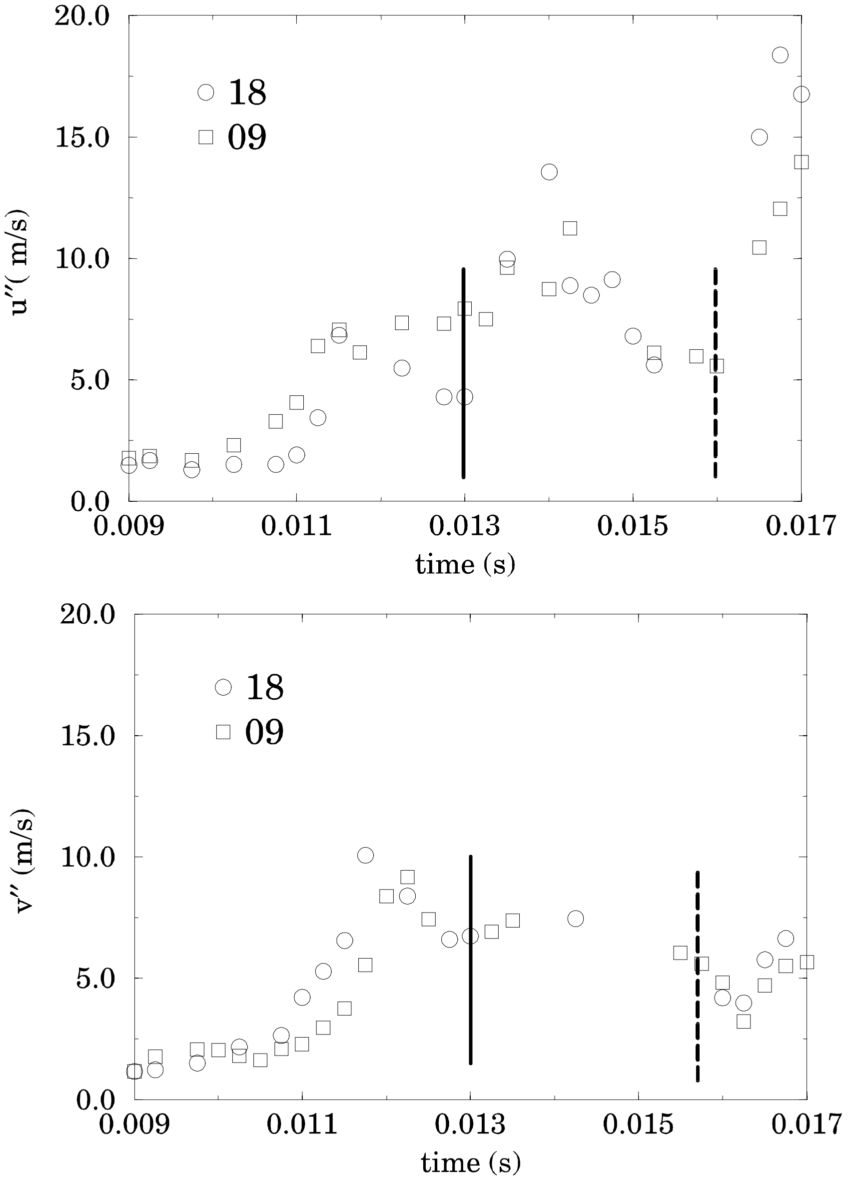

Figure 2. Temporal variations of u” and v” velocities at 9 and 18 mm along the 515 mm plane. The vertical lines indicate the arrival of the flame at the respective locations.