Effectiveness of localised spark ignition in recirculating n-heptane spray flames

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1 Introduction

Spray flame ignition is important from a scientific as well as a practical viewpoint, for example it is relevant to industrial furnaces, boilers, and the high-altitude relight of aeronautical and rocket engines. In jet engine combustors, the ignition of fuel sprays must be fast and flame stabilization must be ensured. There are many studies on ignition of homogeneous gaseous fuel-air mixtures, but the literature on spray ignition is quite scarce. One of the first comprehensive works regarding ignition with sprays was done from Lefebvre and Ballal [1-2]. Their test rig comprised one-dimensional turbulent flows, homogeneously premixed with gaseous fuels or uniformly loaded with droplets, to study the effects of varying the spark parameters, turbulence levels, droplet properties, and overall equivalence ratio on ignition. In particular, their research is focused on the dependence of ignition energy and duration time of the spark on important parameters such as droplet size, equivalence ratio, and velocity. However, their emphasis was on the initiation of a kernel only. This may be equivalent to flame propagation in one-dimensional flows, but can be different from whole flame ignition in complicated recirculating flows and inhomogeneous spray patterns expected in realistic combustor geometries. Other work is useful to understand the combustion characteristics of the droplet cloud [3-5], but not many studies focus on the ignition of a polydisperse spray in a swirled airflow that represents the realistic working condition in engine systems [6-8].

The main purpose of this paper is to describe the ignition behaviour of a bluff body swirled spray flame. In particular, the approach of this work is based on the gaseous non-premixed flame ignition study of Ahmed and Mastorakos [9], where the stochastic nature of ignition in non-premixed systems from a small spark was explored by measuring the ignition probability, with ignition defined as initiation of a kernel and successful flame establishment. This draft paper contains ignition probability results, visualization of the flame evolution with a high-speed camera, spray drop size and velocity measurements obtained by PDA, and air axial and swirl velocity performed by LDV.

2 Experimental methods

The experimental apparatus, depicted in Fig.1, shows the schematic of the burner assembly, the fuel line and the exhaust system. The burner consists of a 100mm long circular duct of 35 mm inner diameter, fitted with a conical bluff body of diameter 25mm giving a blockage ratio of 50% (Fig. 2). The fuel injection system consists of a pressure swirl atomiser and a feeding tank pressurised by nitrogen. The nozzle exit diameter is

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0.15mm; the spray cone angle is 60^o, while the fuel flow rate is 0.017kg/min at 0.5MPa gauge pressure. N-heptane is used as a fuel.

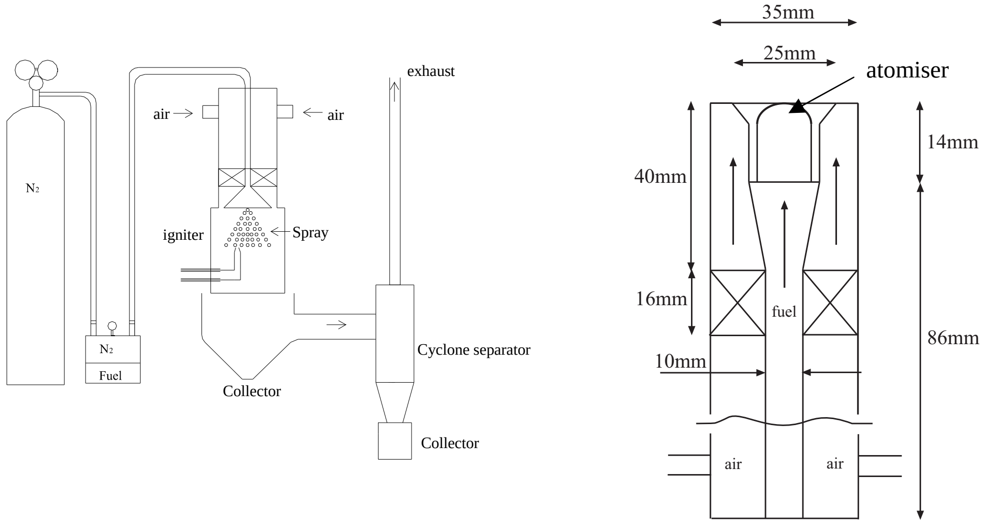


Fig. 1 Overall experimental arrangement and a schematic of the spray burner.

The combustion chamber consists of a 70 mm inner diameter glass tube 80 mm in length. The air enters from the annular open area between the outer duct wall and the bluff body. Swirl is imparted by static swirl vanes at 60° with respect to the flow axis along the flow passage between the inner and outer ducts. The direction of the air swirl is counter-clockwise when looking down at the nozzle. The global equivalence ratio was Φ=0.44 with a bulk air velocity of 17m/s.

The ignition unit used in this study is fully described elsewhere [9]. It was designed to supply sparks whose energy and duration can be varied independently. The electrodes were placed in the test section with their axes normal to the spray direction and mounted on a micrometer traversing assembly, which was used to adjust the spark gap. The electrodes were 1mm diameter tungsten rods with pointed edges to reduce the heat loss from the spark; the gap between them is 3mm. The two electrodes were set-up on a vertical test stand which allows the spark itself to translate both in vertical and horizontal directions relative to a fixed point to within 0.1mm resolution, in order to make the measurement possible in several points in the vertical plane. For this investigation, the spark had duration of 400μs and the electrical energy delivered by the circuit was 200mJ. For each position, 20 independent spark events were performed and the percentage of events resulting in a flame establishment gave the ignition probability.

Fast images of the ignition event were acquired with a Phantom V4.2 digital high-speed camera. The movies were captured with 2,000 frames per second and exposure time 400μs, which is short enough to capture the rate of growth of the ignition kernel. Phase Doppler Anemometry (PDA) was used for the simultaneous measurement of droplet size and axial velocity, while the LDV option of the PDA system in backscattering mode was used for the air velocity, which was measured without the presence of the spray with seeding provided by a smoke generator. The optical probe was mounted on a three-dimensional traversing system with stepper motors in order to allow for a computer controlled traversing of the flow.

3 Results and Discussion

The main objective of this study was to understand the ignition process of a spray in a recirculation zone, which is also very useful for evaluating transient combustion models such as those based on LES. The results of this work include the ignition probability map, the observations of the ignition kernel from fast movies, and the PDA/LDV measurements that allow an interpretation of the ignition probability relative to the local droplet and air velocities.

Ignition probability and air and droplet size and velocity

Here, successful ignition is defined the situation where energy deposition from the spark ignition leads to a flame kernel and appearance of the stable flame, stabilised in the whole combustor. The first observation made was that individual spark events did not always result in full flame establishment, making hence ignition a probabilistic phenomenon. This randomness is due to a spatially inhomogeneous dispersion of the fuel droplets, but also due to the different fates that a flame emanating from the ignition kernel can follow due to the turbulence [9]. Once ignited, this mixture generates an attached and short flame that appears yellow in the centre and blue on the side.

Figures 2 and 3 depict contours of the ignition probability and the mean axial velocity of the droplets respectively. The highest ignition probability values are measured in the central recirculation zone (CRZ), formed in the wake of the bluff body, until the axial location z=32 mm. The probability then starts to drop so that at 35 mm it is around 10%. Downstream of that position there is no ignition. The ignition probability is zero also in a thin area along the symmetry axis (radial coordinate r= ±2mm) up to a distance from the bluff body around 16 mm where the values of the droplets axial velocity are high and positive (Fig. 3). In addition, there is no ignition possibility in the side recirculation zone, where again the droplet velocity is positive. Therefore it is evident that the region of high ignition probability corresponds to the region of negative axial droplet velocity. At the centre, the spray is dense, the droplets have positive velocities (Fig. 4) and are large (Fig. 5); this may explain the zero ignition probability there. Figure 5 also shows high values of the Sauter mean diameter of the droplets in the bulk of the annular air flow, because large droplets have large inertia and are hence able to penetrate this region. Despite the fact that the mean air velocity is negative (i.e. towards the bluff body) at z=40mm (Fig. 6), the droplet mean velocity is positive there. It seems that successful flame establishment requires not only the presence of droplets, but droplet and air velocities that can carry the kernel towards the base of the flame.

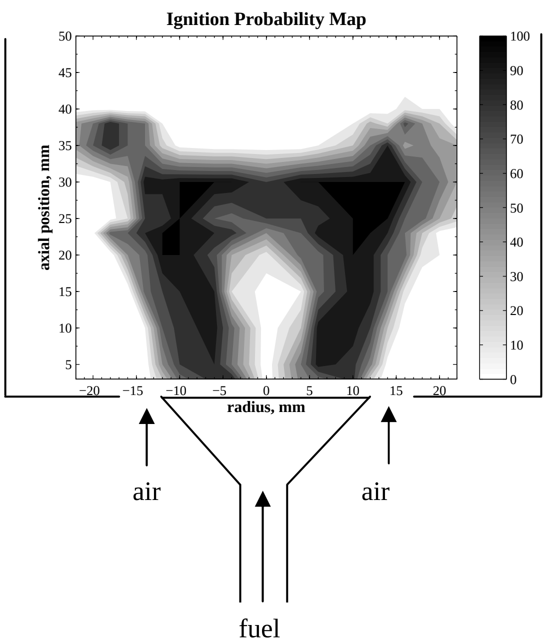


Fig.2. Ignition probability map

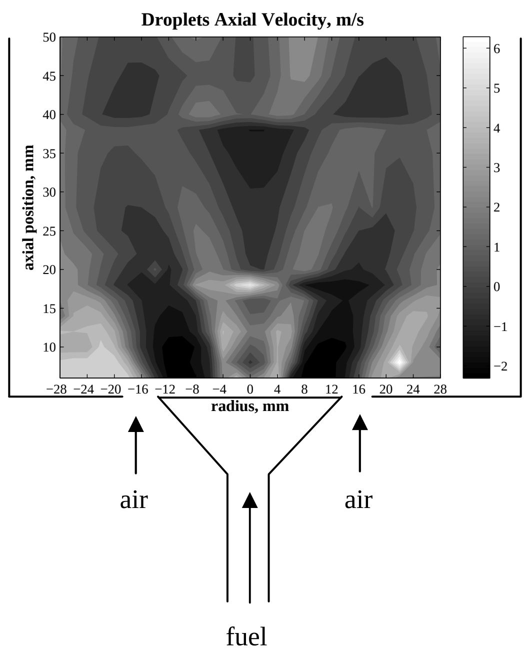


Fig.3 Mean axial velocity of the droplets.

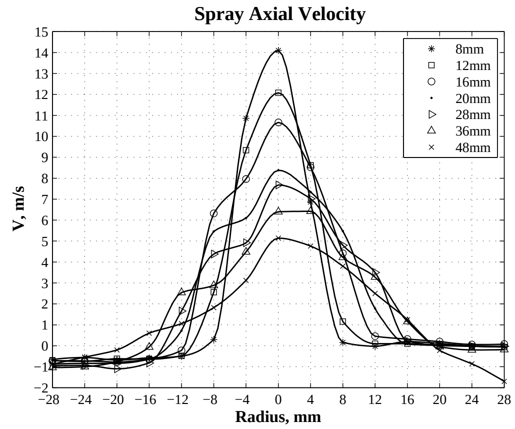


Fig. 4 Radial profile of mean droplet axial velocity.

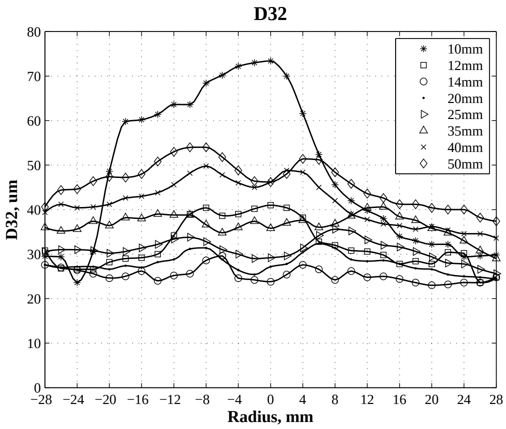


Fig. 5 Radial profile of Sauter Mean Diameter

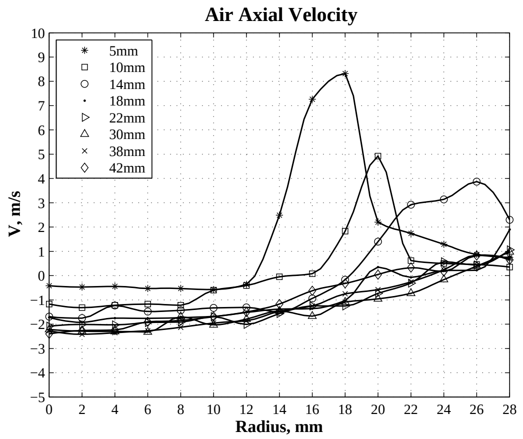


Fig. 6 Radial profile of the mean air axial velocity

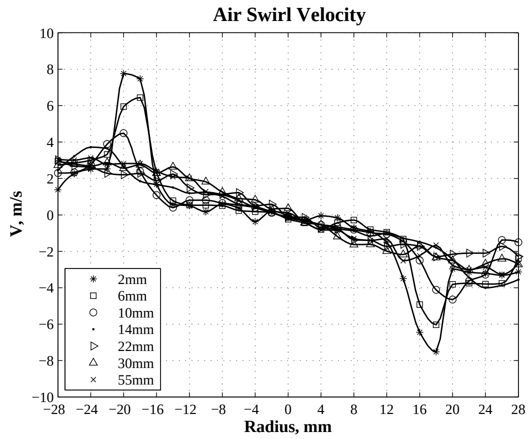
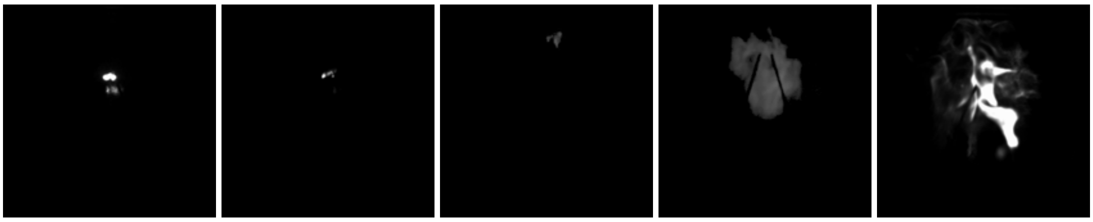


Fig. 7 Radial profile of the mean air swirl velocity

Visualization of ignition kernel

In Fig. 8, frames of a typical successful ignition event are shown with the spark located at the centreline and at 25 mm from the bluff body. The first frame of the movie recorded shows a bright kernel produced by the spark. The light emission from the kernel starts to decay rapidly; it persists just into the next frame (0.45 ms), which corresponds to the spark duration. In the following frames, the kernel starts to grow until the onset of the stabilized flame (14.4 ms). From the fast movies it can be observed that the kernel starts to grow very soon after the spark, it goes towards the nozzle due to the negative axial velocity and it runs around the electrodes of the spark following the tangential direction of the swirling air flow (Fig.7), until the flame eventually spreads near the bluff body surface. There seems to be little direct upstream propagation when the flame is not close to the centreline. With successful events with the spark off the centreline, the flame seems to follow mainly the swirling motion and expand slowly in both upstream and downstream directions.

The visualization has revealed two different types of failed ignition events. In the first, a small kernel is generated from the spark that disappears in a short time after a limited propagation. The second shows no kernel generation at all, i.e. no light is emitted once the spark energy deposition stops. In Fig. 9 it is possible to see an example of the first kind of ignition failure: the light emission from the spark (t=0) and the small kernel (t=0.9 ms) that disappears after 2.7 ms; the second type of ignition failure is presented by the fast images in Fig. 10. In this case, we can see only the emission from the spark.



t=0ms t=0.45ms t=0.9ms t=5.4ms t=14.4ms

Fig. 8 High-speed images of ignition event with spark at r=0 and z=23mm. The bluff body is at the top of these images.

t=0ms t=0.9ms t=1.8ms t=2.7ms

Fig. 9 High-speed images of failed ignition with spark at r=0 and z=23mm.

t=0ms t=0.9ms

Fig. 10 High-speed images of failed ignition with spark at r=-10 and z=40mm.

4 Conclusions and Future Work

This work studied spark ignition of a spray in a turbulent recirculating flow. Experiments were carried out to measure the ignition probability and to understand, by high-speed images, by PDA measurements of the droplet size and velocity and by LDV measurements of the air velocity, the conditions under which ignition is successful. The most important observations are: the ignition probability value was high in the central recirculation zone, and in particular in regions where the air and droplet velocities were negative; no ignition could occur in the thin central region near the atomizer, probably due to the high velocity and large size of the droplets there. Moreover, no ignition was observed in the side recirculation area and in the main annular air flow, despite the presence of droplet there, possibly because of the high air axial velocity in this area. From the fast movies and the velocity measurements it was clear that successful ignition locations were those with relatively small droplets and velocities towards the bluff body.

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