Measurements of the probability of ignition and subsequent flame propagation speed in turbulent non-premixed jets

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Summary

This paper describes an experimental investigation of the ignition probability as a function of flow velocity and of spark position, duration, size, and energy in a turbulent non-premixed jet of methane in air. The subsequent evolution of the flame is also characterised by measurements of its propagation speed by a fast digital camera. The results show that energetic sparks with long-durations or from large electrode gaps give higher probability of ignition at a given point and the ignition probability contour is consistent with previous experiments in jets. The measured net flame speed decreases from about 0.65 m/s to 0.25 m/s for jet velocities of 12 and 25 m/s, while the corresponding estimated relative flame propagation speed along the stoichiometric contour is about 1.5 and 2.5 m/s respectively. The measurements can assist theoretical efforts aimed at constructing models for spark ignition engines with inhomogeneous mixtures and for the performance of ignitors for aviation gas turbines.

Introduction

The spark ignition of non-premixed flames has not been studied as much as the spark ignition of homogeneous mixtures. The presence of turbulence can introduce randomness in the ignitability of jets due to the random composition of the fluid in the spark location and it has been found that the ignition probability follows to a large extent the probability of finding mixture within the flammability limits [1-3]. Additional possible influences of turbulence are on the failure of the spark to ignite a mixture nominally in the flammable range due to high local strain rates [4] and on the evolution of a spherical kernel into an edge flame that must eventually be formed to establish the whole diffusion flame. The practical importance of these phenomena involve safety considerations of accidental releases, high altitude relight of aviation gas turbines, spark ignition engines with very inhomogeneous mixtures, and even the evolution of flames in diesel engines following autoignition.

In an effort to understand the impact of mixture inhomogeneities on ignition and subsequent flame evolution, an experiment with a methane jet in a slow co-flow of air has been undertaken. The specific objectives were (i) to measure ignition probability; and (ii) to measure the propagation speed of the flame evolving from the spark. The results complement previous ignitability measurements in jets and focus more on the spark properties and flame propagation. The measurements can assist the development of models for spark ignition engines with inhomogeneous mixtures and for ignition in aviation gas turbines.

Experimental methods

The experiment consists of a 5 mm internal diameter stainless steel tube with length to diameter ratio of 128 (tube length = 640 mm) to assure a fully developed turbulent flow at the jet exist in a wider co-flow of air. The jet velocity U_j varied between 9 and 30 m/s and pure methane (99.99% purity) or methane premixed with small amounts of air (30% by vol.) has been used. This has been done to alter the stoichiometric mixture fraction and to minimize the amount of unburnt fuel used during the experiment. The co-flow of air originates from a 200 mm tube fitted with flow straighteners and was set at 0.1 m/s.

The spark was created by a custom-made circuit with which the spark energy and duration could be controlled independently. The main features of the ignition unit are the following: breakdown voltage (fully variable) 0 to 25 kV; maximum spark current 400 mA; spark energy 0 to 300 mJ; and spark duration 300 to 600 μs. The electrodes were made of stainless steel wire of diameter 1 mm and were mounted vertically from a horizontal arm attached to a traversing mechanism. This configuration causes minimum interference with the flow field [2]. The two electrodes end with a sharp point to reduce the heat transfer to the electrodes [5]. The spark gap width was set at 1, 2 or 3 mm. For each spark position, 30 independent spark events were performed and the percentage of events resulting in a flame establishment (i.e. flame kernel growing with time and propagating across and along the jet) was determined. The fuel flow rate was measured by calibrated rotameters.

The flame was imaged with a Phantom V4.2 digital high speed camera fitted with a fast intensifier. The sampling rate was 4.2 kHz. Since these images were two-dimensional projections of the whole flame, it was not possible to distinguish between a flame sheet at the edge of the jet from a flame sheet crossing the jet axis. Nevertheless, an estimate of the global propagation speed was inferred by measuring the flame position along the jet axis as a function of time.

Results and discussion

Figure 1 shows a typical two-dimensional contour of ignition probability. The contours have been assembled from a matrix of 42x12 points across and along the jet respectively. It is evident that there are regions of zero probability (close to the nozzle and away from the jet axis) and also small regions of almost unity probability (i.e. the flame always ignited). The iso-probability contours shown in Fig. 1 follow well the contours of ignitability factor [3], hence further validating the concept that the statistics of ignition of non-premixed flames are closely related to the statistics of finding mixture fraction within the flammable range. The regions of unity probability were larger when the spark gap was longer or the spark energy higher. A long spark duration is more effective to cause ignition, as Fig. 2 shows. A salient difference from the experiments of Refs. [1-2] is that the present spark duration was around 0.4 to 0.6 ms, which is of the same order as the Kolmogorov timescale in the jet at z/d=40, unlike the spark in the previous experiments that lasted about 20 ms falling well in the inertial range. A long spark may increase the chances of ignition because it increases the chances of sampling flammable material.

Figure 3 shows the flame position as a function of time when the spark was located at the centreline of the jet. Initially, the flame kernel seems to be convected downstream from the spark, but then the flame expands and begins to propagate upstream. At very long times from the spark, the flame has stabilised at the lift-off height. As the jet velocity increases, the lift-off height increases and the time taken to reach it also increases. We cannot draw solid conclusions yet as to the nature of the flame during the various phases of this evolution, but initially the flame seems a spherical kernel and later, when stabilised, it must have assumed the typical structure of an edge or a triple flame [6].

The net propagation speed can be determined from the slope of the curves in Fig. 3. These curves are averages from about 10 individual realisations (i.e. flame evolution), which show little scatter. It is evident that the propagation speed is not constant, since it is high initially and then reduces to zero as the lift-off height is reached. The propagation speed determined from Fig. 3 is shown in Fig. 4. This speed is quite low, about 0.25 to 0.65 m/s, and is lower at the high-speed jet. If we assume that for most of this propagation the flame would propagate along the stoichiometric contour away from the axis of the jet, we may approximate the actual propagation speed relative to the moving fluid by estimating the fluid velocity at the stoichiometric contour. To do this, the empirical correlations of Ref. [7] were used and evaluated at a mixture fraction of 0.0976, which corresponds to the stoichiometric mixture fraction for the dilution used here.

It is evident that the estimated flame speed relative to the fluid is around 2.5 m/s for the high velocity jet and about 1.5 m/s for the low velocity jet (Fig. 4) for most of the duration of flame propagation. This propagation speed is about 4 to 6 times higher than the laminar burning velocity of methane in air (*ca.* 0.4 m/s), a ratio higher than the propagation speed of edge flames [8] found in DNS. The net speed decreases to zero as the stabilisation point is reached (Fig. 3), where the local fluid velocity is around 7 m/s (Fig. 4) for U_j = 12.5 m/s, and about 2.5 m/s for U_j = 25.5 m/s.

Further experiments with double-pulse OH-PLIF are planned to elucidate further the structure of the flame at various instants of its evolution and to measure the net propagation speed of the actual flame, rather than its projection as performed here. Simultaneous mixture fraction measurements are also needed to correlate the flame position and propagation speed to the local mixture.

References

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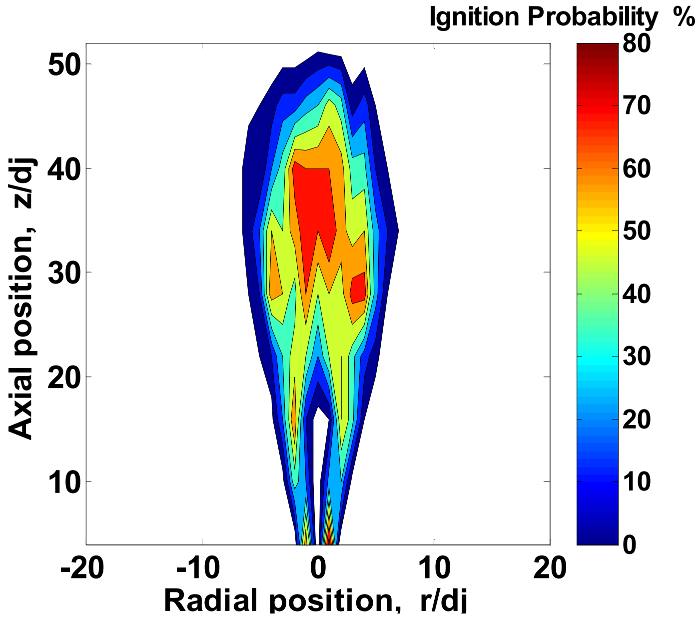

Figure 1. Ignition probability of a diluted methane jet flame (70%CH_4, 30%air) U_j =12.5 m/s. Spark: 400 µs, 100 mJ, 1 mm electrode, 1 mm gap.

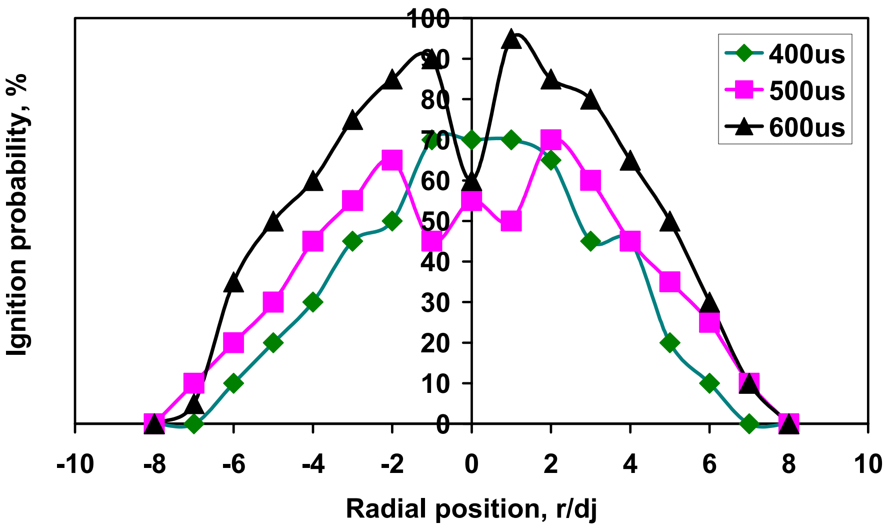

Figure 2. Radial profile of the ignition probability as a function of spark duration. z/dj = 40, U_j = 12.5 m/s. Spark: 100 mJ, 1 mm electrode, 1 mm gap.

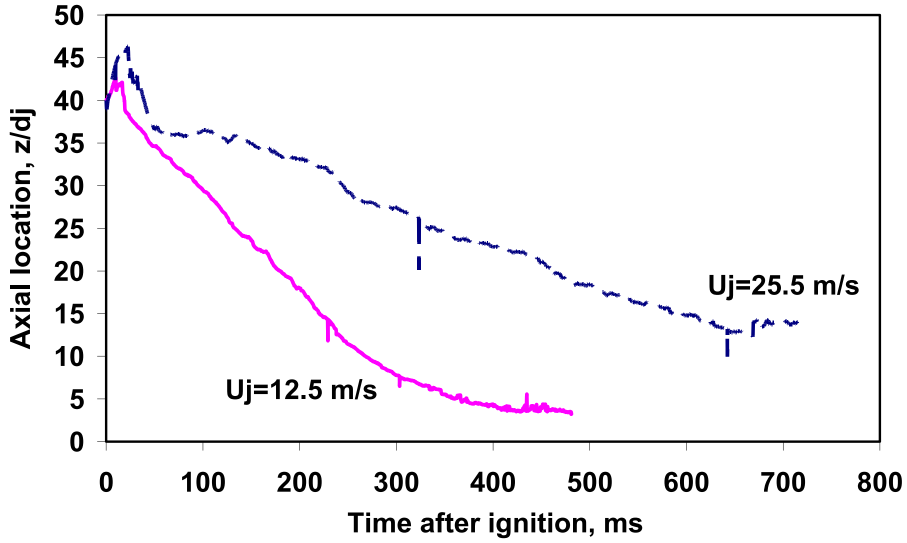

Figure 3. Flame position as a function of time for a mixture 70%CH_4 and 30%air (by vol.). Spark: 400 μs, 100 mJ, 1 mm electrode, 1 mm gap.

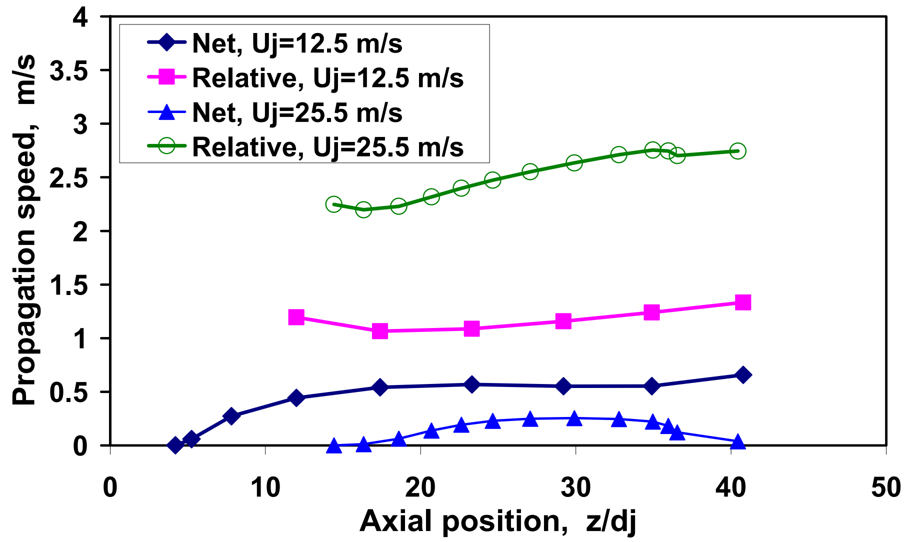

Figure 4. The net speed from Fig.3 added to the estimated fluid velocity at the stoichiometric contour from Ref. [7].