Fuel 164 (2016) 297–304

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Spark ignition of a turbulent shear-less fuel–air mixing layer

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 30 July 2015
Accepted 1 October 2015
Available online 11 October 2015

Keywords:
Spark ignition
Ignition probability
Turbulent mixing layer
Flame propagation

ABSTRACT

A planar methane–air mixing layer with equal velocity in the two streams has been used to examine the ignition probability and the non-premixed edge flame speed following spark ignition. The mixing layer has approximately homogeneous turbulent intensity and lengthscale. Mean local mixture fraction has also been measured for the whole flow field. The ignition and subsequent flame propagation were visualized with a high-speed camera and the flame's edges in the upstream, downstream and cross-stream directions have been identified. The average rate of flame evolution in these directions allowed an estimation of the average absolute flame speed. Ignition probability contour of the mixing layer takes a V-shape, which matches the shape of the lean and rich flammability limits with a little discrepancy in the rich side. By subtracting the uniform mean velocity resulted in estimates of the mean relative edge flame speed. This quantity was approximately $2.5S_L$, where S_L is the laminar burning velocity of stoichiometric methane–air premixed flames. The results are consistent with DNS of turbulent edge flames.

1. Introduction

Spark ignition of non-premixed combustion is important in high-altitude relight of aviation gas turbines, industrial furnaces, and some GDI automotive engines. Our physical understanding of such processes is not yet at a point that quantitative theoretical predictions can be made. Experiments with spark ignition of jet diffusion flames [1,2] showed that the probability of the emergence of an initial flame kernel in the spark neighbourhood is approximately equal to the probability of finding air–fuel mixture within the flammability limits. This concept has been further explored to provide a quantitative explosion risk assessment [3] with CFD and a presumed shape of the PDF of the mixture fraction. Recently, spark ignition of non-premixed flames has been revisited with jet [4], counter-flow [5], and bluff-body methane flames [6]. It was shown that, if ignition means the achievement of a full diffusion flame and not just the emergence of a small kernel that may be convected with the flow without causing flame ignition, the ignition probability is reduced and can be zero even in locations that have finite probability of flammable mixture fractions. The difference was attributed to local strain effects or high velocities that may not allow the flame kernel to grow or a flame to propagate, despite the local mixture fraction being flammable. This finding has been confirmed by studying the probabilistic nature of ignition of fully premixed turbulent flames in similar flow configurations [7] and in a swirled partially premixed burner [8]. It was noted that, in locations with high strain rates and/or high turbulence, these parameters have the detrimental effect on the ignition probability regardless of the mixture strength at these locations. In addition, the non-local effects, heat convection from the spark for instance, can play a very important part in determining the success of ignition [5], so that the ignition probability was finite even in regions of zero probability of finding flammable mixtures.

Simulations of spark ignition in a laminar non-premixed counterflow flame [9] reproduced these conjectures: ignition of the stoichiometric fluid could be achieved due to heat diffusion from the sparked region, even if that was located at rich or lean positions, and there was a critical strain rate, depending on the spark position and energy, above which ignition could not be achieved.

One additional reason why the ignition probability is less than unity, and why it is different than the probability of just establishing a small kernel, is that the flame cannot propagate against the flow to ignite the whole combustor. This, for example, has been visualized in simple recirculating flames [7,10], but also in realistic gas turbine combustors [11–13]. Hence, to understand this problem better, the speed at which flames propagate in turbulent non-premixed reactants must be quantified. This propagation takes place, in principle, along the stoichiometric mixture fraction contour. When the mixture fraction fluctuates little about a nominally flammable value, so that it is always lean or always rich,

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http://dx.doi.org/10.1016/j.fuel.2015.10.001
0016-2361/

premixed flame concepts can be used to describe flame propagation [14–16]. We may call this "stratified-charge premixed flame". When the mixture fraction fluctuates around the stoichiometric value, combustion occurs in a lean premixed, rich premixed, and non-premixed mode and the flame structure is reminiscent of so-called triple flames, which can merge under high strain rate to become edge flames [17]. Propagation of turbulent flames in this mode, which could be called "turbulent non-premixed edge flame", has not been studied well enough, although some relevant information has become available from studies on turbulent jet lifted flames [18,19]. In particular, from analyzing high-speed images of the flame at the stabilization height in jet flames [19], it has been concluded that the average edge flame speed is of the same order as the laminar burning velocity of the stoichiometric mixture S_L. The relative speed (i.e. flame edge speed relative to the fluid immediately ahead of the triple point) has been measured in the counterflow configuration [20] and its average value was around $0.75S_L$. Similar data from Direct Numerical Simulations of spark ignition and ensuing flame propagation in turbulent mixing layers in isotropic decaying turbulence [21–23] have revealed the detrimental effects of intense turbulence on absolute and relative edge flame propagation speed [21,22] and the effects of mixture fraction gradient and spark position on the structure and speed of the flame [23].

A detailed experiment study of spark ignition and flame propagation in the canonical problem of the turbulent mixing layer has not been performed yet. Hence, in this paper, we present the characteristics of such a fuel–air mixing layer and we examine its ignition probability defined as the number of successful ignition events that result in a stable flame over the total number of spark attempts at certain location. In addition, the propagation speeds (relative to fixed coordinates) of the flame edge, as it expands along the layer have been measured. This propagation occurs against the flow on one side of the flame, with the flow on the other side, and against zero mean flow in the direction across the mean flow (parallel to the mixing layer). Hence the experiment allows various insights into edge flame propagation. The fact that the flow velocity is uniform facilitates an estimate of the average relative propagation speed. The experimental methods are presented next, while the results are presented and discussed in Section 3.

2. Experimental methods

2.1. Apparatus

The burner, Fig. 1, consists of two stainless steel channels with rectangular cross-section, whose two sides are $W = 46$ mm and 20.5 mm, both being 500 mm long. The walls of the channels have a thickness of 2.5 mm. The two channels are attached along their length and their common wall is machined to produce a slope of 2.5°, which results essentially in a splitter plate separating the two flows. At the edge of this plate (the exit of the channels), the height of each channel is $H/2 = 23$ mm. A quartz section of width W and height H is then fitted to provide optical access to the planar mixing layer formed downstream of the splitter plate between the flows in the two channels. A perforated plate with 40% solidity and holes of size $M = 3$ mm to create turbulence is fitted 50 mm upstream of the splitter plate edge as shown in Fig. 1.

One channel of the burner carries air from the laboratory compressor and the other a fuel–air mixture. The fuel was methane (99.96% purity) and was mixed with 80% air ($X = 80\%$, by vol.). At this level of premixedness, the fuel–air stream is above the rich flammability limit and hence the flame formed between the two streams is of a non-premixed character. The air and fuel stream velocities at the exit were equal and, for most of the experiments reported here, the bulk velocities were $U_b = 3.0$ m/s and, for some experiments, $U_b = 1.5$ m/s. Both air and fuel flow rates were controlled by mass flow controllers. The Reynolds number of the flow in the channel before the perforated plate was 6720 (based on the hydraulic diameter).

The experiment has been designed in an effort to reproduce, at a smaller scale and adapted to the limitations imposed by safely performing a lab-scale combustion experiment, the shearless turbulent mixing layer studied experimentally by Ma and Warhaft [24]. It is also the experimental analogue of the DNS studied previously [21–23]. In particular, this experiment has turbulent Reynolds numbers close to those in the DNS, which facilitates some comparisons. To measure the streamwise (x) component of the velocity at various locations, a hot wire system was employed. A single constant-temperature Dantec 55P16 platinum-plated tungsten hot wire (diameter 5 μm and length 1.25 mm) was used with a DISA 55M01 standard bridge. The hot wire was placed perpendicular to the main flow direction and aligned with the z-direction. The measurements were taken with 10 kHz sampling rate and about 60,000 samples were recorded at each location using a DAQ system. The maximum statistical uncertainty for the reported mean velocities is estimated as 2%. All velocities reported are from the unignited condition.

2.2. Ignition unit

An ignition system was especially designed to produce repeatable sparks whose energy and duration could be varied independently. The main features of the unit can be found in Ref. [4]. The spark was created between two tungsten electrodes of 1 mm diameter, which were placed as shown in Fig. 1 to ensure minimum disturbance to the flow field. The electrodes had pointed edges to reduce the heat loss from the spark and the distance between them was 2 mm. The two electrodes were attached to a twin-bore ceramic tube, which was traversed axially and radially to cover the whole flow field with 0.1 mm resolution. For the experiments described here, the spark had duration of 400 μs and the electrical energy delivered by the circuit was 100 mJ. It should be mentioned that the repeatability of the spark energy produced from the ignition unit has been examined by using a Tektronix 6015A×1000 high voltage probe and an Ion Physics CM-1-L current transformer. Both devices have been connected to the spark electrodes and then the spark voltage and current waveforms have been detected by a Tektronix TDS 3012 digital oscilloscope with sampling rate of 1 MHz at the moment of spark. These waveforms have been presented in Refs. [4,25]. It was found that the maximum uncertainty of the spark energy produced from this ignition unit does not exceed 0.8% [25].

The ignition probability contour was measured by applying 50 single sparks at every chosen point. The number of successful ignition attempts that form a stable flame was divided by 50 to calculate the ignition probability at this location, which implies an uncertainty of 7.5% at 50% ignition probability [2]. For the current igniter configuration, about 30% of the spark energy is actually transferred to the combustible mixture [4]. This energy is much higher than the minimum ignition energy (6.41 mJ) required to ignite flammable methane–air mixtures under atmospheric conditions [26]. Each of the ignition probability contours measured here was assembled from a matrix of 25 × 25 points across and along the burner.

2.3. High-speed imaging

The ignition events were monitored with a Phantom V4.2 Digital High Speed Camera fitted with a fast intensifier. A number of movies were captured with 4200 fps for successful and failed