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Laser ignition and flame characteristics of pulsed methane jets in homogeneous isotropic turbulence without mean flow

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Abstract

The influence of turbulence on the minimum ignition energy (MIE) and ignited flame characteristics is investigated for pulsed methane diffusion jets ignited by laser-induced plasma. The methane jet is injected in a volume of homogeneous and isotropic air turbulence without mean flow, with the level of turbulence being controlled independently. The study is carried out for a range of fuel jet (Re_{jet}) Reynolds number, namely 1000, 2000, and 3000, and a range of turbulent (Re_{λ}) Reynolds number, namely 0–207. The results show that the position of the maximum intensity of flame emission was randomly scattered due to the fact that the ignited flame is deflected from the nozzle axis by the turbulent velocity fluctuations. The effect is more profound at higher Re_{jet}. The value of the MIE, determined according to 50% ignitibility of mixture, increases by a factor of 2 for an increase of Re_{λ} from 0 to 207 and by a factor of 5 for an increase of Re_{jet} from 1000 to 3000. Two trends are observed on MIE with Re_{λ}. For low Re_{λ}, MIE is independent of Re_{λ}. Past a critical value of Re_{λ}, MIE increases as a linear function of Re_{λ}. This transition occurs at critical values of $Re_{\lambda,c}$ = 158, 197 and 202 for Re_{jet}= 1000, 2000 and 3000, respectively. The mean value of MIE for ignition before and after transition is a linear function of Re_{jet}. The difference between the mean value of MIE before transition and after transition is around 5 mJ for all considered Re_{jet}.

Keywords: Laser ignition; Homogeneous and isotropic turbulence; Pulsed jet; Diffusion flame; Minimum ignition energy

1. Introduction

Modern low-NO_x combustion systems for gas turbines and internal combustion engines run on lean and ultra-lean operating conditions in order

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to reduce fuel consumption and satisfy stringent emission regulations, but ignition may be an issue. The evolution of ignition methods from direct contact ignition, e.g. conventional spark plug, to non-intrusive laser induced spark ignition has significant technological challenges. An important quantity for successful laser ignition is the minimum ignition energy (MIE), which depends on mean flow and turbulence among other factors. Therefore, new understanding of MIE is necessary for new combustion systems.

Research on the effects of turbulence and equivalence ratio on MIE and its transition in premixed air/fuel mixtures has been published [1–15]. Huang et al. [4] measured the MIE of lean methane/air mixtures in a large fan-stirred burner and found that MIE depends on turbulent intensity and there is a change in behaviour with turbulent intensity due to different combustion modes. Studies [5,6] found that MIE transition due to different modes of turbulent combustion depends on a turbulent Karlovitz number and a reaction zone Péclet number for different equivalence ratios. Recently, Cardin et al. [9,10] investigated MIE transition of lean turbulent premixed flames and concluded that turbulence affected the hot kernel before the initiation of chain-branching reactions. An observation is that larger deposited energy is required to compensate for high values of turbulent scalar dissipation and obtain a self-sustained flame.

Mastorakos [16] reviewed ignition of turbulent non-premixed flames and emphasised that the stochastic local character of ignition is determined by mixture fraction and Scalar Dissipation Rate (SDR) at the ignition location. DNS have shown that high reaction rate in transient fuel jets is associated with low values of SDR conditional on mixture fraction [17] and the contribution of premixed and diffusion combustion to heat release rate is affected by the local mixture fraction and SDR [18].

Few researches [19–21] have reported laser ignition characteristics for diffusion flames. Phouc et al. [20] reported laser ignition of a jet diffusion flame and showed that the location of the optimum air/fuel ratio for successful ignition varies with the flow conditions. Li et al. [21] investigated the effects of equivalence ratio, flow rate and ignition position on laser MIE and ignition probability and time, but the effects of flow and turbulence on MIE transition were not reported for diffusion flames.

Since the turbulent velocity fluctuations are linked with mean velocity gradients, one challenge is to identify how turbulence influences the MIE transition. Most ignition studies of premixed and diffusion flames have studied the effect of turbulence on the MIE and its transition in a mean flow field.

A ‘box of turbulence’ facility that generates a stationary volume of homogeneous and isotropic turbulence (HIT) without mean flow provides an opportunity to study turbulent ignition without the effect of the mean flow. Such a facility is used here to evaluate the combined effects of fuel injection speed and surrounding HIT turbulence without mean flow on laser ignition and flame characteristics for a methane diffusion pulsed jet. Flame visualisation evaluates flame location after ignition and the influence of fuel flow and turbulence on propagated flames. The MIE as function of fuel injection rate and turbulent Reynolds numbers is measured and its transition is compared to previous measurements [6,10].

2. Experimental methods and conditions

A schematic of the experimental set-up is shown in Fig. 1(a). The experimental arrangement comprised a ‘box of turbulence’ facility, which generated 3-D HIT without mean flow, a methane injection system, a laser ignition system and an imaging system. The ‘box of turbulence’ facility is composed of 8 loudspeakers (20MC8A, Davis Acoustics), placed at the vertices of a cube and pointing towards the cube centre. The loudspeakers are capped by perforated plates, which have 55 holes (6 mm diameter) that are arranged in a triangular mesh pattern. The loudspeakers are driven at 50 Hz with sinusoidal voltages and 8 sets of synthetic jet arrays are formed. When the induced synthetic jet array flows interact at the centre of the cube, the mean flow is cancelled out while the generated turbulence is HIT. The level of turbulence is adjustable by controlling the amplitude of the loudspeaker driving voltage. Details of the ‘box of turbulence’ are described in [22–24]. Eight levels of turbulence are considered in this study, as summarised in Table 1 (turbulent velocity fluctuations, u_t and corresponding turbulent Reynolds number, Re_λ). The inhomogeneity and anisotropy of turbulence in all cases remained below 10%, as reported in [22–24] and shown in Fig. 1(b) and (c).

Methane was selected as a gaseous fuel, since its chemistry is well developed, and the experimental results can assist the evaluation of ignition models without uncertainties with the chemistry. The methane pulsed jet is injected within the HIT flow field. The round nozzle, shown in Fig. 1(a), (inner diameter 2 mm, lip thickness 0.6 mm) is made of stainless steel. The nozzle tip was positioned 25 mm below the geometrical centre of the cube in order to maximise the interaction of the jet with the 50 mm^3 volume of HIT. Therefore, the jet and the laser ignition point were inside the HIT flow. Methane is supplied to the nozzle through a solenoid valve (Series 9, Parker Hannifin) with response time < 5 ms, located about 50 mm upstream of the nozzle tip. The methane flow rate is controlled by a metering valve (S series, Swagelok) and the injection pressure is monitored by a pressure transducer (IND series, RS). Fluctuations of the pulsed injection velocity were attenuated by a