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Full Length Article

Assessment of flame kernel propagation in partially premixed turbulent jet under different turbulence levels

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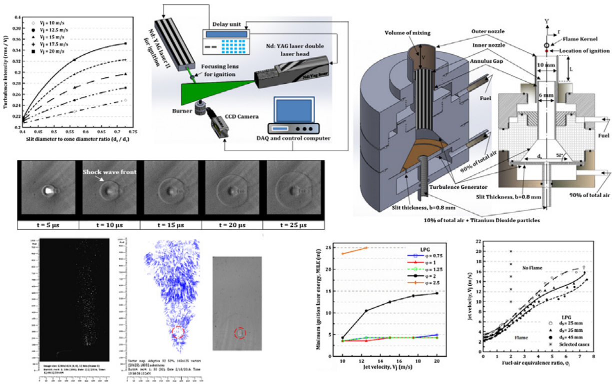
HIGHLIGHTS

- Effects of the jet velocity and equivalence ratio on the minimum ignition laser energy and stability limits were examined.
- Effects of the turbulence generator disk diameters on the turbulence intensity were investigated.
- Effects of the turbulence generator diameters on the structure and propagation of the flame kernel were investigated.
- Effect of the laser plasma on the shock wave propagation was visualized.

GRAPHICAL ABSTRACT



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ABSTRACT

Experimental optical tests were carried out in two concentric tubes burner, to obtain a comprehensive understanding of the turbulence level effects on flame kernel propagation in partially premixed flames. Two ND-YAG lasers with first and second harmonic wavelengths were employed for laser ignition and flow field velocity measurements, respectively. For the current study two parameters were considered, first the geometrical parameter, namely turbulence generator disk diameter (ds), which changes the turbulence intensity, whilst the second parameter was the jet velocity. These parameters were investigated under constant degree of partial premixing, and Liquid petroleum gas (LPG) was used as a fuel. The effect of the equivalence ratio and the jet velocity on the minimum ignition laser energy (MILE) and flame stability maps of different turbulence generator diameters were measured and employed to determine the suitable overall equivalence ratio and the operating conditions for the current study. Based on the analysis of the MILE and the stability limits, one constant jet equivalence ratio of $\varphi = 2$ and different jet velocities were used for the whole tests. The turbulent flow field was captured using two-dimension particle image velocimetry (2D PIV) system, and after times of 150, 300, 500, 1000, 1500, and 2500 μs from the start of ignition. The results demonstrated that the MILE for LPG increased as the equivalence ratio increased, especially for rich conditions. In addition, near the stoichiometric conditions, the MILE trends were closely matched for all the jet velocities, although the MILE trends of lean condition were marginally higher. The flame stability maps of different turbulence generator diameters illustrated three extinction curves, which were separated

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between two regions, lifted flames and blowout. Smaller (ds) was more stable compared to other (ds). The turbulence chemistry interactions influenced the flame kernel propagation rate; at lower jet velocities chemistry effects were dominant, whilst at higher jet velocities turbulence became dominant. The propagation rate for LPG flames increased either by increasing ds or by increasing jet velocity.

Nomenclature

MILE	minimum ignition laser energy	DOF	the depth of field
d_s	turbulence generator slit diameter	f	lens focal length
2D	two-dimension	d	laser beam diameter
PIV	particle image velocimetry	λ	laser wavelength
LPG	liquid petroleum gas	U_j	jet velocity
DNS	direct numerical simulations	K	eddy-breakup time
LIS	laser-induced spark	φ	fuel-air equivalence ratio
L/D	distance to outer tube inner diameter ratio	d_C	cone diameter
b	slit thickness	PLIF	planar laser induced fluorescence
CCD	charge-coupled device	Y	axial distance from the burner
C_3H_8	propane	C_4H_{10}	butane
Rms	root mean square	S_L	laminar burning velocity
r	the laser beam waist radius		

1. Introduction

The investigation of turbulent flow field impacts on propagation of partially premixed flame is of great practical importance in the design and optimization of efficient internal combustion engine and low emission burners [1–3]. Intense turbulence increase the turbulent flame propagation rate to a higher value compared to the laminar burning velocity (S_L) in the same mixture [2]. This consequently enhances the rate of heat release and the power generated from both the internal combustion engines and the combustor of a given size. However, increasing turbulence beyond a certain level can lead to quenching of the flame [1]. This effect is particularly pronounced when the RMS velocity fluctuation of the turbulent flow becomes significantly higher compared to S_L.

The early stages of flame development play a dominant role in evaluating the subsequent behavior of that flame, and thereby influence the engine performance and emissions [4,5]. These stages are represented by the flame kernel evolution. Flame kernel development yielded approximately 30% of the total burn time over the combustion process of an IC engine. However, the mass fraction of reactants consumed during this phase was approximately 2% [6,7]. Cycle-to-cycle variation in engine performance and emissions linked significantly to the variations in the initial growth of flame kernel [8]. Flow field, mixing field, spark energy and rate of energy release considered the key parameters which had a great impact on flame kernel development [9]. The kernel growth had been characterized as a two-stage process: in the early short stage, the pressure wave and expanding plasma kernel controlled both mass and energy transfer processes; whilst for the next much longer stage during the self-sustained flame, thermal conduction and diffusion dominated mass and energy transfer [10].

Mulla et al. [11] investigated the early stages of flame-kernel evolution for methane-air mixture emerging from Bunsen burner and ignited using laser-induced spark. Their study revealed that at higher velocities a great change occurred to the shape of the flame-kernel, whilst the kernel size did not change significantly for a certain time from the start of ignition. Additionally, Mansour et al. [12] further investigated the flame kernel structure and propagation in turbulent premixed methane-air mixture ignited using laser ignition. They demonstrated that at the beginning, the flame kernel was shaped like a sphere and then changed gradually to peanut-like structure, then to mushroom-like structure and eventually disturbed by the turbulence. Also, Beduneau et al. [13] investigated different stages of the laser-induced breakdown of methane and propane air mixtures, particularly the transition process from a flame kernel to a self-sustaining flame. Eisazadeh et al. [14] carried out experimental and theoretical studies to investigate the effects of chemical energy, spark energy and energy losses on plasma kernel formation and propagation of premixed gases. They exhibited that the initial kernel temperature and volume had a great effect on the growth and temperature of the plasma kernel. Furthermore, the size and temperature of the kernel depend mainly on the amount of electrical energy input.

The flow field and mixing field are considered a key parameter affecting the flame kernel propagation. Elbaz et al. [15,16] investigated flame kernel propagation of natural gas flames for different degree of partial premixing and a variety of mixture equivalence ratios. They revealed that at stoichiometric conditions the propagation of flame kernel enhanced and provided the largest kernel speed. Furthermore, Xiong et al. [17] investigated in a quiescent combustion chamber the interaction between a flame kernel and a laminar vortex kernel. Their study demonstrated that the rate of kernel growth due to the variation in laminar vortices strengths and sizes increased by three times at least compared to that of quiescent laminar environment. Consequently, the combustion reaction rates significantly increased due to the highly stretched and curved flame fronts. Jenkins et al. [18] utilized three-dimensional compressible direct numerical simulations (DNS) with single-step Arrhenius chemistry, for further investigation of turbulent premixed flame kernels development, under strain rate and curvature effects. They displayed that the mean density-weighted displacement speed of flame kernels varies significantly over the flame brush.

Ignition source is considered one of the important parameter for internal combustion engines to initiate the combustion process. Ignition is a complicated phenomenon known to strongly affect the subsequent combustion [19]. It especially embodies the early stages of flame formation, which have strong implications on pollutant formation, flame propagation and quenching. Ignition is as