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Experimental study of turbulent flame kernel propagation

Mohy Mansour [a,*], Norbert Peters [b], Lars-Uve Schrader [b]

[a] *National Institute of Laser Enhanced Sciences, Cairo University, Giza, Egypt*
[b] *Institute of Combustion Technology, Aachen, Federal Republic of Germany*

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Abstract

Flame kernels in spark ignited combustion systems dominate the flame propagation and combustion stability and performance. They are likely controlled by the spark energy, flow field and mixing field. The aim of the present work is to experimentally investigate the structure and propagation of the flame kernel in turbulent premixed methane flow using advanced laser-based techniques. The spark is generated using pulsed Nd:YAG laser with 20 mJ pulse energy in order to avoid the effect of the electrodes on the flame kernel structure and the variation of spark energy from shot-to-shot. Four flames have been investigated at equivalence ratios, φ_j, of 0.8 and 1.0 and jet velocities, U_j, of 6 and 12 m/s. A combined two-dimensional Rayleigh and LIPF-OH technique has been applied. The flame kernel structure has been collected at several time intervals from the laser ignition between 10 μs and 2 ms. The data show that the flame kernel structure starts with spherical shape and changes gradually to peanut-like, then to mushroom-like and finally disturbed by the turbulence. The mushroom-like structure lasts longer in the stoichiometric and slower jet velocity. The growth rate of the average flame kernel radius is divided into two linear relations; the first one during the first 100 μs is almost three times faster than that at the later stage between 100 and 2000 μs. The flame propagation is slightly faster in leaner flames. The trends of the flame propagation, flame radius, flame cross-sectional area and mean flame temperature are related to the jet velocity and equivalence ratio. The relations obtained in the present work allow the prediction of any of these parameters at different conditions.

Keywords: Flame kernel; Laser diagnostics; Rayleigh; Laser; Turbulent; Premixed

1. Introduction

The early phase of combustion in spark ignited combustion systems affects the flame propagation, stability and hence the performance of the combustion process and the system efficiency. Flame kernel represents this phase and is likely affected by spark energy, rate of energy release, flowfield and mixing field. In spark ignited engines the cycle-to-cycle variation can be highly attributed to the initial growth of flame kernel [1]. Studying the development of flame kernels has thus a great importance in understanding the combustion process. This should also lead to better designs of spark ignited combustion systems with higher combustion efficiency and less pollutants formation. Some earlier experiments were designed to generate high turbulence level, isotropic, homogeneous with well controlled length scales in order to study the flame kernel propagation [2–5].

In most practical spark ignited combustion systems the turbulence level is high and the flames are more likely to be within the thin reaction zones regime [6]. Flame kernel has attracted many experimental research groups [4,7–9] and DNS research groups [8,10–13] for studying flame kernel evolution in turbulent environment and the main factors that control its propagation. Many parameters have been investigated to study their effects on the flame kernel propagation, e.g. flame shape, wrinkling and curvature. Gashi et al. [8] have investigated the effects of curvature and wrinkling on the growth of turbulent premixed flame kernels using DNS with simplified chemistry. They

* Corresponding author. Tel.: +20 121630863; fax: +20 235729499.
E-mail address: mansour@niles.edu.eg (M. Mansour).
URL: http://www.niles.edu.eg (M. Mansour).

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Nomenclature

A	flame cross-sectional area	t	time
DNS	direct numerical simulation	T	temperature
FK	flame kernel	U	velocity
r	radial coordinate	x	height above the burner
Re	Reynolds number	Z	axial location of the flame kernel
R_{Av}	the ratio between the average cross-sectional areas for the flames at the same jet velocity		
$R_{\mathrm{A}\varphi}$	the ratio of the flame cross-sectional areas for the flames at the same jet equivalence ratio	*Subscript*	
R_{Tv}	the ratio of the average temperature of the flames at the same velocity	ave	average
$R_{\mathrm{T}\varphi}$	the ratio of the average temperature of the flames at the same equivalence ratio	J	jet
R_{Z}	the ratio of the average flame propagation at the same velocity	rms	root mean square
		Symbol	
		ϕ	equivalence ratio

compared the 3-D DNS calculations with the 2-D laser measurements and concluded good agreement. Jenkins et al. [13] have also used DNS with single-step Arrhenius chemistry and concluded that the flame wrinkling and curvature have great effect on the flame kernel propagation in the thin reaction zone regime of Peters [6].

In the present work, a free jet with well defined mixing and flow fields was selected as the proper environment for flame kernels in the thin reaction zone regime. The flame kernels were generated using laser pulses in order to eliminate the effect of the electrodes on the flame structure and stability. The flames have been selected at different values of equivalence ratio and jet velocity in order to study the effect of turbulence/chemistry interactions. Advanced laser facilities have been used for quantitative measurements of the flame kernel structure and its propagation. The aim of this work is to study the structure and evolution of turbulent flame kernels.

2. Burner and flames

The burner consists of a 40 mm nozzle diameter sitting at the top of conical turbulence generator as shown in Fig. 1. The nozzle height is 56 mm and the turbulence is generated using the idea of Videto and Santavicca [14]. In their [14] idea the jet passes through a narrow circular slit followed by cone. This provides a ring-like cylindrical flow which is broken at the inner cone wall to generate a wide range of multi-scale eddies. This leads to high turbulence level. The idea has been successfully applied in a low swirl burner by Bedat and Cheng [15]. The slit thickness in the present burner is 0.8 mm. The turbulence intensity can reach as high as 25% in this configuration [16]. A premixed methane–air mixture flows through a porous brass plate before the slit in order to secure safe operation against possible flash back. The flame kernels are generated near the nozzle exit using pulsed laser for ignition. The flow field is not designed for stable flames and thus the flame kernels are generated and propagated through the flow field before blow out. This allows the study of the flame kernel developments for many events without the need of switching the flame off between consecutive ignition events.

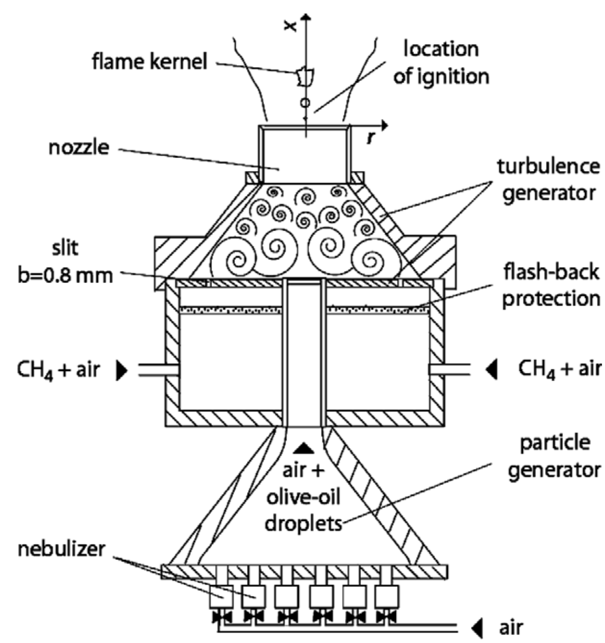

Fig. 1. A schematic diagram of the burner geometry and turbulence generator.

The burner design provides seeding mechanism of the cold flow in order to characterize the flow field, as shown in Fig. 1. The seeding droplets are generated using nebulizers filled with olive-oil.

Four flames have been selected for the present work at different jet velocity and jet equivalence ratio. The flames conditions are listed in Table 1 below. Two velocities at 6 and 12 m/s and two equivalence ratios at 0.8 and 1.0 were selected. The flame kernels are generated and propagated