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Lean partially premixed turbulent flame equivalence ratio measurements using laser-induced breakdown spectroscopy

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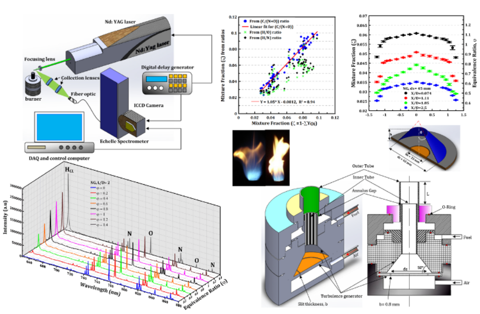
GRAPHICAL ABSTRACT



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ABSTRACT

The creation of a more stable flame along with the extension of flammability limits under lean mixture combustion was the main motivation to develop a new burner design, which has been investigated in this research. The current burner configuration was utilized to create a wide range of higher turbulent intensities and to produce different degrees of mixture inhomogeneity, which acted to promote minimum pollution, highest performance and higher flame stability. The burner stability assessment was investigated using two types of fuel: natural gas (NG) and liquefied petroleum gas (LPG). They were tested under different degrees of partial premixing, and two turbulence generator disks for lean mixture at an equivalence ratio of $\varphi = 0.8$ were used. Following this, the Laser Induced Breakdown Spectroscopy (LIBS) technique was utilized to characterize and quantify the impact of changing the disk slit diameter on the distributions profiles of equivalence ratio or mixture fraction for a NG/air partially premixed flame. A series of homogeneous NG/air mixtures with different equivalence ratios were used to obtain the correlations between the measured emission lines of LIBS spectra and the global flame equivalence ratio. Consequently, the emission spectral lines ratios of H/N, H/O and C/N + O were utilized to predict the equivalence ratio distributions. The results demonstrated that for all of the mixing lengths, NG/air mixture with larger disk generator diameter yielded the maximum burner stability, whilst the LPG/air mixture with a larger disk generator diameter resulted in the minimum burner stability. Furthermore,

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the flame associated with the larger disk slit diameter had a uniform local equivalence ratio distribution and lower RMS fluctuation profiles of equivalence ratio in comparison to the lower disk slit diameter.

Nomenclature

LIBS	laser induced breakdown spectroscopy	r	radial distance, mm
d_s	turbulence generator diameter	R	inner radius of the outer tube, mm
ξ	mixture fraction	Y_{fi}	mass fractions of the fuel elements
NG	natural gas	L_k	Kolmogorov scale
PPFs	partially premixed flames	HI	hydrogen intensity
ICCD	intensified charge-coupled device	λ	laser wavelength
L	mixing length, mm	V_j	jet velocity
b	slit thickness	τ_{mix}	mixing time
LTE	local thermal equilibrium	φ	equivalence ratio
C_3H_8	propane	d_C	cone diameter
Rms	root mean square	X	axial distance above the burner tip
PI	Princeton instruments	C_4H_{10}	butane
NI	nitrogen intensity	δ	convection-diffusion laminar flame thickness
CI	carbon intensity	OI	oxygen intensity
D	inner diameter of the outer tube, mm	θ	cone half angle
Do	outer diameter of the outer tube, mm	d	inner diameter of the inner tube, mm
		do	outer diameter of the inner tube, mm
		X	axial distance, mm

1. Introduction

The mixture stratification process and the generation of higher turbulence levels are the two main established techniques to extend the lean combustion limit [1]. Therefore, the new combustion system design, directed towards partially premixing combustion, is a promising technology, which offers the potential to meet ever stringent emission regulations, as well as improving the system efficiency [2]. The performance of the combustion processes is mainly linked to the local equivalence ratio distributions near the ignition event, and based on these distributions, the combustion characteristics and the level of emissions such as CO, NOx, etc. will be strongly affected [3,4]. This influence is mainly linked to the change of both the local properties of the reaction zone and the global behaviour of the combustion system associated with the flame propagation within spatial variations of the equivalence ratio [5]. Therefore, quantifications of this ratio are essential to sustain the higher stability of the combustion process and to minimize the soot emissions [6].

Richardson et al. [7] demonstrated that the laminar flame propagation speed was affected by the equivalence ratio gradients, due to the gradients effects on the molecular transport of hot products and radical species into the reaction zone. Furthermore, Dold [8] concluded that as the mixture fraction or equivalence ratio gradient increased, the flame propagation speed was reduced. This was attributed to the lower conduction heat transfer associated with the increased flame front curvature, which consequently reduced the preheating process of the unburned mixture. Likewise, Richardson and Chen [4] investigated turbulent flame propagation under the impacts of equivalence ratio-stratification for methane air flame using DNS analysis. They concluded that the stratification process influences significantly on the flame surface area due to the variation caused by equivalence ratio gradient orientation on the flame surface averaged consumption speed with surface averaged equivalence ratio.

In order to measure and obtain comprehensive information regarding global and local equivalence ratios distributions in turbulent flames, laser induced break down spectroscopy (LIBS) was used in this research. The principle of laser induced breakdown spectroscopy depends mainly on the interaction of a very short-duration focused pulsed laser beam onto the surface of the substance to be analysed, causing the breakdown of the sample's chemical bonds, followed by the formation of plasma, which is composed of ionized matter [9,10]. During the subsequent relaxation of the constituent excited species, the spectral emission occurred, and it was collected and spectrographically analysed using an Intensified CCD (ICCD) detector attached to a spectrograph detector [11]. The elemental composition of any material can be identified based on their fingerprint spectral lines, and consequently, the concentration of such elements will be quantified from the spectral line intensities. The main advantages of the LIBS technique lies in its ability to rapidly analyse samples remotely and in situ, with minimal sample preparation [12,13]. Furthermore, LIBS has the potential of simultaneous multi-elemental analysis with minimum equipment [14]. The aforementioned advantages make the LIBS technique to an attractive tool for the majority of applications including liquids [15,16], solids [17,18] and quantitiative analysis of gases and gas mixtures, which are all essential tasks in the field of security, environmental and chemical analysis [19,20].

Over the past few years, the LIBS technique has been applied extensively to the field of combustion diagnostics [21,22] for equivalence ratio measurements which can be obtained based on the atomic species concentrations in flames. Kotzagianni et al. [23] established a new calibration scheme for equivalence ratio measurements of non-premixed and premixed methane turbulent flames using the LIBS technique. They concluded that for a lower mole fraction of methane in the range 0–0.3, the ratio of Hα (656.3 nm) over O (777.3 nm), (Hα/O), should be utilized for equivalence ratio calculations. Additionally, they found that, for a higher mole fraction of methane in the range 0.3–1, the ratio of C_2 over CN, (C_2/CN), should be used to identify the equivalence ratio. The majority of past LIBS studies were mainly focused on using the ratios of some spectral lines of the atomic origin, such as the carbon line to nitrogen [C (833 nm)/N (744 nm)], the carbon line to oxygen [C (833 nm)/O (777 nm)] [24], or the ratio of the intensity of a carbon line to the sum of the intensities of a nitrogen and an oxygen line, [C (711 nm)]/[N (744 nm) + O (777 nm)] [25]. These ratios have been successfully utilized to delineate the relationship between the spectral intensity and the mixture equivalence ratio. The most commonly used ratios were between the hydrogen line to an atomic emission of oxygen line [Hα (656.3 nm)/O (777 nm)] or hydrogen line to an atomic emission of nitrogen [Hα (656.3 nm)/N (746.8 nm)] [26–28]. Alongside the equivalence ratio measurements, LIBS has been utilized for further analysis of the turbulent flame