Fuel 220 (2018) 942–957

Contents lists available at ScienceDirect

Fuel

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

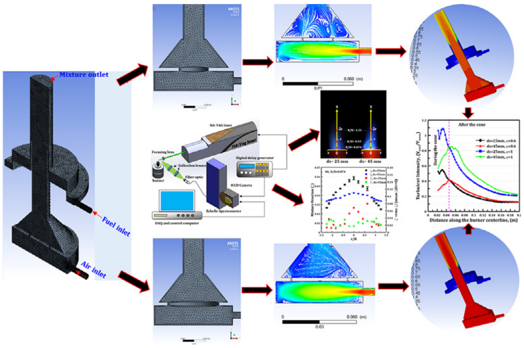
Full Length Article

New developed burner towards stable lean turbulent partially premixed flames

Tawfik Badawy[a,b,*], Mahmoud Hamza[a,*], Abdalqader Ahmad[b], Mohy S. Mansour[a,c], Abdel-Hafez H. Abdel-Hafez[a], Hisham Imam[d]

[a] *Mechanical Power Engineering Department, Cairo University, Egypt*
[b] *Mechanical Engineering Department, University of Birmingham, Birmingham B15 2TT, UK*
[c] *Mechanical Engineering Department, The American University in Cairo, Egypt*
[d] *National Institute of Laser Enhanced Sciences, Cairo University, Giza, Egypt*

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Mixture fraction
LIBS
Turbulence
Partially premixed
Laser breakdown
Stability
Multiphase flow

ABSTRACT

A new burner was developed in order to achieve very stable lean flames at lower equivalence ratio and higher level of turbulence intensity. The air-fuel mixing process of the current burner was controlled either by using different levels of partially premixed or by changing the turbulence generator disk slit diameter, ds. Initially, the distributions of turbulent intensity and air volume fraction inside the burner were numerically investigated using three-dimensional computational fluid dynamic (CFD) modelling. Then the lean flame stability limits corresponding to the lean natural gas (NG)/air mixture at an equivalence ratio of $\varphi = 0.6$, under five degrees of partially premixed and two turbulent generators disk slit diameters were delineated. Based on the stability limits map, laser induced breakdown spectroscopy (LIBS) technique was employed for further quantitative measurements of the mixture fraction or the equivalence ratio distributions of NG/air mixture. The results indicated that the maximum burner stability for smaller ds was achieved at mixing length to diameter ratio (L/D) of 1:1, whilst for larger ds the maximum stability was achieved at L/D ratio of 2:1. Furthermore, the largest disk slit diameter yielded a homogeneous mixture fraction distribution and lower rms fluctuation, compared to that of lower disk slit diameter. Consequently, this improved the conduction effectiveness in preheating the unburned gases layers resulting in higher flame propagation speed.

---

* Corresponding authors at: Mechanical Power Engineering Department, Cairo University, Egypt.
E-mail addresses: tsb308@bham.ac.uk, tsb308@outlook.com (T. Badawy), hamzami@mail.uc.edu (M. Hamza).

https://doi.org/10.1016/j.fuel.2017.11.121
Received 1 August 2017; Received in revised form 7 October 2017; Accepted 28 November 2017

Nomenclature

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

1. Introduction

The development of low emission burner is of practical importance for reducing the fuel consumption, improve efficiency and minimize the negative environmental impacts associated with those emissions [1]. The lower emissions accompanied with Lean combustion was attributed to the lower flame temperature and consequently resulting in lower NOx formation. Likewise, the hydrocarbon and carbon monoxide emissions associated with lean hydrocarbon combustion were reduced due to the higher oxygen content which promote more complete burnout of fuel [2]. However, the burner design required to accomplish such enhancements and to meet the future demands of combustion systems, is restricted by the burning characteristics of lean premixed flame which are precisely controlled by several key parameters including the local air-fuel ratio, low reaction rates, extinction, turbulent intensity and the stabilization mechanism employed for lean flames [3].

Partially premixed combustion exhibit the combined advantage of both premixed and diffusion flames and therefore is considered one of the popular mixing strategy for both gas turbines [4,5], and stratified-charge internal-combustion engines [6,7]. In addition, lean partially premixed combustion is an effective technique developed for further thermal efficiency enhancements and emission reductions [8]. Recently, the extension of the lean operational limit of both the combustor and internal combustion engine was achieved by using two developed techniques. The first technique was utilized to create a new design for the combustion chamber or the burner that has the ability to increase the turbulence intensity generation and consequently improve the mixing process of the combustion mixture close to the ignition event. The second technique exploited the presence of a small pocket of relatively rich mixture associated with the concept of partially-stratified charge around the ignition event. Consequently, this will facilitate the ignition process of partially premixed charge in comparison to the conventional main, very lean, premixed combustion charge [9]. However, at higher turbulence levels, lean combustion is extremely susceptible to lean blowout [8]. Therefore, to assist the stability characteristics of lean turbulent partially premixed flames experimentally, real-time measurements of the local fuel/air ratio are essential to shed more lights into the turbulent mixing phenomena [10].

Over several years, Laser Induced Breakdown Spectroscopy (LIBS) grew quickly and recently established as a powerful diagnostic technique for a real-time and in-situ simultaneous multi-element quantitative analysis [11]. Furthermore, LIBS demonstrated higher sensitivity to the light elements including C, H, O, Li, B and N which are difficult to be detected by other analytical techniques. Due to the aforementioned inherent advantages of LIBS technique, it was employed for elemental analysis of different materials including gases [12,13], solids [14–17] and liquids [18,19] and is of practical importance for dangerous and hostile environments [20,21]. Furthermore, LIBS is extensively employed for combustion system to identify the temperature, fuel–air ratio and fuel composition of the mixture. The measuring principle of LIBS is based on the investigation of micro-plasma emission produced by focusing a higher-power laser pulse to dissociate, excite, or ionize molecules in the flame region [22]. The gas constituents electrons by means of inverse bremsstrahlung process will gain the photon energy of the laser beam and consequently the energetic electrons will induce, by collision causing excitation, dissociation and ionization [23]. Then, during the decay process, the exited species will emit emissions (e.g., atoms and ions) and hence can be recorded and analysed spectroscopically in order to obtain qualitative and quantitative measurements of the sample elemental compositions. Consequently, the concentrations of the constituents are feasible due to the linear correlation between the intensity of spectral emission line and the population of the atomic excited state [22,24].

Phuoc and White [10] employed LIBS technique to investigate the equivalence ratio distributions of methane air mixture based on the linear correlation between the radiation intensity ratio of the Hα (656.3 nm) to the O triplet (near 777 nm) (Hα/O) with the equivalence ratio. Furthermore, Kotzagianni et al. [25] explored the feasibility of LIBS technique for instantaneous and local equivalence ratio measurements of turbulent premixed and non-premixed flames. In addition, Ferioli and Buckley [26] used LIBS technique to estimate the equivalence ratio distributions of methane, propane and carbon dioxide in air based on the C/(N + O) atomic ratio. Michalakou et al. [27] examined the local equivalence ratio distributions for various ethylene-, propane-, and methane-air mixtures. Also, Mansour et al. [28] investigated the feasibility of using LIBS technique for turbulent partially premixed equivalence ratio measurements of methane/air flames. Recently, Sturm and Noll [29] investigated the capability of LIBS technique for equivalence ratio measurements using different gas mixtures of C_3H_8–N_2, C_3H_8–CO_2 and CO_2–air and they delineate the calibration curves between the ratio of elemental emissions of C, H, O, and N and the mixture compositions. The aforementioned studies defined the equivalence ratio of hydrocarbon fuels based on the intensity ratios of C/(N + O), C/N and H/O within the probe volume. Moreover, several studies have been carried out to investigate the impact of several key parameters including laser pulse energy, delay time with respect to the triggering signal (delay time), aperture time of the camera's shutter (exposure time), gas pressure and gas flow rate on the LIBS measurements. In addition, LIBS has been employed to measure the temperature [30], gas density and concentration [31]in turbulent flames.

The main objective of this study is to obtain high quality database of partially premixed flames that assists the development of new lean,