Experimental Thermal and Fluid Science 91 (2018) 214–229

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

A concentric flow slot burner for stabilizing turbulent partially premixed inhomogeneous flames of gaseous fuels

Mohy S. Mansour[a,b,*], Heinz Pitsch[c], Stephan Kruse[c], Mohamed F. Zayed[b], Mohamed S. Senosy[d], Mrinal Juddoo[e], Joachim Beeckmann[c], Assaad R. Masri[e]

[a] *Mechanical Engineering Department, the American University in Cairo, Egypt*
[b] *Mechanical Power Engineering Department, Faculty of Engineering, Cairo University, Egypt*
[c] *Institute of Combustion Technology, Aachen University, Aachen, Germany*
[d] *National Institute of Laser Enhanced Sciences, Cairo University, Giza, Egypt*
[e] *School of Aerospace Mechanical and Mechatronic Engineering, Faculty of Engineering and Information Technology, The University of Sydney, Australia*

ARTICLE INFO

Keywords:
Slot burner
Turbulent combustion
Gaseous fuels
Inhomogeneous mixtures
OH-PLIF
C_2H_x-PLIF

ABSTRACT

Combustion of turbulent inhomogeneous mixtures of air and fuel is common in many practical systems providing improved stability for both gaseous and liquid fuels. Understanding the structure and stability of turbulent flames in this mode has been the aim of many research groups who employed special burner designs to control the fuel and air mixing process. In this work, a modified design inspired by the Wolfhard-Parker slot burner was developed for planar turbulent flames with inlet conditions that are overall lean yet either compositionally inhomogeneous or partially premixed. The new burner is referred as the Concentric Flow Slot Burner (CFSB). The stability characteristics and flame structure are investigated for methane and natural gas fuels using planar laser induced fluorescence of C_2H_x and high speed PLIF-OH. The effects of the jet equivalence ratio, the level of inhomogeneity, and the Reynolds number are investigated in this work. The data show that the flames with inhomogeneous mixture are more stable than fully premixed flames. Lean flames are stabilized in the CFSB burner. Stability is significantly improved by the use of a hollow truncated rectangular pyramid nozzle at the burner exit. The reaction zone structure varies significantly in the current burner from thin structures in rich flames to distributed with thick preheat zones in lean flames. The effect of the level of inhomogeneity on the reaction zone structure is presented and discussed. The new CFSB burner is able to generate a wide range of turbulent planar flames spanning the entire range from non-premixed to fully premixed flames. In addition, the high stability level of the burner allows for the study of highly turbulent flames of practical interest.

1. Introduction

The combustion process in many practical combustion systems is significantly affected by the nature and level of mixing between fuel and oxidizer. The fuel type, the level of turbulence, the burner geometry and the mixing process are key parameters that affect the combustion efficiency, stability and level of pollution. While combustion systems are nominally classified in two broad categories of premixed and non-premixed, actual combustors involve mixed-modes of burning due to compositional inhomogeneities that are introduced either by design or by the operational characteristics of the combustor. Non-premixed and premixed combustion are well-established modes in laminar and turbulent combustion. However, in many combustion systems, the mixture is inhomogeneous and the combustion process cannot be described by those modes and is usually classified as partially premixed [1–6]. This mode covers a wide range of mixtures between premixed and non-premixed combustion. Understanding this mode of combustion requires extensive studies of fundamental flames with inhomogeneous as well as homogeneous partially premixed mixtures. The wide range of applications of this mode of combustion has attracted many research studies [7–14] in order to generate quantitative sets of data in well-defined boundary conditions for better description of the combustion process. In addition, the development of combustion codes for partially premixed combustion requires quantitative sets of data in well-defined boundary conditions of flames within this mode. Studying the combustion process in inhomogeneous mixtures of air and fuel has led to experimental [7–10,13,14] and theoretical [11,12] research in order to understand the role of the mixing process on the combustion characteristics. Masri [7] recently provided a comprehensive review article covering the different modes in partially premixed flames.

* Corresponding author at: Mechanical Engineering Department, The American University in Cairo, AUC Avenue, P.O. Box 74, New Cairo 11835, Egypt.
E-mail address: mansourm@aucegypt.edu (M.S. Mansour).

http://dx.doi.org/10.1016/j.expthermflusci.2017.10.021
Received 24 August 2017; Received in revised form 20 October 2017; Accepted 21 October 2017
Available online 23 October 2017
0894-1777/

Nomenclature

A_i	area of the inner slot for air, m^2
A_o	area of the outer slots for fuel, m^2
A_s	area of the slots, m^2
a	length along the slot, m
a_s	slot length, mm
b_s	slot width, mm
b_{is}	inner slot width, mm
b_{os}	outer slot width, mm
D_H	hydraulic diameter
H	lift-off height, mm
L	mixing length, mm
$\dot{m}_a$	air flow rate, kg/s
$\dot{m}_f$	fuel flow rate, kg/s
P_s	perimeter of the slot, m
$U_{co\text{-}flow}$	co-flow velocity, m/s
Re	Reynolds number,
Re_{air}	air stream Reynolds number
Re_F	fuel stream Reynolds number
U	axial velocity, m/s
U_a	air stream velocity, m/s
U_f	fuel stream velocity, m/s
U_j	jet velocity, m/s
W	flame base spacing, mm

Greek letters

Φ_j	jet equivalence ratio
ν	kinematic viscosity, m^2/s

Production of quantitative data sets of the flame structure in partially premixed and inhomogeneous mixtures requires special burner design capable of controlling the level of mixture inhomogeneity. Few burners were developed [e.g. 8,9,13–19], to control the level of inhomogeneity of the mixture in simple design. Early partially premixed flames were developed in counterflow burners [18,19] where two opposed jets are used with different stoichiometry to generate partially premixed flames with multiple-reaction zones [18]. The flow field in these burners is simple and the gradients of the mixture fraction are well-controlled by the adjustment of the mixture fraction in each jet. This design avoids the effect of the flame curvature in normal jet flames. However, such burners cannot simulate the inhomogeneous structure in practical combustion systems. A new concentric flow burner design, where the mixing level is controlled by a simple mechanism of two concentric tubes, was developed by Mansour [15] and Lee et al. [9]. The first burner design [15] has an additional conical nozzle to stabilize the flames at high turbulence levels. A similar burner with pilot flame at the nozzle exit replacing the conical nozzle was also developed [17] to stabilize the flames at high Reynolds number. Several measurements of the flame structure were conducted in different partially premixed flames [20,21]. Recently Mansour et al. [10] presented an intensive investigation of the effect of the mixing field on the flame structure. However, those burners are not able to generate stable lean flames and the nozzle diameter should affect the flame stability [15].

Accordingly, the aim of this work is to develop a new burner for turbulent flames with either inhomogeneous or partially premixed planar jet flames for better understanding of the reaction zone structure within a wide range of mixture inhomogeneity. The generated data base can thus be used for model assessment. The burner should be relatively simple and able to generate highly stabilized turbulent flames that are lean overall yet span a wide degree of compositional inhomogeneity. In addition, the burner design should reduce the curvature effect of jet flames issuing from circular nozzles. The Wolfhard-Parker slot burner arrangement was thus selected for the current burner design which is referred to as the Concentric Flow Slot Burner (CFSB). The slots of the burner are adjusted to control the level of mixture inhomogeneity, as explained below. The slot size and area ratio between the fuel and air are adjusted to generate highly turbulent flames. In addition, higher stability is achieved by the use of an expanding nozzle. The objective of this work is to conduct stability and reaction zone measurements inside and outside the nozzle in order to discuss the flame structure at different operating conditions. The burner is thus proposed as a candidate for model assessment of mixed-mode combustion in turbulent planar flames.

2. The concentric flow slot burner (CFSB) design

Mansour [15] has developed a concentric flow conical nozzle (CFCN) burner for highly stabilized flames of partially premixed and inhomogeneous jets of gaseous fuels. The inhomogeneous flames in the CFCN burner are more stable than the fully premixed or non-premixed counterparts [23] due to the control of the level of mixture inhomogeneity at the nozzle exit [10]. The mixing level can be optimized for maximum stability at a certain level of mixture fraction [23]. The

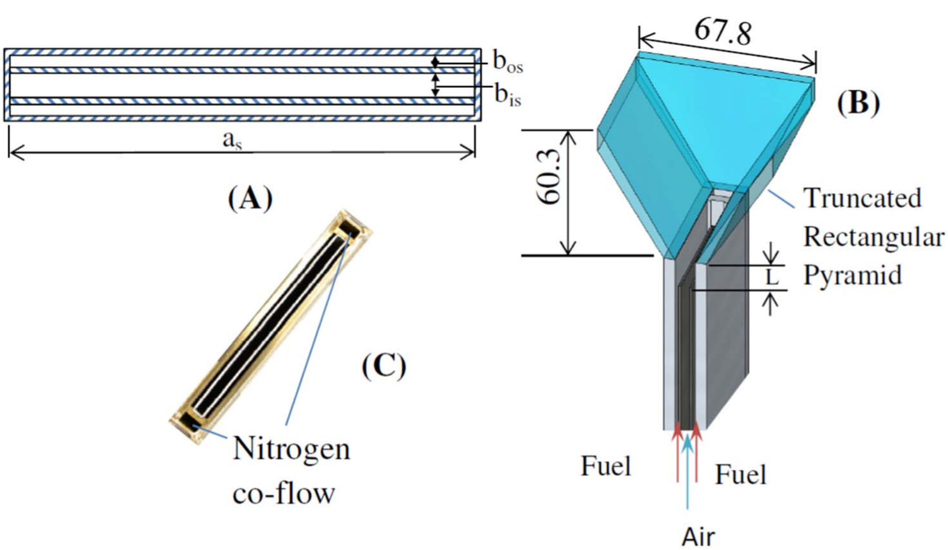

Fig. 1. A schematic diagram of the CFSB Burner. (A) Top view of the slot. (B) 3-D drawing of the burner showing the mixing length, L, and inlets of air and fuel streams with a truncated rectangular pyramid nozzle on the top of the outer duct. Dimensions are in mm. (C) Image of the slot exit showing the nitrogen co-flow ducts.