INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 13594–13603

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

Examination of thermo-acoustic instability in a low swirl burner

M. Emadi*, K. Kaufman, M.W. Burkhalter, T. Salameh, T. Gentry, A. Ratner

Department of Mechanical and Industrial Engineering, University of Iowa, 3131 Seamans Center, Iowa City, IA 52242, USA

ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form
4 August 2015
Accepted 8 August 2015
Available online 29 August 2015

Keywords:
Low-swirl burner
Hydrogen–methane mixture
Flame surface density
Acoustic coupling
Flame frequency response
Flame curvature

ABSTRACT

Low-swirl burners are of interest in industrial applications due to their low NO_x emissions. In the present work, a 3.81 cm diameter low-swirl burner is acoustically forced with different fuel mixtures. The measured results are compared to 2.54 cm diameter low-swirl burner data to infer scaling properties. The experiments and analysis show that three coupling modes were present in the 3.81 cm burner: base mode coupling, shear layer generated coupling, and transitional coupling. The 3.81 cm burner was observed to have a critical acoustic driving pressure amplitude, similar to the 2.54 cm burner; however, the 3.81 cm burner had higher frequency natural acoustic modes. This counter-intuitive result is shown to arise because the modes are tied to shear layer behavior rather than burner size. It was also observed that adding hydrogen to the fuel stream resulted in less coherence. This is likely the result of increased flame speed and decreased ignition limit, allowing the flame to interact less with both large and small vortices. Small scale interaction leads to more small scale wrinkling while strong large scale vortices produce more flame role up and displacement of heat release zones. The ability of hydrogen addition to negate these effects suggests selective hydrogen addition as a possible method of inhibiting combustion instability.

Introduction

Pollution is of great concern to the power generation and transportation industries as both are required to reduce emissions by public policy [1]. The low swirl burner (LSB) is one of many promising technologies used to reduce a prevalent pollutant, NO_x, and extensive computational and experimental work has already been performed on the LSB [2–5]. Johnson et al. [6] compared emissions and flow field of a LSB to high swirl burners. They observed that LSB flames are stable over a wider range of equivalence ratios and the resulting emissions are lower. There are two primary ways that an LSB reduces NO_x emissions. First, the LSB creates a flame with shorter chemical residence time, hence, producing lower NO_x levels in comparison to other lean, premixed burners [7–9]. Second, the LSB operates at lower equivalence ratios. The resulting flame temperature is lower, reducing NO_x emissions. However, when operating in a lean combustion mode, the burner is more susceptible to reactant flow perturbations which make combustion instability more likely [10].

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* *Corresponding author*. Tel.: +1 319 335 5939; fax: +1 319 335 5669.
E-mail address: Majid-emadi@uiowa.edu (M. Emadi).

http://dx.doi.org/10.1016/j.ijhydene.2015.08.016

Combustion instability is characterized as large amplitude acoustic fluctuations caused by the coupling of flame dynamics and combustion chamber acoustics [11]. This phenomenon can result in flame oscillation [12], flame flashback [13], flame blowout [14], and structural failure [1]. Several informative reviews and books [1,15–17] comprise a body of work on combustion instability. In an effort to decompose the many factors influencing combustion instability, specific studies have examined flow induced vortex shedding [18], geometric effects [19], operating conditions [20], flame surface interaction [21], and the effect of equivalence ratio fluctuation [22].

Measuring the flame response to acoustic forcing is the primary method used to study thermo-acoustic instability. The Flame Transfer Function (FTF) is often used to describe the change in the flame behavior due to the presence of an acoustic field. FTF is characterized by changes in flame heat release, both spatially and temporally, and these are often related to changes in the flow field (versus chemistry) which can be measured in a variety of ways. Palies et al. [23] calculated FTF by measuring acoustic velocity fluctuations in a turbulent swirl-stabilized burner with acoustic forcing. A parametric study by Kim et al. [24] has shown that the dynamics of swirl-stabilized, turbulent, premixed flames are characterized by three relevant parameters: the Strouhal number, the flame length, and the flame angle. Thumuluru et al. [25] investigated acoustically-excited swirl flames and observed a relationship between velocity fluctuation and flame surface area. Bellows et al. [26] found vortex roll-up and flame liftoff to be key mechanisms governing saturation of the FTF. Pun et al. [27] used a novel experimental technique to directly measure the response of burners to an acoustic perturbation in an optically accessible combustion system. For that study, both aerodynamically and bluff body stabilized burners were analyzed using OH-PLIF generated Rayleigh index maps to locate regions of thermo-acoustic coupling. It has also been demonstrated by other researchers that OH-PLIF is a useful method in capturing the detailed flame structure [28–30]. During the Pun et al. study, the acoustic field was forced at low frequencies ranging from 22 to 55 Hz. Building on the work of Pun and coworkers [31], the LSB was studied using OH PLIF driven at frequencies between 22 and 400 Hz. Observations indicated that toroidal structures were developing in the shear layer mixing zone, which was thought to be a result of acoustic forcing. Huang et al. [15] validated this mechanism by examining weak forcing of a LSB where it was found that acoustic perturbations couple with shear layer vortex generation. The effect of hydrogen–methane fuel mixtures on thermo-acoustic coupling of a LSB was studied by Yilmaz [32]. It was found that coupling occurred at the flame base and the flame shape was altered by hydrogen enrichment.

Previous studies have demonstrated that thermo-acoustic coupling exists in a 2.54 cm diameter LSB through a shear layer triggered mechanism [15,32]. The goal of this study is to observe the flame topology and thermo-acoustic coupling of a 3.81 cm LSB. Furthermore, examining the change in acoustic coupling between the two burner diameters allows the construction of basic geometric scaling for this instability. Geometric scaling is critically important as full-scale burners run from approximately 6.35 cm for a pilot to 8.9 cm for a primary burner. The 50% increase in size assessed here can directly inform the 100% size change to the pilot and approximately 200% change to a primary.

Another interesting aspect is the forcing amplitude. Bellows [26] is typical of many previous experimental studies investigating swirl-stabilized, premixed, turbulent flames which have examined the effects of forcing with large amplitudes (5% of the mean pressure). The larger amplitude forcing is typical for limit cycles; however, for this work, the focus is on the initial growth of instabilities from small perturbations, similar to that of ambient engine conditions. Therefore, the present work examines thermo-acoustic coupling in a lean, premixed LSB with weak forcing of 0.03%–0.3% of the mean pressure, driven at frequencies between 45 and 195 Hz for both pure methane fuel and a hydrogen–methane fuel mixture.

Material and methods

A schematic of the experimental apparatus is shown in Fig. 1. The T-shaped combustion chamber has an internal diameter of 30 cm and a height of 185 cm. To provide the acoustic forcing, four speakers are installed downstream of the flame. The pressure response to acoustic forcing is detected by a model PCB 106b high-resolution piezoelectric pressure transducer at a rate of 20 kHz. Quartz windows, located in the lower section of the combustion chamber, provide full optical access to the flame. Unlike other experimental systems previously used to study combustion instabilities, the current apparatus eliminates interactions between the flame and chamber walls by using air co-flow. The air co-flow isolates the flame, keeping the chamber walls within reasonable operating temperatures. The flow rate of the oxidant (air) is recorded and controlled using a Hastings HFC-D-307 flow meter. Similarly, a Hastings HFC-D-303 flow meter and an Omega FMA5500 flow meter is used to measure and control methane and hydrogen flow rates. Flow rate consistency is maintained throughout

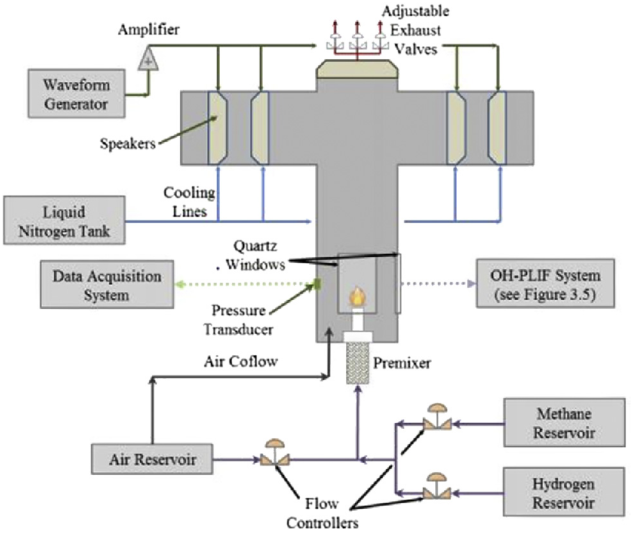

Fig. 1 – Schematic and photo of the combustion acoustics chamber and associated systems [33].