Combustion and Flame 157 (2010) 686–700

Contents lists available at ScienceDirect

Combustion and Flame

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

Mitigation of thermoacoustic instability utilizing steady air injection near the flame anchoring zone

H. Murat Altay, Duane E. Hudgins, Raymond L. Speth, Anuradha M. Annaswamy, Ahmed F. Ghoniem *

Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA 02139, United States

ARTICLE INFO

Article history:
Received 20 April 2009
Received in revised form 19 July 2009
Accepted 18 January 2010

Keywords:
Control of thermoacoustic instability
Instability suppression
Flame anchoring
Air injection
Passive control

ABSTRACT

The objective of this work is to investigate the effectiveness of steady air injection near the flame anchoring zone in suppressing thermoacoustic instabilities driven by flame–vortex interaction mechanism. We perform a systematic experimental study which involves using two different configurations of air injection in an atmospheric pressure backward-facing step combustor. The first configuration utilizes a row of micro-diameter holes allowing for air injection in the cross-stream direction just upstream of the step. The second configuration utilizes an array of micro-diameter holes located on the face of the step, allowing for air injection in the streamwise direction. The effects of each of these configurations are analyzed to determine which one is more effective in suppressing thermoacoustic instabilities at different operating conditions. The tests are conducted while varying the equivalence ratio and the inlet temperature. The secondary air temperature is always the same as the inlet temperature. We used pure propane or propane/hydrogen mixtures as fuels. Combustion dynamics are explored through simultaneous pressure and heat release-rate measurements, and high-speed video images. When the equivalence ratio of the reactant mixture is high, it causes the flame to flashback towards the inlet channel. When air is injected in the cross-stream direction, the flame anchors slightly upstream of the step, which suppresses the instability. When air is injected in the streamwise direction near the edge of step, thermoacoustic instability could be eliminated at an optimum secondary air flow rate, which depends on the operating conditions. When effective, the streamwise air injection prevents the shedding of an unsteady vortex, thus eliminating the flame–vortex interaction mechanism and resulting in a compact, stable flame to form near the step.

1. Introduction

A phenomenon often observed in continuous combustion systems is self- sustained pressure and flow oscillations forming as a result of the resonant interactions between unsteady heat release mechanisms and the acoustic modes of the system, referred to as the thermoacoustic instability [1,2]. Thermoacoustic instability occurs under lean burn conditions, where most emissions and efficiency benefits are achieved, or near stoichiometry, where high power density is the objective. Thermoacoustic instability is undesirable since it may cause flame extinction, structural vibration, flame flashback and even structural damage. Several mechanisms appear to be present in a combustor that instigate the unsteady heat release, including: flame–acoustic wave interactions, flame–vortex interactions, equivalence ratio oscillations, flame wall interactions and unsteady stretch rate, all of which may be present individually or simultaneously [3–5], and hence promoting thermoacoustic instability.

Active combustion control strategies that modulates the fuel flow rate [6–13], or air flow rate [14] can be applied to suppress thermoacoustic instabilities in premixed combustors by disrupting the coupling mechanisms that support these instabilities. While effective in suppressing the instabilities, these approaches require high speed actuators and add significant complexity to the design of the combustors. For this reason, developing simple, passive control strategies that directly impact the flame anchoring zone with minimal complexity are desirable.

The potential for suppressing thermoacoustic instability by injecting steady air [11,15,16], or by injecting open-loop, low-frequency modulated air [17] near the flame anchoring zone has been shown in the past. In these approaches, the secondary air flow is thought to change the velocity field and disrupt the flame–vortex interaction, which has been shown to be the primary instability mechanism in dump combustors [18]. In this paper, we inject steady air flow near the flame anchoring zone through choked micro-diameter holes. The small hole diameter allows for large velocities with low air flow rates. We perform a systematic experimental study with extensive range of operating conditions, which involves using two different configurations of secondary air injection in an

* Corresponding author.
E-mail address: ghoniem@mit.edu (A.F. Ghoniem).

0010-2180/$ - see front matter © 2010 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.combustflame.2010.01.012

atmospheric pressure backward-facing step combustor. The first configuration is a row of microjets allowing for air injection in the cross-stream direction just upstream of the step. The second configuration is an array of microjets located on the face of the step, allowing for air injection in the streamwise direction. The effects of each of these configurations are analyzed to determine which one is more effective in suppressing thermoacoustic instabilities at different operating conditions. The tests are conducted while varying the equivalence ratio and the inlet temperature. The secondary air temperature is always the same as the inlet temperature. Previous studies have shown that enriching hydrocarbon fuels with small amounts of hydrogen significantly reduces the equivalence ratio at the lean blowout limit of the combustor [19–22]. For this reason, we add small amounts of hydrogen to the primary fuel, in this case propane. In order to understand the role of air injection in suppressing the instabilities, we record the flame images using a high speed video camera and investigate the effect of secondary air injection on combustion dynamics.

2. Combustor description

Fig. 1 shows a schematic diagram of the backward-facing step combustor. The combustor consists of a rectangular stainless steel duct with a cross section 40 mm high and 160 mm wide. The air inlet to the combustor is choked. 0.45 m downstream from the choke plate, a 0.15 m long ramp contracts the channel height from 40 mm to 20 mm followed by a 0.4 m long constant-area section that ends with a sudden expansion back to 40 mm. The step height is 20 mm. The overall length of the combustor is 5.0 m. A circular exhaust pipe comprises the last 3.0 m of the combustor. The combustor is equipped with quartz viewing windows. An air compressor supplies air up to 110 g/s at 883 kPa. A pair of Sierra C100M mass flow controllers allow arbitrary propane/H_2 mixtures at maximum flow rates of 2.36 g/s for propane and 0.30 g/s for hydrogen. Fuel is injected through several spanwise holes in a manifold located 93 cm upstream of the step. At this fuel injection location, equivalence ratio oscillations are not present and the instability is solely driven by the flame–vortex interaction mechanism [18]. Images of the flame are captured using an image-intensified Phantom v7.1 high-speed camera and used to examine the combustion dynamics. An optical bandpass filter centered at 430 nm is placed in front of a Hamamatsu H9306-02 photosensor module to measure the integrated CH^* chemiluminescence emitted by the flame, which is proportional to the instantaneous heat-release rate [23,24]. Pressure measurements are obtained using Kulite high intensity microphones designed for laboratory investigations. The inlet and secondary air temperatures are adjusted using Osram Sylvania 18 kW and 4 kW in-line electric heaters, respectively, with on/off temperature controller. All data are acquired using a National Instruments PCIe-6259 data acquisition board and the Matlab Data Acquisition Toolbox. A custom Matlab code is used to store the data and control the experiment.

Secondary air can be injected from 12 and 0.5 mm diameter choked holes drilled along the combustor width in the cross-stream direction 5 mm upstream of the step, or in the streamwise direction near the corner of the step. These two air injection configurations are termed respectively the *normal* microjets and the *axial* microjets. Their positions are shown schematically in Fig. 2. Since the flow from the microjets is choked, it does not couple with the acoustics of the combustor allowing for steady flow rates.

3. Results

By performing a parametric study we determined the optimum secondary air flow rate required to suppress the instabilities using both normal and axial microjets. By changing the equivalence ratio, inlet temperature, secondary air temperature and fuel composition we compare the effectiveness of microjet air injection using each injection configuration at different operating conditions. Using high-speed video images, we captured the combustion dynamics at each microjet configuration at distinct operating modes. We compare the pressure amplitudes under different operating conditions and microjet flow rates. We report the pressure amplitude in terms of the overall sound pressure level (OASPL) using the pressure sensor located 1.28 m downstream of the choke plate, which is near the location of the flame, unless otherwise is mentioned. The OASPL in dB is defined as:

$$\mathrm{OASPL} = 10\,\log_{10}\overline{\left[\frac{p(t)-\overline{p(t)}}{p_o}\right]^2} \quad (1)$$

where overbars indicate average values, $p(t)$ is the pressure measured in an interval $t_1 < t < t_2$ and $p_o = 2\times10^{-5}$ Pa. The Reynolds number is fixed at 6500, which is based on the step height, and the primary air flow rate.

3.1. Combustion dynamics without passive control (baseline)

We investigated the stability map and combustion dynamics by systematically varying the operating conditions without passive control. Fig. 3 shows the OASPL as a function of the equivalence ratio at inlet temperatures of $T_{in} = 300$ K and 600 K, using pure propane or propane enriched with 50% by volume hydrogen (4.4% by mass; 10.6% by LHV) as the fuel.

Examining Fig. 3 in detail, for $T_{in} = 300$ K, we observe three distinct operating bands independent of the fuel composition. The band near the lean blowout limit, with an OASPL of around 130 dB, is the stable band, where small vortices are shed from

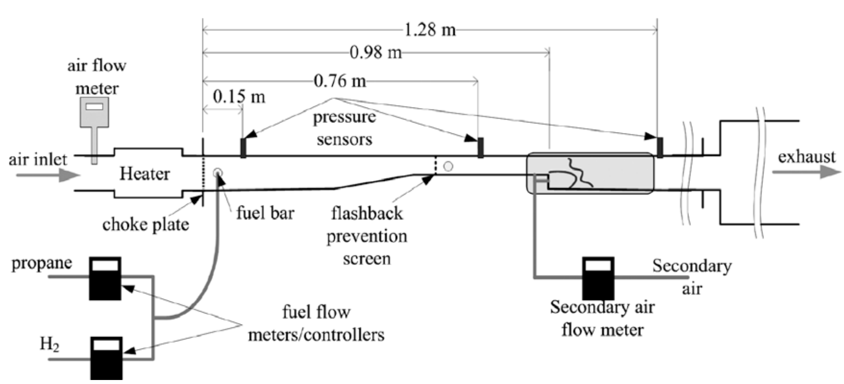

Fig. 1. The schematic diagram of the experimental combustor setup.