Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Proceedings of the Combustion Institute 30 (2005) 1783–1790

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Mechanism of combustion dynamics in a backward-facing step stabilized premixed flame

Ahmed F. Ghoniem*, Sungbae Park, Adam Wachsman, Anuradha Annaswamy, Daehyun Wee, H. Murat Altay

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract

Combustion dynamics leading to thermoacoustic instability in a rearward-facing step stabilized premixed flame is experimentally examined with the objective of investigating the fluid dynamic mechanism that drives heat release rate fluctuations, and how it couples with the acoustic field. The field is probed visually, using linear photodiode arrays that capture the spatiotemporal distribution of CH* and OH*; an equivalence ratio monitor; and a number of pressure sensors. Results show resonance between the acoustic quarter wave mode of the combustion tunnel and a fluid dynamic mode of the wake. Under unstable conditions, the flame is convoluted around a large vortex that extends several step heights downstream. During a typical cycle, while the velocity is decreasing, the vortex grows, and the flame extends downstream around its outer edge. As the velocity reaches its minimum, becoming mostly negative, the vortex reaches its maximum size, and the flame collides with the upper wall; its leading edge folds, trapping reactants pockets, and its trailing edge propagates far upstream of the step. In the next phase, while the velocity is increasing, the heat release grows rapidly as trapped reactant' pockets are consumed by flames converging towards their centers, and the upstream flame is dislodged back downstream. The heat release rate reaches its maximum halfway into the velocity rise period, leading the maximum velocity by about 90°. In this quarter-wave mode, the pressure leads the velocity by 90° as well, that is, it is in phase with the heat release rate. Numerical modeling results support this mechanism. Equivalence ratio contribution to the instability mechanism is shown to be minor, i.e., heat release dynamics are governed by the cyclical formation of the wake vortex and its interaction with the flame.

Keywords: Combustion dynamics; Premixed combustion; Flame–vortex interactions; Instability; Numerical modeling

1. Introduction

Combustion dynamics in a rearward-facing step stabilized premixed flame has been examined experimentally and numerically. Despite the careful and valuable results obtained so far, definitive conclusions regarding its essential mechanisms or conditions under which it may be expected to arise have not been reached yet [1–6]. In most cases, it has been observed that under unstable operating conditions, as determined by the mixture equivalence ratio and Reynolds number, one or more large vortices periodically convolute the flame front during part of the instability cycle. It has been suggested that the periodic convolution of the flame leads to oscillations in the heat release

* Corresponding author. Fax: +1 617 253 5981.
E-mail address: ghoniem@mit.edu (A.F. Ghoniem).

1540-7489/$ - see front matter © 2004 Published by Elsevier Inc. on behalf of The Combustion Institute.
doi:10.1016/j.proci.2004.08.201

rate that may couple with the pressure field. To close the loop, pressure must also drive the vortex formation and flame convolution in a way that ensure a positive feedback. This driving mechanism has not been fully explored, although suggestions have been made. Other feedback mechanisms, such as equivalence ratio oscillations, may also be present under these circumstances, and have been suggested for closing the loop. The objective of this paper was to supply more concrete evidence supporting the role of unsteady vortex shedding and flame–vortex interactions in sustaining the combustion instability.

We report experimental results in which unstable conditions in a rearward-facing step stabilized premixed combustion are indeed associated with vortex formation. The combustor is equipped with a high-speed video camera, a Schlieren system, pressure sensors, equivalence ratio monitor, and a linear array consisting of 128 photodiodes to detect CH* chemiluminescence at high spatio-temporal resolution, which is used as a surrogate for heat release rate. The data are processed to determine the velocity field at the step, and the total heat release at different moments with the cycle of flame–vortex interactions. We show that flame–vortex interactions are responsible for heat release oscillations, which drive the pressure field, and the associated velocity oscillations at the step resonate with the wake instability leading to the closing of the feedback loop. The conclusions are confirmed using numerical modeling results.

2. Experiment

2.1. The facility

The combustor shown in Fig. 1 consists of a rectangular stainless steel duct with a cross section 40 mm high and 160 mm wide. Halfway along the length of the combustor, a ramp contracts the channel height from 40 to 20 mm, followed by a constant-area section and a sudden expansion back to 40 mm. The step height is 20 mm. The overall length of the combustor is 1.9 m, with the step located in the middle. The air inlet to the combustor is choked. The exhaust gases are expanded at the end of the channel. The combustor is equipped with quartz viewing windows. An air compressor supplies air up to 110 g/s at 883 kPa. Propane is used as the primary fuel. Fuel is injected at several spanwise holes, from a fuel manifold located upstream of the step, at 175 or 350 mm, in the direction opposite to the flow to improve mixing. High-speed video- and Schlieren images were used to examine the flame dynamics, and pressure gauges are used along the combustion tunnel to determine the acoustic mode shape and frequency.

2.2. The measurements

A linear photodiode array is used to measure CH* chemiluminescence, which has been correlated with the heat release rate, the equivalence ratio, and pressure. Higgins et al. [7] showed that CH* chemiluminescence in methane-air mixtures is proportional to the mass flow rate times the equivalence ratio raised to 2.72. In our experiment, only scaled, qualitative data for the heat release rate are necessary, and for that purpose, we use the CH* measurement as a qualitative indicator. An NMOS linear image sensor (S3901–128Q) from Hamamatsu Photonics, which consists of 128 individual photodiodes organized in a linear array, is used in our experiment. Each photodiode is 45 μm wide by 2.5 mm high. Flame images pass through an optical bandpass filter centered at 430 nm, the wavelength of CH* chemiluminescence. The photodiode array has high UV sensitivity, making it suitable for this application. A bi-convex UV fused silica lens is used to focus the flame image onto the chip. The aspect ratio

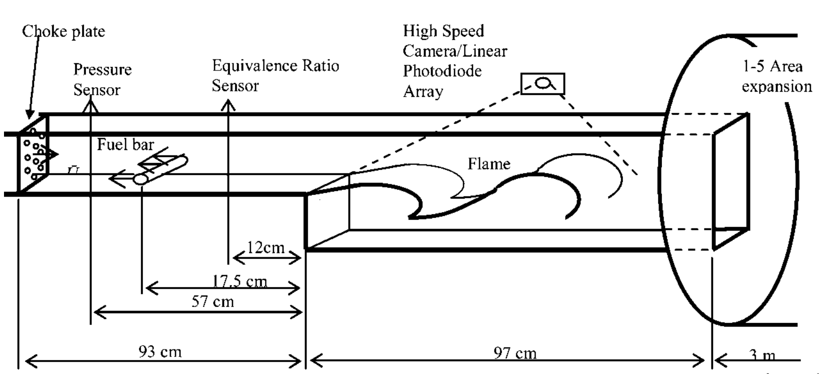

Fig. 1. A schematic diagram of the backward-facing step combustor and the different sensors used to interrogate the flow.