Fuel 222 (2018) 627–637

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Stabilization and blowout characteristics of lean premixed turbulent flames behind a backward-facing step in a rectangular combustor with heated propane-air mixtures

Byung Chul Choi[a,*], Ahmed F. Ghoniem[b]

[a] R&D Center, Korean Register of Shipping, Busan 618-814, Republic of Korea
[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, MA 02139, USA

ARTICLE INFO

Keywords:
Lean premixed turbulent flame
Backward-facing step
Blowout velocity
Flame distance
Propane-air
Initial temperature

ABSTRACT

The flame stabilization and blowout velocity of lean premixed turbulent flames in a backward-facing step combustor were investigated experimentally with well-defined stable flames. The dynamic pressure in the combustor was monitored to select a stable regime among overall flame behaviors. The responses in the flame behaviors to changes in the initial conditions of equivalence ratio, inlet temperature, and Reynolds number were simultaneously captured using high-speed CH* chemiluminescence. The results showed that the flame modes were categorized into four representative regimes according to their dynamic behavior, overall sound pressure level, and frequency spectrum: (1) stable regime, (2) unstable regime, (3) quasi-unstable regime, and (4) transition regime. For lean premixed turbulent flames in the stable regime, the flame distance, defined as distance x from the step to flame appearance, increased with the decrease in the initial equivalence ratio, and blowout occurred near the lower flammability limits. The blowout velocities linearly correlated with both the inverse of chemical reaction time $(\alpha_0/S_{L,0}{}^2)^{-1}$ and extinction strain rate $\varepsilon_{ext,0}$ under different initial conditions. The two chemical time scales were obtained using different flame models based on either the premixed laminar flame-speed or premixed opposed-flow flame model. In addition, the flame distances showed a linear correlation of $d_f \propto U_0/S_{L,0}{}^2$ for all the data in the stable regime. This result implies that the lean premixed turbulent flames could be stabilized at flame distances where the local mean flow velocity is balanced with the turbulent flame speed, which is proportional to the square of laminar burning velocity.

1. Introduction

Flame stabilization is the key issue in the designing of a combustor for a gas turbine engine and several industrial power systems [1]. Various flow configurations of fuel and air in the combustor have been developed in response to many technical requirements in terms of high efficiency, low emissions, and wide stability limits. Nonpremixed turbulent flames, in which the air is separated prior to combustion and combines with the fuel through diffusion, are frequently employed in combustors of conventional gas turbines. Although the nonpremixed flames deliver stable flame under wide stability limits, the application technology of lean premixed turbulent flames has been attracting considerable attention of researchers and engineers because of the increasing interest in reducing environmental pollution. However, while the combustor operates under ultra-lean conditions to maintain a low flame temperature to reduce NO$_x$ emissions, flame stabilization methods to prevent combustion instability and flame blowout can be a major influence on operational performance.

Various experimental studies on flame stabilization have been conducted on the turbulent flames stabilized behind a backward-facing step. Kawamura [2] conducted an experimental study on the ignition front of a nonpremixed jet flame at standard temperature and pressure conditions. Propane was ejected parallel to the air stream from the fuel nozzle placed at the top of the step. The ignition front was defined as the distance from the nozzle to the flame. The result showed that the square of the ignition front distance was mainly proportional to the ratio between the fuel and air velocities, fuel nozzle width, and displacement thickness of the laminar boundary layer of the air stream; however, the effects of the step height and floor plate length were minimal up to the step. Furthermore, Takahashi et al. [3] studied the flame suppression effect of a fire-extinguishing agent supplied through the inlet air stream on the stabilization of a nonpremixed methane flame. The methane was ejected upward from a porous plate on the bottom surface behind the step. Two distinct flame regimes were observed: a rim-attached flame at a lower inlet velocity and wake-

---

[*] Corresponding author.
E-mail address: byungchul.choi@hotmail.com (B.C. Choi).

https://doi.org/10.1016/j.fuel.2018.02.160
Received 29 October 2017; Received in revised form 31 January 2018; Accepted 24 February 2018

stabilized flame at a higher inlet velocity. In addition, Ganji and Sawyer [4] experimentally measured the mean distance of the eddy formation position with respect to the step edge in a shear flow both with and without turbulent combustion. Propane–air mixtures were examined for various inlet velocities, temperatures, and equivalence ratios. Although they assumed that the flame propagation depended on the growth of the eddy in the downstream, their study did not identify a correlation between the flame distance and eddy formation position. Recently, Hong et al. [5] conducted an experimental investigation on the recirculation zone for the various fuel compositions of propane and hydrogen at room temperature and at a Reynolds number $\mathrm{Re} = 6500$ in the step combustor identical to the present setup. The previous work intensively analyzed the size and structure of the recirculation zone. As a result, the criteria of stability boundaries for the blowoff and flashback limits were proposed according to the strained flame model in a counterflow burner. This survey of relevant literature shows the mechanism of stabilizing the premixed turbulent flame remains ambiguous and requires further research.

In a practical combustor applied with the premixed flames, a flameholder could generate a vortex, turbulence, and recirculation zone; these are formed as a result of the dependence of the flow separation on various bluff-body shapes, sudden expansion of the flow area, and other things to anchor the premixed flame at the desired location. Despite the complexity of the flow configuration, various prediction models have been developed for the premixed turbulent flames [6]. The theories were evaluated based on different assumptions; however, the results could conclude that the theories might commonly follow the concept of the Damköhler number. However, the experimental validation of the prediction models was limited to the characteristics of the blowoff phenomenon, according to which the attached flame is directly blown and disappears downstream without experiencing stable lifted flames. This is because most of the premixed turbulent flames stabilized in the wake vicinity of a flame-holder typically exhibit attached flames on the flame-holder. Thus, a systematic study on the flame distances for premixed turbulent flames is still comparatively lacking in terms of the stabilization mechanism of flames clearly lifted from the flame-holder.

With this motivation, the objective of the current study is to examine the flame distances from the step to the flame appearance for various equivalence ratios, according to variations of initial temperature and velocity at the inlet of the step combustor. Propane was selected as a single-component fuel to characterize flame stabilization and blowout for a general hydrocarbon fuel and remove the dramatic changes in chemical kinetics.

2. Experimental setup

Fig. 1a shows the schematic of the test section in the backward-facing step combustor. The details of the experimental setup have been reported previously [5,7]. The combustion duct made of stainless steel had a rectangular cross-section with a height and width of 0.04 and 0.16 m, respectively. Its overall length was 1.9 m, with the step located in its middle. The inlet air supplied from a compressor (Atlas Copco, GA30FF) was controlled using a valve actuator (Badger Meter, 807) equipped with an electro-pneumatic converter (Omega, EP510) and was measured using a mass flow meter (Sierra, 780S). The initial temperature of air was elevated using an inline electric heater of 18 kW (Osram Sylvania, F063007) with a PID control unit.

The heated air-inlet was choked. At 0.02 m downstream of the choke plate, the gaseous propane fuel controlled using a mass flow controller (Sierra, C100M) was injected into the duct inlet through several spanwise holes from a cylindrical manifold, in an opposite direction of the flow of inlet air to improve mixing. To minimize the turbulent intensity of the inlet mixture flow, a honeycomb-shaped flow straightener was inserted at 0.3 m downstream from the choke plate. At a location 0.45 m downstream from the choke plate, a long ramp of 0.15 m contracted the channel height from 40 to 20 mm followed by the contraction of a constant area section of 0.4 m that suddenly expanded back to 40 mm at the final stage. Step height H was 20 mm and the step was located 0.98 m downstream of the choke plate. The step combustor was operated at atmospheric pressure. To exclude significant thermoacoustic instability [8,9], the outlet was open to an exhaust hood connected to a ventilation system.

Pressure in the combustor was measured at 0.20 m upstream of the step by using a dynamic pressure sensor (Kistler, 7061B), through an amplifier (Kistler, 5010). The initial temperature was measured at 0.20 m upstream of the step by using a K-type thermocouple. The test section was equipped with quartz windows for optical access. Images of the flame were captured at 80 frames per second and an exposure time of 10 ms by using a high-speed CMOS camera (NAC, GX-1) with an F-mount lens (Nikon, f/2.8). The image had a dimension of 589 pixels (width) × 256 pixels (height), with a spatial resolution of 0.2857 mm/pixel in the direction of the width. A narrow bandpass filter of 433 nm central wavelength with an FWHM of 10 nm (La Vision, 1108566) was attached in front of the camera lens to visualize the CH^* chemiluminescence emitted from the flame. All data was managed using a data acquisition board (National Instruments, PCIe-6259) and a custom code (Matlab, Data Acquisition Toolbox). A real-time control was used in the mass flow rate of fuel and air to be operated at the target inlet condition, based on an open-loop method.

The schematic in Fig. 1b shows a representative configuration of the mean flow field behind the backward-facing step. The streamlines of the mean flow were presented as gray dashed lines, superimposed on a stabilized flame represented by red solid lines. The zero-velocity contours represented by blue solid lines were overlaid on the streamlines of the mean flow. The streamlines together with the zero-velocity contours displayed the recirculation zone structure consisting of a primary and secondary eddy. The outer blue line indicates the zero-velocity contour of the primary recirculation zone and the inner blue line indicates the zero-velocity contour of the secondary recirculation zone. It has been reported that the general structure of the recirculation zone near the backward-facing step is comprised of the primary and secondary eddies [5]. The microscopic investigation of flame and flow interactions will be studied in the future.

3. Results and discussion

3.1. Overall flame responses

Both the initial temperature T_0 and Reynolds number Re were systematically varied at the inlet of the step combustor. The Reynolds number is defined as $\mathrm{Re} = U_0 h/\nu_0$, where U_0 is the initial inlet velocity, $h = 20$ mm is the inlet duct height, and ν_0 is the initial kinematic viscosity of inlet mixtures at the initial temperature. The value of U_0 varied by less than $\sim 2\%$ across all the tested equivalence ratios at a given (T_0, Re). The pressure responses of the combustor and CH^* chemiluminescence images of the flame were concurrently measured while varying the initial equivalence ratio Φ_0 of propane–air mixtures. In this study, we report on the global behaviors of the flame response under the variations of initial conditions, in which the operational modes of the step combustor were classified into four distinct regimes: (1) stable regime, (2) unstable regime, (3) quasi-unstable regime, and (4) transition regime, based on the results of experimental observation. Furthermore, the primary analytical focus will be on the blowout velocity and flame distance in the stable regime with well-stabilized flames.

To illustrate the representative flame modes, the CH^* chemiluminescence images captured by the high-speed camera were represented with time intervals in Fig. 2. For (T_0, Re) = (300 K, 5000), Fig. 2a indicates stable flames. These flame tips were located at $x/H \approx 2$ when the Φ_0 was fixed to 0.73. When Φ_0 was fixed to 0.83, as shown in Fig. 2b; however, unstable flames appeared from $x/H < 1$ near the step, and the CH^* chemiluminescence intensities were remarkably