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Combustion and Flame 136 (2004) 383–389
Combustion and Flame
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Brief Communication

Bifurcation of flame structure in a lean-premixed swirl-stabilized combustor: transition from stable to unstable flame

Ying Huang and Vigor Yang *

Department of Mechanical Engineering, Pennsylvania State University, University Park, PA 16802, USA

Received 25 April 2003; received in revised form 20 October 2003; accepted 5 November 2003

Abstract

The present work addresses unsteady flame dynamics in a lean-premixed swirl-stabilized combustor, with attention focused on the transition of flame structure from a stable to an unstable state. It was found that the inlet temperature and equivalence ratio are the two most important variables determining the stability characteristics of the combustor. A slight increase in the inlet mixture temperature across the stability boundary leads to a sudden increase in acoustic flow oscillation. One major factor contributing to this phenomenon is that as the inlet mixture temperature increases, the flame, which is originally anchored in the center recirculation zone, penetrates into the corner recirculation zone and flashes back, due to the increased flame speed. As a consequence, the flame is stabilized by both the corner- and the center-recirculating flows and exhibits a compact enveloped configuration. The flame flaps dynamically and drives flow oscillations through its influence on unsteady heat release. This problem has not previously been studied mechanistically. The results improve our understanding of the mechanisms of initiation and sustenance of combustion instabilities in gas-turbine engines with lean-premixed combustion.

1. Introduction

It is well established that the flow and flame dynamics in a combustion chamber can change dramatically as the governing parameters pass through their critical values at which bifurcation points are located. Combustion processes alone may or may not exhibit bifurcation phenomena, but when they take place in the presence of the nonlinear behavior of the chamber dynamics, this sort of characteristic is indeed observed in many combustion devices [1–3]. Sometimes, when bifurcation takes place, which may arise from disturbances of the governing parameters, transition from a stable operation (characterized by a limit cycle with small oscillation or no oscillation) to an unstable operation (characterized by a limit cycle with large oscillation) is observed. The self-excited large unsteady flow oscillations in combustors, which are usually referred to as combustion instability, have hindered the development of gas-turbine engines with lean-premixed (LPM) combustion for many years. Understanding of the mechanisms responsible for inducing bifurcation is important for passive and active control of combustion instability [3,4].

Several experimental studies [1–8] have been conducted to investigate combustion dynamics with bifurcation phenomena. Culick and colleagues [1,4] investigated the hysteresis behavior of combustion instability in a dump combustor as a function of the mixture equivalence ratio, in which several attractors coexist for a given parameter value and the transition from a stable to an unstable state and its reverse occur at different critical parameter values. Lieuwen [3] studied the limit-cycle oscillations in a gas-turbine

* Corresponding author.
E-mail address: vigor@psu.edu (V. Yang).

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doi:10.1016/j.combustflame.2003.10.006

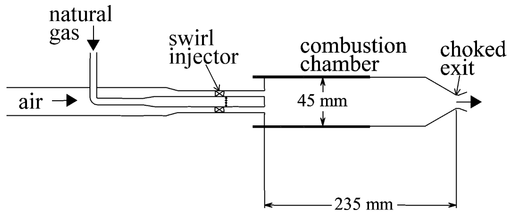

Fig. 1. Schematic of a model swirl-stabilized gas-turbine combustor (after Broda et al. [2]; used by permission of the publisher).

combustor. It was suggested that cyclic variability is caused by background noise. The inlet velocity not only plays an important role in determining the stability characteristics of the combustor, but also affects the amplitudes of the oscillations. Broda et al. [2] performed an experimental study of combustion dynamics in a swirl-stabilized gas-turbine combustor. The system consists of a single-swirl injector, an axisymmetric chamber, and a choked nozzle, as shown schematically in Fig. 1. The estimated swirl number is 0.76 for a 45° swirler with a constant chord (c) and angle (ϕ). Natural gas is injected radially from the center body through 10 holes immediately downstream of the swirler vanes. The fuel/air mixture is assumed to be well mixed before entering the combustor. A broad range of equivalence ratio and inlet air temperature was considered systematically. Figure 2 shows stability maps as a function of inlet air temperature and equivalence ratio. Instabilities occur only when the inlet air temperature is greater than a threshold value T_{in}^* around 660 K and the equivalence ratio falls into the range between 0.5 and 0.7. Figure 3 shows typical photographic images of a stable and an unstable flame with an equivalence ratio 0.6. As the inlet temperature increases and exceeds the threshold value T_{in}^*, the flame structure transforms from a stable to an unstable state, and the amplitude of pressure oscillation increases and reaches another limit cycle. This kind of bifurcation in flame structure, as the inlet temperature varies, will be investigated numerically in the present study.

Since the flowfield of concern is highly unsteady and dominated by turbulent motions that need to be adequately resolved computationally, a large eddy simulation (LES) technique is adopted. Several attempts have been made to study combustion dynamics using LES. Thibaut and Candel [9] studied the flashback phenomenon in a backward-facing step configuration using two-dimensional LES. The mechanism of flashback associated with combustion dynamics was investigated. Kim et al. [10] investigated a swirl-stabilized gas-turbine combustor flow. Their work suggests that high swirl results in a very complex vortex-shedding pattern with significant azimuthal structures. Angelberger et al. [11] conducted a two-dimensional simulation of a premixed dump combustor with acoustic forcing. Fureby [12] investigated the combustion instabilities of a dump combustor and a model afterburner. Vortex shedding was found to be a main attribute of the combustion instabilities observed. For LPM combustion with swirling flows, a comprehensive numerical study was recently performed by the authors [13], demonstrating the capability of LES in treating detailed combustion dynamics.

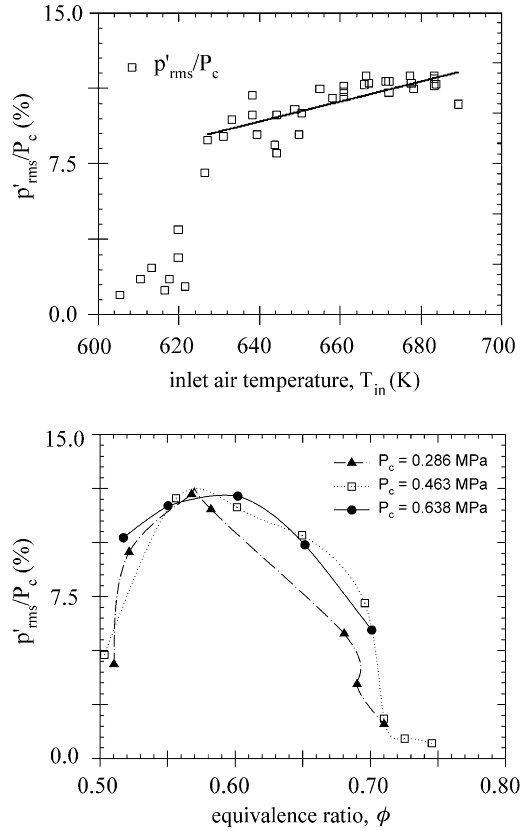

Fig. 2. Stability maps as a function of inlet air temperature and equivalence ratio (after Seo [8]; used by permission of the publisher).

The purpose of this work is to study the effects of inlet flow temperature on the flame bifurcation phenomenon, simulating the experimental conditions reported in Refs. [2] and [8]. In an earlier paper [13], the flame dynamics under an unstable condition was studied. The present analysis will focus on the transition from a stable to an unstable flame when the inlet temperature exceeds a threshold value. The situation with a stable flame will also be addressed to serve as a reference. The basis of the analysis is the LES code previously developed for investigating LPM combustion instability [13]. Various fundamental processes

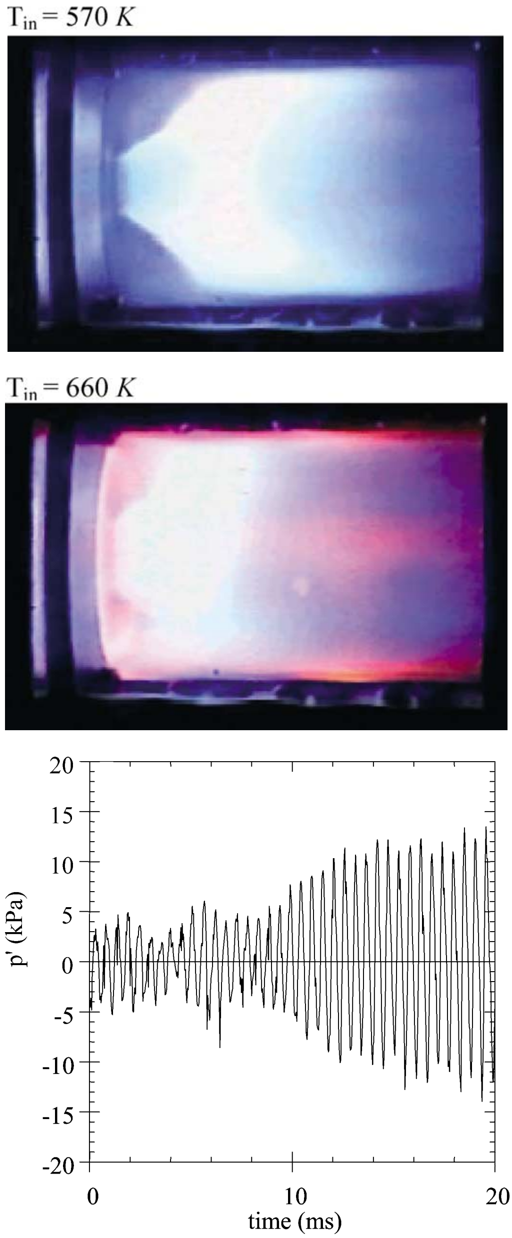

Fig. 3. Top: Photographic images of stable and unstable flames. Bottom: Pressure–time trace (after Seo [8]; used by permission of the publisher).

responsible for the flame transition from a stable to an unstable state, such as high-temperature mixture filling, flame trapping, and the vortex flashback process, are carefully identified and quantified.

2. Theoretical formulation and numerical method

The formulation is based on the Favre-filtered conservation equations of mass, momentum, and energy. The subgrid-scale terms are modeled using a compressible-flow version of the Smagorinsky model suggested by Erlebacher et al. [14]. The damping function of Van-Driest is used to take into account the inhomogeneities near the wall. For treating turbulent combustion within the context of LES, combustion models are often needed on the subgrid scales. A level-set flamelet library approach, which has been successfully applied to study premixed turbulent combustion [13,15], is used here.

Boundary conditions must be specified to complete the formulation. The no-slip and adiabatic conditions are enforced along all of the solid walls. At the inlet boundary, the mass flow rate and temperature are specified. The pressure is obtained from a one-dimensional approximation to the axial momentum equation, i.e., $\partial p/\partial x = -\rho\partial u/\partial t - \rho u\partial u/\partial x$. The mean axial-velocity distribution follows the one-seventh power law by assuming a fully developed turbulent pipe flow. The radial and azimuthal velocities are determined from the swirler vane angle. Turbulence properties at the inlet are specified by superimposing broadband disturbances with an intensity of 15% of the mean quantity onto the mean velocity profiles. The nonreflecting boundary conditions proposed by Poinsot and Lele [16] are applied at the exit boundary.

The resultant governing equations and boundary conditions are solved numerically by means of a density-based, finite-volume methodology. The spatial discretization employs a second-order, central-differencing method in generalized coordinates. A fourth-order matrix dissipation with a total-variation-diminishing switch developed by Swanson and Turkel [17] and tested by Oefelein and Yang [18] is included to ensure computational stability and to prevent numerical oscillations in regions with steep gradients. Temporal discretization is obtained using a four-step Runge–Kutta integration scheme. A multiblock domain decomposition technique along with static load balance is used to facilitate the implementation of parallel computation with message passing interface at the domain boundaries. The theoretical and numerical framework described above has been validated by Huang et al. [13] and Apte and Yang [19] against a wide variety of flow problems in order to establish its creditability and accuracy.

3. Results and discussion

The model combustor shown in Fig. 1 and described in the preceding section is considered in the present study. More detailed information about the experimental facility and results can be found in Ref. [2]. The chamber measures 45 mm in diameter and 235 mm in length. The baseline condition includes an equivalence ratio of 0.573 and a chamber pressure of 0.463 MPa. The mass flow rates of natural gas and air are 1.71 and 50.70 g/s, respectively. The inlet flow velocity is 86.6 m/s and the corresponding Reynolds number based on the inlet flow velocity and height of the inlet annulus is 35,000.

Because of the enormous computational effort required for calculating the flowfield in the entire chamber, only a cylindrical sector with periodic boundary conditions specified in the azimuthal direction is treated herein. The analysis, despite the lack of vortex-stretching mechanism, has been shown to be able to capture the salient features of the turbulent flowfields and unsteady flame propagation [9,13]. The computational domain includes the upstream half of the chamber and part of the inlet duct. The entire grid system consists of 375 × 140 points along the axial and radial directions, respectively, of which 75 axial points are used to cover the inlet section. The largest grid size falls in the inertial subrange of the turbulent energy spectrum, based on the inlet Reynolds number. The grids are clustered in the shear-layer regions downstream of the dump plane and near the solid walls to resolve the shear-layer and near-wall gradients. The computational domain is divided into 17 blocks and the analysis was conducted on a distributed-memory parallel computer with each block calculated on a single processor.

Stable flame evolution was first obtained for an inlet mixture temperature of 600 K (below the threshold value T_{in}^* for the onset of combustion oscillation). The flame bifurcation phenomenon was then investigated by increasing the inlet temperature from 600 to 660 K. The mean chamber pressure is 0.463 MPa. Figure 4 shows the mean temperature contours and pseudo-streamlines on the x–r plane based on the mean axial and radial velocity components for a stable flame. A central torodial recirculation zone (CTRZ) is established in the wake of the center body under the effects of the swirling flow. The CTRZ, a form of vortex breakdown, serves as a flame stabilization region, where hot products are mixed with the incoming mixture of air and fuel. In addition, as a result of the sudden increase in combustor area, a corner recirculation zone is formed downstream of the backward-facing step.

The calculated pressure and velocity fields exhibit small-amplitude fluctuations with a dominant harmonic mode at 3214 Hz, corresponding to the frequency of the vortex shedding from the center body. Figure 5 presents the flame evolution and vortex shedding process in the upstream region of the chamber over one cycle of oscillation. The pressure and velocity are measured at the middle point of the inlet annulus exit. The phase angle θ is referenced with respect to the acoustic velocity at the interface between the inlet and combustor. The entire process is dictated by the temporal evolution and spatial distribution of the flame front, which moves back and forth under the influences of the vortical motion (indicated by the concentrated streamlines) in the chamber. A new vortex begins to shed from the center body at $\theta = 90°$, accompanying a higher local flow velocity. As the vortex moves downstream ($\theta = 180°$–$270°$), it distorts the flame front or even produces a separated flame pocket. At the same time, the higher speed mixture pushes the flame downstream. When

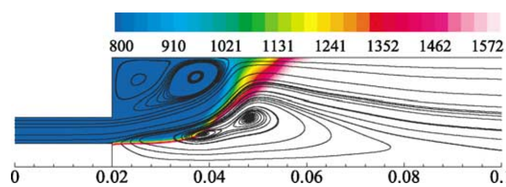

Fig. 4. Mean temperature contours and streamlines of stable flame.

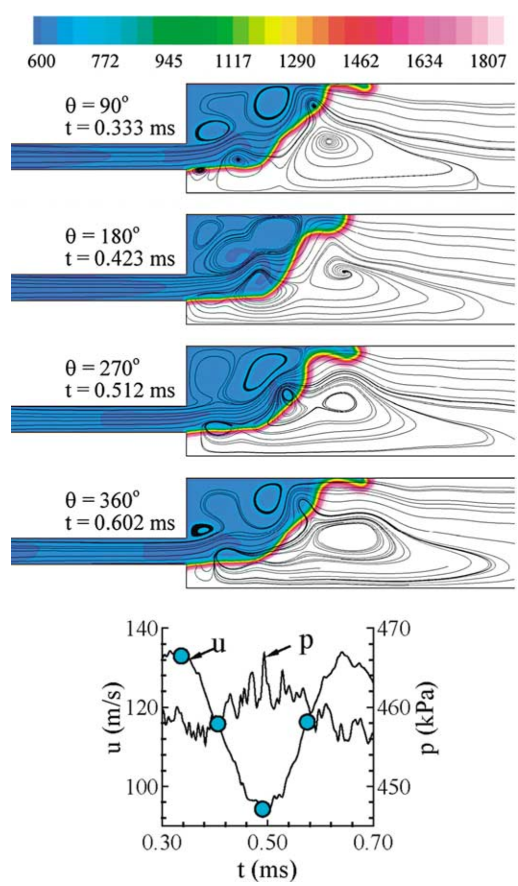

Fig. 5. Stable flame evolution over one cycle of oscillation (3214 Hz): temperature contours and streamlines.

the vortex moves away from the flame ($\theta = 360°$) and dissipates into small-scale structures, the flame front propagates upstream (since the higher speed mixture is convected downstream) and interacts with another incoming vortex. During this process, a new vortex appears at the corner of the center body and another cycle repeats.

The inlet temperature has enormous effects on the flame dynamics in the system. On the one hand, when the inlet temperature increases, for a fixed mass flow rate, the flow velocity also increases and pushes the flame downstream. On the other hand, the increased inlet temperature leads to an increase in the flame speed and consequently causes the flame to propagate upstream. In addition, flashback may occur near the wall due to the small local flow velocity. The combined effects of flow acceleration, flame-speed enhancement, and flashback determine the final form of the flame structure.

In the present study, as the inlet temperature increases from 600 to 660 K, flame bifurcation takes place. The flame originally anchored in the center recirculation zone penetrates into the corner recirculation zone and flashes back. Consequently, the flame is stabilized by both the corner- and the center-recirculating flows and forms a compact enveloped configuration. The flame flaps dynamically and drives flow oscillations through its influence on unsteady heat release. At the same time, the pressure oscillation increases and reaches another limit cycle with a much larger amplitude. The entire bifurcation process can be divided into three stages: high-temperature mixture-filling process, flame-trapping process, and vortex-flashback process, as shown in Fig. 6, in which $t = 0$ ms denotes the time at which the inlet mixture temperature starts to increase from 600 to 660 K.

Figures 6a–6c show the high-temperature mixture-filling process. As the inlet mixture temperature increases, the flow speed increases due to the decreased density for a fixed mass flow rate. As a result, the original low-temperature mixture is pushed downstream toward the flame. Although a flashback phenomenon is observed near the wall, the high-temperature mixture has not reached the flame front near the wall and the flame speed remains unchanged at this stage.

Figures 6d and 6e show the flame-trapping process. Once the high-temperature mixture reaches the flame front, with the help of the increased flame speed, the near-wall flashback overshadows the flow acceleration effects. Consequently, the flame front penetrates into the corner recirculation zone and is trapped by the local vortical motion.

In the vortex-flashback process, as shown in Figs. 6f–6h, the flame propagates upstream under the influence of the vortical motion. A counterclockwise rotating vortex originally shed from the edge of

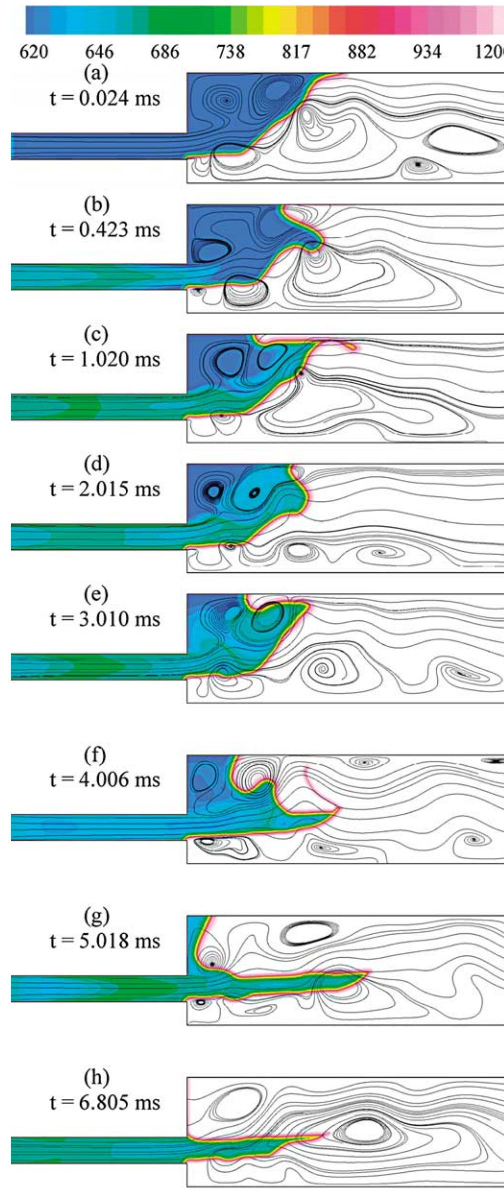

Fig. 6. Transition from stable to unstable flame with increased inlet temperature from 600 to 660 K.

the backward-facing step approaches the flame front in the corner recirculation zone and then pushes it toward the dump plane. At the same time, a small flame pocket is produced and separated from the main stream. After this vortex is convected downstream and passes through the flame, another vortex approaches and interacts with the flame. This process continues and eventually the fresh reactants in the corner recirculation zone are completely burned. The flame is stabilized by both the corner- and the center-recirculating flows and its overall length is substantially reduced. This situation renders the combustor more prone to instabilities according to the Rayleigh criterion [13,20], since considerable heat is released within a short distance close to the chamber head-end (i.e., the acoustic anti-node point).

In our previous work [13], a fully three-dimensional LES study was performed to investigate the dynamics of an unstable flame. Several mechanisms responsible for driving combustion instabilities in the chamber were identified and quantified. The energy cascade from chemical reactions in the flame zone to acoustic fluctuations in the chamber was found to be characterized by a feedback closed-loop process which includes the mutual coupling between acoustic motion, vortex shedding, flame propagation, and heat-release oscillation.

Once the flame becomes unstable when the inlet flow temperature exceeds the critical value T_{in}^*, it becomes rather difficult to reestablish stable operation unless the inlet temperature is reduced to a level significantly lower than T_{in}^*. This phenomenon is commonly referred to as hysteresis and has been experimentally observed by many researchers (see, for example, Ref. [2]). The occurrence of hysteresis under the current circumstance may be explained as follows. During unstable combustion, the corner recirculation zone is filled with high-temperature products and the chamber wall in this region is heated to reach the local flame temperature. To recover stable operation, the cold flow needs not only to extinguish the flame stabilized by the corner-recirculating flow through entrainment or flame lift-off, but also to offset the effects of high-temperature wall, which tend to increase the local gas temperature and inhibit extinction and near-wall flashback. Consequently, a much lower inlet temperature is required to regain stable operation. Numerical simulation of the hysteresis phenomenon necessitates a refined treatment of flame extinction and wall boundary conditions, a subject for subsequent research.

In light of the above observations, we conclude that the flashback phenomenon dictates the flame bifurcation process. Flashback in premixed combustion has been the subject of a number of experimental, analytical, and numerical studies in the past. Its occurrence is usually attributed to two mechanisms. The first involves flame propagation in the boundary layer along a solid wall, where the local velocity diminishes toward the surface. The second mechanism is associated with flow reversal, which is usually caused by vortical motions or acoustic oscillations. Both mechanisms are observed in the present case.

A criterion for the occurrence of near-wall flashback was proposed by Lewis and Von Elbe [21], who state that flashback occurs if the velocity gradient at the wall is less than the ratio of the flame speed and the quenching distance. This criterion, however, is qualitatively correct only for isothermal walls and is not applicable for adiabatic walls due to the lack of a quenching distance. Another criterion, valid for both adiabatic and isothermal walls, was recently proposed by Kurdyumov et al. [22]. Flashback occurs if the Karlovitz number, defined as $\alpha A/S_L^2$, with α being the thermal diffusivity and A the velocity gradient at the wall, is less than a critical value. Although this criterion is formulated for laminar flows, the result can be qualitatively extended to flames in turbulent boundary layers. In the present case, the flame speed increases as the inlet temperature increases. Consequently, the flame is more prone to flashback through the wall boundary layers according to Kurdyumov's criterion. Flashback arising from local flow reversal has also been investigated by many researchers (see, for example, Refs. [9] and [23]). Large vortical structures and turbulent flame speed play important roles in this kind of phenomenon. The latter is essential because it controls the rate of mixture consumption.

For lean-premixed combustion, the laminar flame speed S_L increases with an increase in the equivalence ratio ϕ. Thus, increases in the equivalence ratio and inlet temperature exert similar effects on the flame evolution. However, the chemical reaction rate and heat release are much more sensitive to variations in the equivalence ratio under lean conditions than under stoichiometric conditions. Moreover, near the lean blowout limit, perturbations in the equivalence ratio ϕ can cause periodic extinction of the flame. As a result, the equivalence ratio oscillation under lean conditions is prone to inducing flow oscillation [5] and subsequently increases turbulent velocity fluctuation v'. This suggests that a lean-premixed turbulent flame is more susceptible to flashback, since the turbulent flame speed S_T increases not only with the laminar flame speed S_L but also with turbulent velocity fluctuation v' [24]. The result helps explain why the transition from a stable to an unstable state as described in Ref. [2] occurs only when the equivalence ratio falls in the range between 0.5 and 0.7.

Since the flame bifurcation is largely determined by the flashback phenomenon in the corner recirculation zone in the present case, one effective way to avoid its occurrence is to inject cold flow into that region. This procedure suppresses the local flame upstream propagation and consequently leads to a much more stable system.

4. Conclusions

The unsteady flame dynamics in a lean-premixed, swirl-stabilized combustor has been studied using a large-eddy-simulation technique along with the level-set flamelet library approach. Special attention was focused on the transition of flame structure from a stable to an unstable state. Results indicate that the inlet temperature and equivalence ratio are the key parameters determining the stability characteristics of the combustor. A slight increase in the inlet airflow temperature across the stability boundary leads to a sudden increase in the chamber flow oscillations. One major factor contributing to this phenomenon is that as the inlet mixture temperature increases, the flame originally anchored in the center recirculation zone flashes back through the wall boundary layers and the vortical flow downstream of the dump plane. As a result, the flame becomes stabilized by both the corner- and the center-recirculating flows. The flame then flaps dynamically and drives flow oscillations through its influence on unsteady heat release. Much information has been obtained to shed light on the fundamental mechanisms of the initiation and sustenance of combustion instabilities in gas-turbine engines with lean-premixed combustion. The present study, however, did not consider the influence of stretch rate on flame dynamics, which may alter the local flame structure and cause flame extinction or lift-off. This will be explored in subsequent work.

Acknowledgment

The work reported in this paper was sponsored by the Air Force Office of Scientific Research, Grant F49620-99-1-0290.

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