Combustion and Flame 162 (2015) 3100–3114

Contents lists available at ScienceDirect

Combustion and Flame

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

Formation and flame-induced suppression of the precessing vortex core in a swirl combustor: Experiments and linear stability analysis

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ARTICLE INFO

Article history:
Received 11 July 2014
Received in revised form 17 February 2015
Accepted 20 February 2015
Available online 20 May 2015

Keywords:
Precessing vortex core
Turbulent swirl flames
Linear hydrodynamic instability
Coherent structures

ABSTRACT

The precessing vortex core (PVC) is a coherent flow structure that is often encountered in swirling flows in gas turbine (GT) combustors. In some swirl combustors, it has been observed that a PVC is present under non-reacting conditions but disappears in the corresponding reacting cases. Since numerous studies have shown that a PVC has strong effects on the flame stabilization, it is desirable to understand the formation and suppression of PVCs in GT combustors. The present work experimentally studies the flow field in a GT model combustor at atmospheric pressure. Whereas all non-reacting conditions and detached M-shaped flames exhibit a PVC, the PVC is suppressed for attached V-shaped flames. A local linear stability analysis is then applied to the measured time-averaged velocity and density fields. For the cases where a PVC appeared in the experiment, the analysis shows a global hydrodynamic instability that manifests in a single-helical mode with its wavemaker located at the combustor inlet. The frequency of the global mode is in excellent agreement with the measured oscillation frequency and the growth rate is approximately zero, indicating the marginally stable limit-cycle. For the attached V-flame without PVC, strong radial density/temperature gradients are present at the inlet, which are shown to suppress the global instability. The interplay between the PVC and the flame is further investigated by considering a bi-stable case with intermittent transitions between V- and M-flame. The flame and flow transients are investigated experimentally via simultaneous highspeed PIV and OH-PLIF. The experiments reveal a sequence of events wherein the PVC forms prior to the transition of the flame shape. The results demonstrate the essential role of the PVC in the flame stabilization, and thereby the importance of a hydrodynamic stability analysis in the design of a swirl combustor.

1. Introduction

In modern gas turbine (GT) combustors, the flames are commonly stabilized aerodynamically by imposing a swirling flow on the reactants. Vortex breakdown that manifests in the combustion chamber leads to the formation of an inner recirculation zone (IRZ), where hot burned gas is mixed with the unburned reactants. This enhances ignition of the unburned gas and thus helps to operate the flames under the required fuel-lean and highly turbulent conditions.

The formation of the IRZ is often (but not always) accompanied by the occurence of coherent flow structures such as the precessing vortex core (PVC). The PVC is characterized by a periodical off-axis precession of the center of rotation [1]. Numerous studies have shown that PVCs affect the stabilization of swirl flames in various ways. For instance, the PVC can lead to enhanced fuel–air mixing [2–5], enhanced mixing of burned and unburned gas [6,7] and roll-up, stretch or local quenching of reaction zones [7,8]. The PVC may also interact with thermoacoustic oscillations of the flame [9,10]. Due to these strong effects on the flame, it is desirable to assess the occurence or absence of a PVC during the design of a combustor.

In some GT combustors, PVCs are encountered for both non-reacting and reacting conditions [7,11–13]. In other combustors, the PVC forms for non-reacting cases, while it is suppressed for certain, but not necessarily all reacting cases [14–18]. It was further observed that the suppression of the PVC in a swirl flame can be triggered by changes of steam content and preheat temperature [19], swirl number [20], thermal power [21], pilot flow rate [22], or axial air injection [23]. The suppression of a PVC in a flame is usually accompanied by a major change of the

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http://dx.doi.org/10.1016/j.combustflame.2015.02.015
0010-2180/

flame shape [20], which in turn affects the combustor performance in terms of thermoacoustics, NO_x emissions, flashback or blowout.

The occurrence of a PVC is not limited to combustor flows but was reported in all types of swirling flows [24]. Since the early literature, it was distinguished between a steady, axisymmetric bubble type vortex breakdown and an unsteady, helical spiral vortex breakdown [25,26]. Later investigations came to the conclusion that vortex breakdown is essentially axisymmetric, and the so-called spiral type vortex breakdown is a superposition of the axisymmetric vortex breakdown and a helical flow instability [27]. Following Benjamin [28] and Squire [29], vortex breakdown is caused by the criticality of the vortex core and not by the hydrodynamic stability. The formation of vortex breakdown and associated helical instabilities were further investigated analytically for swirling pipe flows [30], through direct numerical simulations of laminar swirling jets [31] in conjunction with a linear stability analysis [32–34], and through experimental investigations of laminar [35] and turbulent [36,37] swirling jets. All these studies confirm that vortex breakdown occurs due to the criticality of the vortex core and remains axisymmetrical until the onset of a super-critical Hopf bifurcation to a helical hydrodynamic global instability, which manifests in the PVC.

Although these findings are well established in fundamental research, the concept of global instability has only recently entered the combustion community. This is attributed to the fact that combustor flows are typically highly turbulent and feature strong density fluctuations, which make flow-instability considerations less apparent. Yet, from fundamental flow studies, it is known that the density field has a significant impact on the flow stability [38,39]. In particular, it was shown that the suppression of the PVC at certain operating conditions can be related to the change of the density field [40,41].

The aim of the present work is to characterize and explain the formation and suppression of the PVC in a GT-typical swirl combustor by means of experiments and linear stability analysis. Velocity fields, density distributions, and the occurrence and frequency of the PVC are measured for ranges of thermal power and equivalence ratio. While the non-reacting flows in the combustor always feature a PVC, the PVC is suppressed at certain reacting conditions. Stability analysis is equipped with an eddy viscosity model and applied to the time-averaged turbulent flow. As already mentioned by Juniper [42], the stability analysis of the mean flow is an analytic tool, revealing the mechanisms that drive the instability at its limit-cycle.

In this article the analytic approach is described in detail, and then applied to one non-reacting and two reacting cases (with and without PVC). For each case, the occurrence and, if present, the frequency of the PVC is evaluated from the stability analysis and compared to the measurements. The analysis reveals regions of absolute instability that drive the global mode and identifies the so-called global mode wavemaker that determines the PVC frequency and growth rate. For the reacting cases, the influence of the density field on the suppression of the PVC is examined. Finally, the transient dynamics of flow and reaction is studied using high-speed laser diagnostics at an operating condition where the PVC appears intermittently. By analyzing the transient dynamics in combination with the results of the LSA, the complex interplay of the flow/density field, hydrodynamic instability and flame propagation is examined that governs the stabilization of turbulent swirl flames.

2. Combustor and measuring techniques

2.1. Gas turbine model combustor

Experimental studies were performed in a gas turbine model combustor derived from an industrial design by Turbomeca, which can be operated in a partially premixed [43,44] and a perfectly premixed [21] configuration. In this work, the combustor is operated at atmospheric pressure with perfectly premixed methane and air as shown in Fig. 1. The reactants first enter the plenum and then pass through a swirl generator with 12 radial vanes. The swirling flow then enters the combustor chamber through a burner nozzle with a diameter of $D = 27.85$ mm and a conical inner bluff body. The chamber has a square cross-section of 85×85 mm^2 and a height of 114 mm. Optical access to the chamber is provided by side walls made of quartz glass held by metal posts in the corners. The exit is composed of a conical part followed by an exhaust duct with 40 mm inner diameter.

Cartesian coordinates are used for the measurements with the position vector $\mathbf{x} = (x, y, z)^T$ and corresponding velocity vector $\mathbf{u} = (u_x, u_y, u_z)^T$, while cylindrical coordinates are used for the stability analysis with the position vector $\mathbf{x} = (x, r, \theta)^T$ and the corresponding velocity vector $\mathbf{u} = (u_x, u_r, u_\theta)^T$. The orientation of both coordinate systems is indicated in Fig. 1, with the x-axis centered to the combustor inlet and orientated in streamwise direction.

2.2. Particle image velocimetry

Three-component velocity fields were measured using stereoscopic particle image velocimetry (PIV) with a repetition rate of 5 Hz. The system (FlowMaster, LaVision) consisted of a frequency-doubled dual-head Nd:YAG laser (NewWave Solo 120, 120 mJ per pulse at 532 nm), two double-shutter CCD cameras (LaVision Imager Intense, 1376×1040 pixels) and a programmable timing unit (PTU 9, LaVision). The laser beam was expanded to a light sheet that covered the central vertical section of the combustion chamber. The thickness of the laser sheet was around 1 mm. The cameras were equipped with a wide-angle lens (f = 16 mm, set to f/2) and a bandpass filter (532 ± 5 nm) in order to reduce the influence of flame luminosity. Both cameras were mounted on Scheimpflug adapters in order to align their focal plane with the laser sheet. The two cameras were located as close as possible to the combustor in order to image the full vertical section of the chamber (marked in Fig. 1) with a reasonably large stereoscopic angle. In the present configuration, the distance between the camera lenses and the measurement plane was 20 cm, and the angle of view of the cameras was 20°. An infrared filter was mounted between the combustor and the cameras in order to protect the camera from thermal radiation. The air flow was seeded with TiO_2 particles with a nominal diameter of 1 μm, which have a relaxation time of $\tau \approx 5 \cdot 10^{-6}$ s. For the condition with the highest flow rate, the maximal local velocities are $v \approx 60$ m/s and the typical length scale is $l \approx 10$ mm. The resulting Stokes number is $\frac{\tau v}{l} = 0.03$, and thus velocity errors due to particle slip are considered negligible.

Velocity fields were evaluated from particle images using a commercial PIV software (LaVision Davis 8.0). A multi-scale cross-correlation algorithm was used with a final interrogation window size of 16×16 pixel (corresponding to an in-plane spatial resolution of 1.3×1.3 mm^2) and a window overlap of 50%. Based on the ±0.1 pixel uncertainty of the peak-finding algorithm, the estimated random uncertainty of in-plane instantaneous velocities is ±0.8 m/s. With the camera angle of 20°, the uncertainty of the out-of-plane velocity is about three times higher as for the in-plane uncertainty [45].

2.3. Chemiluminescence imaging

Line-of-sight integrated imaging of OH chemiluminescence (CL) was performed using an intensified CMOS camera (LaVision HSS8