Combustion and Flame 161 (2014) 3166–3180

Contents lists available at ScienceDirect

Combustion and Flame

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

Thermo-acoustic velocity coupling in a swirl stabilized gas turbine model combustor

Vincent Caux-Brisebois [a], Adam M. Steinberg [a,*], Christoph M. Arndt [b], Wolfgang Meier [b]

[a] *Institute for Aerospace Studies, University of Toronto, 4925 Dufferin Street, Toronto, Ontario M3H 5T6, Canada*
[b] *Institute of Combustion Technology, German Aerospace Center (DLR), D-70569 Stuttgart, Baden-Württemberg, Germany*

ARTICLE INFO

Article history:
Received 12 March 2014
Received in revised form 16 May 2014
Accepted 21 May 2014
Available online 26 June 2014

Keywords:
Premixed turbulent combustion
Thermo-acoustic coupling
Combustion instability

ABSTRACT

Limit-cycle thermo-acoustic velocity coupling mechanisms are studied in a perfectly-premixed swirl-stabilized combustor using data from 10 kHz repetition-rate stereoscopic particle image velocimetry (S-PIV) and OH planar laser induced fluorescence (PLIF). Five cases over a range of thermal powers and equivalence ratios were investigated, each of which underwent different amplitude limit-cycle oscillations. Proper orthogonal decomposition (POD) of the velocity data showed that each case contained a dynamic helical vortex core (HVC) that rotated around the combustor and greatly affected the flame behavior. Flow and flame statistics were compiled as a function of both the phase in the thermo-acoustic cycle and a phase representing the azimuthal position of the HVC relative to the measurement plane. These data were used to determine the thermo-acoustic energy transfer field at each HVC azimuthal angle, as described by the Rayleigh integral. It was found that periodic deformations of the HVC caused large-scale flame motions, resulting in regions of positive and negative energy transfer. The deformation of the HVC was linked to a swirl number wave that propagated from the burner nozzle. While the mechanism of thermo-acoustic coupling was the same for all cases, the phase between heat release and pressure oscillations varied significantly. This phase relationship was determined by the interaction of the pressure field, swirl wave, HVC deformation, and flame response. It was shown that these can be described by the combination of a Helmholtz resonator and a convective disturbance.

1. Introduction

This paper presents an analysis of the fluid mechanical mechanisms driving self-excited limit-cycle thermo-acoustic oscillations in a gas turbine model combustor (GTMC) burning swirl-stabilized lean-premixed (LP) flames. Natural excitation of thermo-acoustic oscillations is a major problem in modern gas turbine combustors, which often employ LP combustion in order to reduce NO_x emissions [1–3]. The local volumetric heat release rate ($\dot{q}$) from such flames is highly sensitive to various perturbations, particularly fluctuations in the flow field and reactant mixture composition [4]. The former, often referred to as velocity-coupling, leads to changes in the amount and distribution of reactive surface area through flame wrinkling, stretch, ignition, and extinction, whereas the latter changes the heat release rate per unit flame area. Periodic oscillations in both the flow field and reactant mixture can be generated by pressure (p) oscillations, which results in coupling between combustion and pressure.

Local pressure-combustion coupling is described by the Rayleigh integral

$$\theta(\mathbf{x}) = \frac{\gamma - 1}{\gamma}\frac{1}{\bar{p}}\int_{t} p'(\mathbf{x},t)\dot{q}'(\mathbf{x},t)\,\mathrm{d}t \qquad (1)$$

where θ represents the local rate of energy transfer from heat release oscillations to pressure oscillations and $(\cdot)'$ is the local fluctuation relative to the mean $\bar{(\cdot)}$. Positive values of θ indicate that the local coupling drives the oscillations (in-phase pressure and heat-release oscillations), whereas negative θ indicates local damping (out-of-phase oscillations).

Steady-state limit-cycle amplitudes are reached when the net energy transfer in the combustor volume equals the rate at which acoustic energy is transmitted and dissipated by the system [5]. Practical LP gas turbine combustors can exhibit limit-cycle amplitudes at particular conditions that are sufficient to cause major hardware damage, reduced combustion efficiency, increased emissions, and/or global flame extinction through blow-off or flashback. Several control strategies have been devised to mitigate thermo-acoustic instabilities [5–8], though these generally are applied as retrofits to specific combustor models when instabilities

---

* Corresponding author.
E-mail address: steinberg@utias.utoronto.ca (A.M. Steinberg).

http://dx.doi.org/10.1016/j.combustflame.2014.05.020

Nomenclature

Symbols

A_s	area of swirler for Helmholtz resonator analysis
a	POD temporal coefficient
b	damping constant in Helmholtz resonator analysis
f	frequency
k	stiffness constant in Helmholtz resonator analysis
M	POD eigenmode
m_s	mass of fluid in swirler for Helmholtz resonator analysis
N_p	number of phases for doubly-phase-resolved analysis
P_{th}	thermal power
S	Swirl number
v_s	convective velocity of swirl wave

Greek

θ	local thermo-acoustic energy transfer
Σ	flame surface density
φ	equivalence ratio
ϕ	phase angle in oscillation
ψ	local thermo-acoustic energy transfer from doubly-phase-resolved analysis
Ψ	total thermo-acoustic energy transfer from doubly-phase-resolved analysis
ω	vorticity

Mathematical

$(\cdot)'$	instantaneous fluctuation
$(\cdot)''$	root-mean-square fluctuation
$(\bar{\cdot})$	time average
$\{\cdot\}$	property integrated across the field of view
$\langle\cdot\rangle$	property integrated across the field of view width (x) at a particular y
$(\cdot)^{ah}$	doubly-phase-resolved component (Eq. (3))
$(\cdot)^{t}$	turbulent fluctuation relative to doubly-phase-resolved mean (Eq. (3))
$(\bar{\cdot})^{ah}$	doubly-phase-resolved mean (sum of mean and doubly-phase-resolved component) (Eq. (4))
$(\cdot)^{a}$	doubly-phase-resolved oscillation relative to mean over the acoustic cycle (Eq. (5))

are encountered, and are not broadly robust to changes in configuration or operating parameters. The complexity of the driving acoustic/flow/combustion interactions currently makes prediction and efficient control of unstable conditions extremely challenging, particularly in engine-relevant combustors. Doing so requires better understanding of the flow–flame-acoustic interactions driving practical oscillations.

Many investigations have been performed of thermo-acoustic coupling in LP combustion systems, ranging from simple laminar flames to complex gas turbine combustors [9–17]. The response of a flame to perturbations often is represented by a flame transfer function (FTF), which describes the linear response of the system to low-amplitude forcing. Non-linear flame describing functions (FDF) also have been investigated that allow consideration of higher amplitude disturbances [18,19]. FTFs (and FDFs) can be experimentally determined in a combustor geometry of interest by operating the combustor over a range of conditions and, at each condition, forcing the system at a variety of frequencies (and amplitudes). The resulting transfer functions can then be used to determine the unstable modes of the combustor through a dispersion relationship and, in the case of an FDF, may allow estimation of the limit cycle amplitude. However, this approach requires experimental testing of the combustor over a wide set of conditions and forcing parameters, making their application to the design process challenging. Moreover, it is unclear whether the coupling mechanisms initiating instabilities at low perturbation amplitudes persist in high-amplitude limit cycle oscillations.

It therefore is desirable to have a better mechanistic understanding of finite-amplitude thermo-acoustic velocity coupling mechanisms. For simple flames, such as laminar V-flames and conical flames, analytical methods exist that can predict linear FTFs with reasonable accuracy using a flame-sheet approach [20–27]. In these methods, acoustically generated velocity disturbances affect the local heat release oscillations by altering the kinematic balance between flame propagation and the surface-normal flow velocity [28]. Different types of disturbance convect at different velocities, e.g. shed-vortex induced flame wrinkling or bulk flow oscillations, resulting in a spatially distributed phase relationship between the heat release oscillations and acoustics that depends on the flame geometry and disturbance convective-velocities.

In more complex swirl-stabilized flames, models for the FTF in systems undergoing low-amplitude forcing have recently been investigated. Palies et al. [19,29] studied a swirl-stabilized premixed flame using the G-equation and found that the FTF had a similar form to that for an inverted conical V-flame, with some alterations due to differences in convective velocities of axial and azimuthal disturbances. Jones et al. [30] experimentally studied a premixed swirl flame undergoing velocity forcing at an amplitude of 5%. They found two flame perturbation mechanisms, one driven by shed-vortices that propagated along the flame from the anchoring point, and the other generated in the outer-shear layer.

However, the velocity coupling mechanisms that occur during high-amplitude self-excited oscillations may be considerably different. For example, a commonly reported low-amplitude convective disturbance is associated with periodic vortex shedding from the combustor dump-plane causing flame winkles that propagate up the flame [31–33]. However, it has been shown that intense swirl flames often do not exhibit such shedding, but may instead contain three-dimensional helical vortex cores (HVC) that rotate around the burner at a frequency that is different than the acoustics [34–43]. While the conditions leading to the formation of HVCs remain unclear, parameters such as the mass flow rate, combustor geometry, and mode of premixing are known to be of importance [40,44]. Results from the burner studied here have demonstrated that conditions with high-amplitude self-excited oscillations often exhibit such HVCs, whereas conditions with low-amplitude oscillations generally exhibit periodic vortex shedding [31]. It also has been shown that rapid transition between low- and high-amplitude self-excited oscillations can be associated with rapid transition from periodic vortex shedding to an HVC [45]. Hence, the fundamental velocity coupling mechanism for high-amplitude self-excited oscillations would be very different than those found using low amplitude forcing.

In this paper, such self-excited velocity coupling mechanisms are investigated using high-repetition-rate (10 kHz) OH planar laser induced fluorescence (PLIF) and stereoscopic particle image velocimetry (S-PIV), along with acoustics measurements. The diagnostics are applied in a swirl-stabilized combustor burning perfectly premixed methane–air flames. The combustor studied is geometrically identical to a commonly studied configuration that