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ScienceDirect

Proceedings of the Combustion Institute xxx (2014) xxx–xxx

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

A new pattern of instability observed in an annular combustor: The slanted mode

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Abstract

In annular combustion chambers of aero-engines and gas turbines, acoustic coupling may arise from azimuthal modes which are less well damped than axial modes. Also, since the circumference is the largest length in the combustor, the azimuthal modes have the lowest resonance frequencies and are most prone to instability. Such a coupling raises many scientific issues which are considered in a small number of fundamental experiments. The present investigation focuses on this problem and provides experimental data on a special type of combustion instability in which the thermo-acoustic resonant coupling involves a combination of modes. This produces an unusual pattern of flame responses in which the distribution of heat release rate is slanted. Data are provided in the form of free radical light intensity patterns (interpreted as heat release rate distributions) and microphone signals detected in the plenum and chamber. It is shown that the slanted pattern is the signature of a combination of two modes with coinciding frequencies, the first being a standing azimuthal mode while the second is an axial mode. Measurements of the flame describing function on a single matrix burner at the fundamental frequency are used to explain the observed phase shift and amplitude in the flame responses of the different injectors in the annular combustor.

Keywords: Annular systems; Combustion dynamics; Flame oscillations; Azimuthal mode

1. Introduction

Modern annular combustion chambers are quite sensitive to perturbations giving rise to instabilities. Longitudinal and azimuthal couplings are observed in many practical systems [1–3]. While these issues are of practical importance, there are few detailed measurements in well controlled laboratory scale configurations. The present investigation, which is a part of a larger project on annular combustion dynamics, is undertaken to analyze a new instability pattern involving a combination of azimuthal and longitudinal modes in an annular system.

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http://dx.doi.org/10.1016/j.proci.2014.06.029

Please cite this article in press as: J.F. Bourgouin et al., *Proc. Combust. Inst.* (2014), http://dx.doi.org/10.1016/j.proci.2014.06.029

Self-sustained oscillations in real gas turbine combustors such as that described by Krebs et al. [3] indicate that azimuthal modes switch back and forth from a standing to a purely spinning mode. Recently, two annular laboratory scale combustion chambers were built independently, one in Cambridge [4,5] and the other at the EM2C Lab [6,7]. These two systems comprise a plenum, a periodic set of injectors and an annular chamber open to the atmosphere. They both operate in a premixed mode. With swirl injectors equipped with a large bluff body, Worth and Dawson [4,5] observe a strong azimuthal instability, involving spinning or standing waves with various types of dynamical oscillations. The EM2C annular combustor designated as MICCA has a larger diameter, and its injectors have no central bodies. The system features an azimuthal instability [6], which continuously evolves from a clockwise to a counterclockwise spinning mode, with a transition through the standing mode. A study of the spin ratio indicates that the greatest probability is that of the standing mode.

Some recent large eddy simulations (LES) of azimuthal instabilities in annular combustors with highly turbulent swirl injectors [8–10] confirm that the azimuthal mode continuously evolves from a spinning to a standing oscillation, and conversely but with a preference for the standing mode. As in laboratory scale experiments [4–6], simulations also indicate that the flames essentially execute an axial motion when they are located at a pressure anti-node indicating that the driving mechanism may be linked to the fluctuation in mass flow rate induced by the alternating pressure field at the injector exhaust.

Azimuthal instabilities have been extensively investigated with low-order models adapted to annular geometries [11–19]. If the system features a discrete rotational symmetry, that is, the geometry consists of identical sectors with identical flames, a linear analysis yields azimuthal modes which are degenerate. These degenerate modes permit both standing and spinning solutions. Breaking the rotational symmetry of the system by, for example placing an acoustic damper at a certain circumferential location or using a non-uniform distribution of burners or flame transfer functions, results in the linear solutions featuring only standing modes.

For a perfectly symmetric system with a saturation-type flame describing function, it was shown that the limit cycle solution corresponds to a purely spinning wave, as the standing wave is unstable in this case [17,20]. Nevertheless, standing modes are also observed in nominally symmetric systems. A possible explanation was recently given in terms of an additional effect from transverse velocity fluctuations on the flame that have a stabilizing effect on the standing mode pattern [21]. Switching between standing and spinning modes, which is observed in industrial annular systems was explained by introducing background noise, representing turbulent fluctuations, which stochastically disturb the limit cycle [22].

From the state of the art, one can conclude that predicting the dynamical behavior of annular systems remains a challenge. While the stochastic nature of flow and flames is included in some of the modeling studies [22], the low-order models do not yet allow a full prediction of the azimuthal coupling characteristics.

In recent studies undertaken at EM2C to test theoretical modeling, the MICCA system was equipped with 16 matrix burners each establishing a collection of laminar premixed flames. It is shown that depending on operating conditions, one could observe an azimuthal mode which is purely spinning [23] or an azimuthal mode which is purely standing [24]. These modes are sustained for extended periods of time allowing detailed investigations of the flame dynamics. It was shown that the flame motion is quite sizable at the pressure anti-nodes and is executed in the axial direction.

The present study deals with a novel type of instability in the same annular combustor equipped with matrix burners. We explore a special kind of oscillation giving rise to an unusual pattern of heat release designated as the “slanted mode” because the distribution of heat release from the various injectors changes spatially from low to high in a slanted manner. This article begins with a description of the experimental setup (Section 2). Experimental data are examined in Section 3 and a modal projection is introduced to explain some of the features found in the experiment. The heat release rate signals are then interpreted in Section 4 by making use of flame describing function measurements on a single injection system.

2. Experimental setup

The annular combustor MICCA, shown in Fig. 1, comprises an upstream plenum, a combustion chamber formed by two cylindrical concentric quartz tubes and sixteen injectors mounted on the flange which separates the plenum from the chamber and constitutes the chamber backplane. The inner and outer tubes diameters are 300 mm and 400 mm respectively. In the present experiments the tubes have the same length 200 mm in distinction with previous studies [4–6] where the inner tube had to be shorter than the outer one to obtain azimuthal thermo-acoustic instabilities.

The air/propane mixture delivered by a premixing unit is conveyed to the annular plenum through eight channels which are plugged on the

Please cite this article in press as: J.F. Bourgouin et al., *Proc. Combust. Inst.* (2014), http://dx.doi.org/10.1016/j.proci.2014.06.029