Combustion and Flame 174 (2016) 120–137

Contents lists available at ScienceDirect

Combustion and Flame

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

A multi-chamber model of combustion instabilities and its assessment using kilohertz laser diagnostics in a gas turbine model combustor

YunTao Chen*, James F. Driscoll

Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109, United States

ARTICLE INFO

Article history:
Received 29 October 2015
Revised 12 January 2016
Accepted 26 August 2016
Available online 1 October 2016

Keywords:
Combustion instability
Reduced-oder modeling
Gas turbine combustion
Partially premixed combustion

ABSTRACT

A multi-chamber model for the combustion instabilities manifested in a gas turbine model combustor was developed. The proposed model was used to explain the dependencies of instability frequency on burner geometry and other flow parameters, some of which could not be reconciled with previous models. The new model was built upon the Helmholtz analysis of two connected resonators. The instability frequency as well as the complex pressure ratio between two chambers were predicted by solving ordinary differential equations. To assess the assumptions and predictions of the proposed model, the spectra and magnitude of the oscillations of pressure, heat release rate, and velocity were measured for four different operating conditions: rich (R1), lean (L1), stoichiometric (S1), and reduced flow rate (R2) with a kilohertz laser diagnostic system. These measurements reconfirmed that the instability is of Helmholtz type. A global equivalence ratio that is consistently greater than unity was identified to be an enabling factor for combustion instability. This is also in agreement with the predictions made by the proposed model. Furthermore, the model was shown to be able to predict the right trend of instability frequency when multiple parameters were changed. It is concluded that the current model is an improvement over previous models, because the acoustic coupling between different chambers of the burner was considered.

1. Introduction

1.1. Combustion instability in gas turbine engines

Combustion instability is characterized by the large oscillations of heat release and flame location, coupled with an exponentially growing pressure oscillation amplitude or a limit cycle of pressure oscillations sustained at a large amplitude. Instabilities represent a major obstacle to implementation of low-NO_x lean-premixed technology in gas turbine engines, and they may lead to the catastrophic failure of the engine components. The relationship between pressure and heat release oscillation was investigated by Lord Rayleigh [1], who stated that acoustic oscillations are amplified by heat release when the latter is in phase with pressure oscillations. This is called the Rayleigh criterion. There are many causes for the oscillations, Zinn and Lieuwen [2] and Mongia et al. [3] explained that anchoring a premixed flame within an engine can be difficult. Heat release oscillations can be caused by equivalence ration oscillations [4] as well as flame surface area oscillations [5].

This work focuses on geometries that can lead to a Helmholtz-type instability. It is noted that within a full-scale engine, instability can be caused by standing waves, a Helmholtz resonance, or by a complex acoustic wave pattern. The Helmholtz resonance occurs when a relatively short volume of fluid is connected to a small orifice. For example, Krebs et al. [6] state that in Siemens engines Helmholtz resonances are called “breathing modes” and may occur in the 100–400 Hz range. Full-scale injector studies at Pratt and Whitney by Cohen and Banaszuk [7] and by Cohen et al. [8] found that their instability was due to a Helmholtz resonance at 200 Hz. Previous laboratory-scale experiments also have shown that a Helmholtz resonance occurs when a combustion instability is detected; these findings were reported by Temme et al. [9], Zähringer et al. [10], Uhm and Acharya [11], and Durox et al. [12]. General reviews of the many possible types of instabilities are given by McManus et al. [13], Ducruix et al. [14], Zinn and Lieuwen [2], and Mongia et al. [3].

The combustion chamber of a gas turbine engine can be considered to be a series of connected chambers, as shown in Fig. 1a. Just downstream of the combustor is an exit orifice that leads to the first stage of the turbine. Figure 1b illustrates two chambers and two orifices. Based on this simplifying idea, the DLR (German Aerospace Center) Gas Turbine Model Combustor (GTMC) was

* Corresponding author.
E-mail address: yuntaoc@umich.edu (Y. Chen).

http://dx.doi.org/10.1016/j.combustflame.2016.08.022
0010-2180/

Nomenclature

Acronyms
FoV Field of View
FSA Flame Surface Area
FSD Flame Surface Density
GTMC Gas Turbine Model Combustor
PSD Power Spectral Density
PVC Precessing Vortex Core
ROM Reduced Order Model

Latin Symbols
$\dot{m}$ Mass flow rate
$\dot{Q}$ Heat release rate
$\jmath$ Square root of −1
$\mathscr{P}$ Complex pressure ratio, defined in Eq. (20)
A Element cross section area
C Speed of sound
D Element equivalent diameter
l Element length
P Pressure
T Temperature
t Time
u Axial velocity
v Radial velocity
V Element volume

Greek symbols
Δh_f° Lower heating value
ω System instability frequency
ω_0 Plenum Helmholtz frequency
ω_2 Combustion chamber Helmholtz frequency
Φ Equivalence ratio
ψ_{20} Combust. chamber/plenum phase difference
τ_c Convection time delay
ζ Damping ratio

Mathematical symbols
$\dot{x}$ Rate of variable x
$|x|$ Magnitude of complex number x
$\bar{x}$ Average of variable x
x' Fluctuation of variable x

Subscripts
0 Plenum properties
1 Injector properties
2 Combustion chamber properties
3 Exhaust duct properties

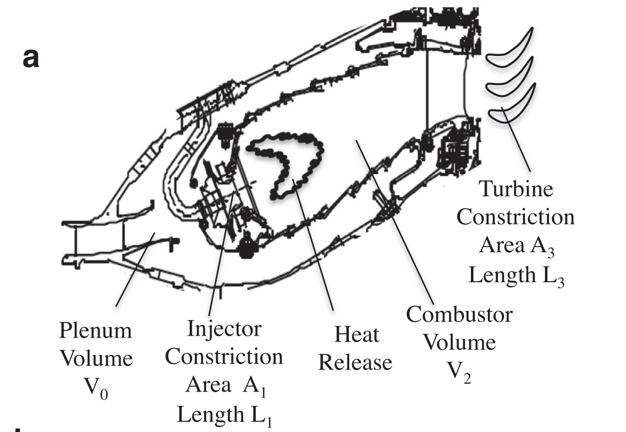

Fig. 1. Schematic of the combustor of a gas turbine engine.

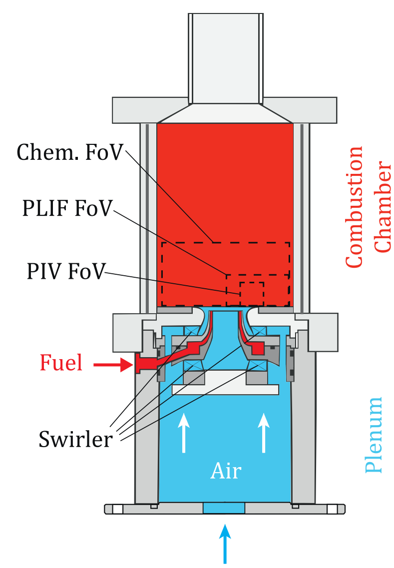

Fig. 2. Schematic of the GMTC [15] with the field of view (FoV) of the chemiluminescence, PLIF, and PIV diagnostics marked.

designed by Meier and colleagues at DLR Stuttgart [15]. As shown in Fig. 2, the GTMC features a ring of fuel injectors surrounded by dual swirling air injectors, in a plenum-injector-combustor-exhaust configuration. It contains the basic feature of a practical combustor within a geometrically simple and optically accessible setup. The experimental measurements and reduced order modeling of combustion instabilities in this work will be based on the GTMC.

1.2. Previous research on the GTMC

Published literature of investigations on GTMC date back as far as 2003 [16,17]. Meier and colleagues made extensive imaging measurements in their GTMC [15,18–25]. One of their main interests was the flame-flow interaction. In particular, they studied how the vortex-like motion of the helical Precessing Vortex Core (PVC) interacts with the flame. They found that the PVC-flame interaction occurs in both cases: when an instability is present [18–21] as well as when it is absent [15,22–25]. They imaged the flame using kilohertz OH Planar Laser Induced Fluorescence (PLIF) and the PVC with kilohertz Particle Image Velocimetry (PIV). They found that the PVC rotation causes flow and flame oscillations at frequencies of 400–500 Hz, while the pressure oscillations associated with the combustion instability occur at a lower frequency around 300 Hz. The fact that the PVC rotation and the combustion instability occur at different frequencies causes complications in the understanding of the physical mechanism of the heat release. They showed that the PVC-flame interaction affects where the heat is released, and it affects the time delay between pressure oscillations and the heat release rate oscillations.