Experimental Thermal and Fluid Science 92 (2018) 125–140

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Lean methane flame stability in a premixed generic swirl burner: Isothermal flow and atmospheric combustion characterization

Jon Runyon[a,*], Richard Marsh[a], Philip Bowen[a], Daniel Pugh[a], Anthony Giles[a], Steven Morris[b]

[a] School of Engineering, Cardiff University, Cardiff, Wales, UK
[b] Gas Turbine Research Centre, Cardiff University, Margam, Wales, UK

A R T I C L E I N F O

Keywords:
Turbulent premixed combustion
Generic swirl burner
Lean blowoff
Flame dynamics
Optical diagnostics

A B S T R A C T

Gas turbine combustors operating in lean premixed mode are known to be susceptible to flame blowoff due to competing influences of increasing chemical timescales and decreasing flow time scales under these conditions. In this study, combustion stability and the onset of flame blowoff in particular, are characterized in a new swirl burner operated with fully premixed methane (CH_4) and air at thermal power of 55 kW, atmospheric combustor inlet pressure, and ambient (~290 K) combustor inlet temperature. The onset of flame blowoff was shown repeatedly to exhibit high amplitude, low frequency combustion instabilities as a result of periodic flame extinction and reignition events. In addition to detailed isothermal characterization of the burner velocity field using particle image velocimetry, a combination of dynamic pressure sensing and optical combustion diagnostics, including OH^* chemiluminescence and OH planar laser induced fluorescence, give indication of the combustion rig acoustic response and changes in flame acoustic response, heat release, and flame anchoring location related to the onset and occurrence of blowoff. This analysis shows that the onset of this instability was preceded by a marked reduction in dominant frequency and amplitude until frequency collapse and high amplitudes were observed throughout the burner inlet mixing plenum, burner pilot, combustion chamber, and exhaust ducting. Acoustic and optical signal analysis show potential viability for use in practical applications for precursor indications of lean blowoff. The flame anchoring location within the combustion chamber was shown to detach from the burner exit nozzle and stabilize within the outer and central recirculation zones near the lean blowoff limit, providing evidence of changes to both chemical and flow time scales. Chemical kinetic modelling is used in support of the empirical studies, in particular highlighting the relationship between maximum heat release rate and OH^* chemiluminescence intensity.

1. Introduction

With ever-increasing regulatory pressure on gas turbine manufacturers and operators to reduce NO_x and CO emissions while maintaining high cycle efficiency, combustion systems for land-based power generation have progressed significantly in recent years towards lean premixed (LPM) modes of operation [1]. While delivering emissions reduction benefits, LPM gas turbine combustors are inherently susceptible to potentially high amplitude, low frequency pressure fluctuations associated with operation near the stability limit of lean flame blowoff [2], resulting in potential structural damage to combustion system components, part-load engine operation, or machine shutdown [3]. This phenomenon results from increasing chemical timescales, τ_{chem}, and decreasing flow timescales, τ_{flow}, which can manifest within the combustion chamber as periodic flame extinction and reignition events [4].

While combustion instabilities can be generally categorized as low frequency ($f <\sim 50$ Hz), mid-frequency (~ 50 Hz $< f < \sim 1000$ Hz), and high frequency ($f > \sim 1000$ Hz) [1], the particular lean blowoff (LBO) instabilities observed and characterized in this work fall within the low frequency range. These low frequency instabilities have been noted to occur in both laboratory scale burners [2,4–7] and industrial gas turbine engines [8,9] under operating conditions near LBO. Muruganandam et al. [4] utilized OH^* chemiluminescence and acoustic measurements to report that the energy content of the low frequency spectrum (10,200 Hz) increased significantly near LBO at an equivalence ratio of $\Phi = 0.745$ in an atmospheric swirl combustor. In a similar experimental setup, Prakash et al. [5] used a number of bandpass acoustic signal frequency filters centered at 15.9, 31.8, and 63.7 Hz as means of LBO detection and subsequent feedback into a pilot fuel injection control system. Taupin et al. [6] detected a non-acoustic low frequency mode measuring up to 15 kPa at 16 Hz near LBO in an

* Corresponding author at: School of Engineering, Queen's Buildings, The Parade, Cardiff, Wales CF24 3AA, United Kingdom.
E-mail address: RunyonJP@cardiff.ac.uk (J. Runyon).

https://doi.org/10.1016/j.expthermflusci.2017.11.019
Received 9 January 2017; Received in revised form 14 November 2017; Accepted 21 November 2017
Available online 22 November 2017

Nomenclature

Abbreviations

AFT	Adiabatic Flame Temperature
AGSB	Atmospheric Generic Swirl Burner
ATAP	Ambient Temperature, Atmospheric Pressure Rig Conditions
BPV	Backpressure Valve
CFD	Computational Fluid Dynamics
CMF	Coriolis Mass Flowmeter
CRZ	Central Recirculation Zone
DPT	Dynamic Pressure Transducer
FCV	Flow Control Valve
GTRC	Gas Turbine Research Centre
HPCR	High-Pressure Combustion Rig
HPGSB	High-Pressure Generic Swirl Burner (Mk. I)
HPGSB-2	High-Pressure Generic Swirl Burner (Mk. II)
HPOC	High-Pressure Optical Chamber
HRR	Heat Release Rate
LBO	Lean Blowoff
LPM	Lean Premixed
ORZ	Outer Recirculation Zone
PIV	Particle Image Velocimetry
PLIF	Planar Laser Induced Fluorescence
PSD	Power Spectral Density
PVC	Precessing Vortex Core
RSL	Rich Stability Limit
VSD	Variable Speed Drive

Symbols

A_{noz}	burner exit nozzle area (m^2)
A_{tan}	Swirler tangential inlet area (m^2)
c	speed of sound (m/s)
D	diameter (mm)
f	frequency (Hz)
He	Helmholtz number
II_{OH*}	mean integrated OH* chemiluminescence intensity
II'_{OH*}	Instantaneous integrated OH* chemiluminescence intensity
L	length (mm)
$\dot{m}_{air}$	air mass flow rate (g/s)
$\dot{m}_{CH4}$	methane mass flow rate (g/s)
p'	dynamic pressure measurement (kPa)
ΔP	pressure drop (kPa)
$P2$	combustor inlet pressure (MPa)
P_{therm}	thermal power (kW)
Q_{noz}	burner exit nozzle volumetric flow rate (m^3)
Q_{tan}	Swirler tangential volumetric flow rate (m^3)
r	radial distance from burner exit nozzle centerline (mm)
r_{noz}	burner exit nozzle radius (m)
r_{tan}	Swirler effective radius of tangential inlet (m)
Re	Reynolds number
S_g	geometric Swirl number
S_L	laminar flame speed (m/s)
St	Strouhal number
$T2$	combustor inlet temperature (K)
$\bar{u}$	mean burner exit nozzle velocity (m/s)
v	axial velocity component (m/s)
y	axial distance from burner exit nozzle (mm)
Φ	equivalence ratio
γ	ratio of specific heats
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
τ_{chem}	chemical time scale (s)
τ_{flow}	flow time scale (s)

Subscripts

comb	combustor
confine	burner confinement
dump	burner dump plane
noz	burner nozzle exit
premix	premixed fuel and air

atmospheric swirl burner at $\Phi = 0.63$. De Zilwa et al. [7] examined the lean extinction limit of a flame stabilized in a rounded duct expansion observing dominant frequencies of near-LBO oscillations of 3–10 Hz which were discrete from the acoustic frequencies of the tested geometry. Instead, these oscillations were related to flame extinction along the reacting shear layer and subsequent flashback resulting from reduced downstream strain. Numerical simulation has also been used to predict periodic ignition and extinction oscillations around 100 Hz for a premixed methane-air flame near blowoff [10].

Hence, both experimental and numerical studies have been used to enhance the understanding of LBO and its onset. However, detailed experimental characterization of stable, transitional, and unstable modes of near-blowoff operation in a geometrically generic swirl burner is lacking under representative conditions, particularly under preheated and pressurized combustion inlet conditions [4,11]. To this end, a high-pressure generic swirl burner (HPGSB-2) has been designed and commissioned in this study specifically for the purposes of enhancing the acoustic and optical measurements capable for fully premixed, confined swirl flames under these operating conditions.

1.1. Research aim

The aim of this work was to characterize experimentally the stable operation, onset, and occurrence of high amplitude, low frequency combustion instabilities observed under lean, fully premixed and near-blowoff conditions in a generic swirl burner. In addition to providing a comprehensive data set for validation of computational fluid dynamics (CFD) models, this study also supports further development of tools for the prediction of the onset of near-blowoff instabilities in practical operating environments. A combination of techniques is therefore investigated based on the acoustic and optical measurements taken under both isothermal and combustion conditions with the goal of reducing near-LBO operating margins.

Isothermal air flow testing and loudspeaker swept-tone acoustic measurements were first undertaken to identify swirl flow structures as well as potential resonant and flow-driven frequencies of the HPGSB-2 and the surrounding rig. Methane-air combustion experimentation under atmospheric conditions was then conducted to evaluate stable operation in addition to LBO precursor events and LBO instabilities. These experiments were undertaken with fully premixed CH_4-air flames at thermal power of $P_{therm} = 55$ kW and ambient combustor inlet temperatures (~ 290 K). The resulting flames are studied experimentally through a combination of measurement techniques, most notably dynamic pressure, particle image velocimetry (PIV), OH* chemiluminescence, and OH planar laser induced fluorescence (PLIF). Additionally, a chemical kinetic modelling approach was undertaken to provide fundamental support for the analysis of flame characteristics in relation to LBO stability.