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Isothermal coherent structures and turbulent flow produced by a gas turbine combustor lean pre-mixed swirl fuel nozzle

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ABSTRACT

The steady and unsteady isothermal fluid dynamics generated by an industrial low emission, lean premixed, fuel swirl nozzle designed by Solar Turbines Incorporated were investigated in this study. The experiments were carried out in a model optical can combustor operating at atmospheric pressures. Non-time resolved, planar Particle Image Velocimetry (PIV) measurements were taken at Reynolds numbers with respect to the nozzle throat diameter of ~50000, ~100000, and ~180000. The time-averaged velocity fields were approximately self-similar, with the highest mass flow exhibiting a central recirculation zone (CRZ) with a slightly larger diameter. The results were analyzed using a methodology based on Proper Orthogonal Decomposition (POD) to extract the periodic structures in the flow and obtain the underlying stochastic turbulence field. This distinction between stochastic and coherent fluctuations is critical to properly model combustor flows. Coherent flow instabilities such as the precessing vortex core (PVC) and the propagation of axial/radial vortices were observed to significantly contribute to the mixing between the nozzle exit flow and the recirculated mass flow. Over 30% of the total fluctuation (difference between instantaneous and time-averaged velocity fields) kinetic energy was attributed to coherent structures throughout the inner shear layer between the swirling jet exiting the nozzle and the CRZ. Stochastic variability was prevalent close the liner wall and throughout the combustor domain after the swirling jet impinged on the wall, with <20% of the total fluctuation attributed to coherent structures. The normalized coherent and stochastic flow fields were also approximately self-similar with Reynolds number.

1. Introduction

Swirling flows within combustors have been extensively studied for the past 50 years; with current work focusing primarily on understanding the vortex breakdown (VB) and unsteady phenomena that affect combustor operation. Comprehensive reviews on combustion in swirling flows were first written in the 1970s and early 80s by Lilley [1], Beér and Chigier [2], Syred and Beér [3], and Gupta et al. [4]. The vast contributions of the research community led to the current understanding and characterization of the central recirculation zone (CRZ), formed as the swirling jet exiting the fuel nozzle expands into the combustion chamber, recovering axial pressure, and eventually triggering the breakdown of the vortex and subsequent backflow [5]. High intensity flames with high combustion efficiencies are attained with swirling jets without the need of a blunt body for flame stabilization. No longer having to cool a blunt body, swirl fuel nozzles simplify cooling requirements while maintaining flame stability, short combustor length, and high combustion efficiency [6]. Recent work has focused on the unsteady behavior and instabilities that emerge in combustor flows as detailed by the work of Lieuwen [7], Lucca-Negro and O'Doherty [8], Syred [9], and Huang and Yang [5]. Different types of VB, as well as periodic oscillations in the flow such as the Precessing Vortex Core (PVC) and the presence of axial-radial vortices, have been identified [9–11].

The size and characteristics of the CRZ and PVC are heavily dependent on the flow properties and velocity profiles at the exit of the nozzle [12–14]. Hallet and Toews [15] succinctly demonstrated experimentally and theoretically the impact the inlet velocity radial profiles have on the onset of flow reversal. Larger recirculation zones have been observed when using a central hub or a diverging fuel nozzle [1]. Seminal flow visualizations by Faler and Leibovich [11] described the dependence of the vortex breakdown phenomena on Reynolds numbers up to 10000 with respect to the nozzle diameter. At their highest tested Reynolds numbers

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Nomenclature

A	cross-sectional area of the fuel nozzle [m^2]
a, b	Fourier polynomial coefficients
CRZ	central recirculation zone
D_N	nozzle diameter
f	generic field (velocity/turbulence)
$\bar{f}$	time averaged field
$\tilde{f}$	coherent/periodic field
f'	total fluctuation field
$\check{f}$	stochastic field
G	axial flux of momentum [N]
ii	total number of vectors in the i direction
jj	total number of vectors in the j direction
K	stochastic turbulent kinetic energy [$m^2\ s^{-2}$]
$\dot{m}$	mass flow [kg/s]
$\dot{m}_{ND}$	non-dimensionalized mass flow
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PVC	Precessing Vortex Core
P_s	static inlet pressure to the combustor
R	nozzle throat radius
S	swirl number
TKE	Turbulent Kinetic Energy [$m^2\ s^{-2}$]
T_s	static inlet temperature to the combustor
u	X-velocity component
V	velocity [$m\ s^{-1}$], bold indicates matrix of all points
V_{ref}	reference velocity for different mass flows [$m\ s^{-1}$]
v	Y-velocity component
w	Z-velocity component
X	axial coordinate along the combustor axis (direction of the bulk flow) [m]
Y	vertical coordinate perpendicular to the combustor axis [m]
Z	horizontal coordinate perpendicular to the combustor axis [m]
χ	eigenvector, bold indicates matrix of eigenvectors
ϕ	POD mode, bold indicates matrix of POD modes
ν^t	turbulent (eddy) viscosity
θ	phase within the period of the coherent fluctuation
τ	Reynolds shear stress
$\mathbf{\Sigma}$	covariance matrix
ξ	generalized coordinate dimension (either X, Y, Z)

Subscripts

k	eigenvector index
n	snapshot index (PIV)
R	radial component
X	axial component
Y	vertical component (perpendicular to axial)
Z	horizontal component (perpendicular to axial)
θ	tangential component

only two breakdown modes, axisymmetric and spiral, were identified. As the Reynolds number was increased, their observations indicated an upstream shift of the recirculation bubble location.

More recently, Terhaar and coauthors [16] have used axial injection to modify the flow profile entering a model combustor and study its effects on the formation and characteristics of the vortex breakdown. They identified a conical type of VB that was triggered at high axial flow injection rates. Carmack et al. [17] have studied radial and axial swirl nozzles used in industrial engines to show the differences in the recirculation bubble and flow characteristics. Strakey and Yip [18] performed isothermal flow field measurements using a representative slot swirler yielding a swirl number of 1.17 and a peak swirl angle of 51°. The authors commented on the unsteadiness and turbulence in the flow, but did not focus on its quantification. Ji and Gore [19] studied the time averaged and instantaneous turbulence and vorticity for an unconfined swirl stabilized flame using a nozzle with a swirl number of 2.4. Their results had limited extent and covered only a portion of the flow field, but provided tremendous insight into the importance of the instantaneous flow and the changes occurring between isothermal and reacting flows.

Notwithstanding, most of the available investigations in the open literature to date have been performed using idealized or representative fuel nozzles that allow for precise control of different geometrical or operating parameters [9,16,18]. The objective of the present investigation is to complement the information on idealized fuel nozzles with steady and unsteady flow field data from a modern industrial fuel injector. The study focuses on the isothermal aerodynamics of the low-emission SoLoNOx® fuel nozzle from Solar Turbines® Inc. Particle Image Velocimetry (PIV) measurements were taken at three different normalized mass flows, one of which was equivalent to the nozzle design point, matching the corresponding inlet Mach numbers. This information is critical for designers using numerical tools and for the validation and development of computational codes. Reynolds-Averaged Navier Stokes (RANS) calculations are routinely used in industry to simulate the flow within combustors. Strakey and Yip [18] have shown however that unsteady RANS models underpredicted the isothermal flow fluctuations. Modeling efforts by Grinstein et al. [20] have focused on predicting swirling flows of practical importance, for which the author stressed that it is critical to rely on accurate velocity radial profiles at the exit of the nozzle. In view of these requirements for the proper modeling of realistic swirling flows within gas turbine combustors, there is still a need to obtain flow and turbulence data for industrial injectors.

To fully understand the unsteady features observed in the flow, the coherent and stochastic temporal components of the flow field were determined by means of a methodology based on Proper Orthogonal Decomposition (POD). In light of the vast amounts of data generated by modern measurements, it is essential to further develop and foment the use of exploratory data analysis techniques that can summarize the available information. Proper Orthogonal Decomposition (POD), also known in different fields as Principal Component Analysis (PCA) or Empirical Mode Decomposition (EMD), is known to be a suitable tool to study coherent structures in turbulent flows [21–25]. Recent work by Lengani et al. [26] have further improved current vortex identification methodologies [22,23] by incorporating a polynomial fit of the velocity fluctuations to better extract the coherent characteristics of the velocity field. These ideas have been recently applied by Berrino and coauthors to study the effects of confinement in a double swirl nozzle [27], proving the potential of the technique to extract the embedded coherent structures in combustor flows and obtain their phase characteristics. Recent interest in alternative uses of POD within the combustion and gas turbine communities include its use for flow validation [28] and structure identification [16]. The present work follows a methodology based on the work by Lengani and coauthors [26] to separate the flow into its mean, peri-