Fuel 139 (2015) 529–536

Contents lists available at ScienceDirect

Fuel

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

Investigations of the effects of spray characteristics on the flame pattern and combustion stability of a swirl-cup combustor

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HIGHLIGHTS

- The effects of gap of nozzle shroud on combustion stability.
- The relationships between spray pattern and the flame pattern, combustion stability.
- Recognition of multi-phase nature of the ignition.
- The flameout when quickly decreasing ΔP_f is induced by sharp change of spray pattern.

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 25 August 2014
Accepted 30 August 2014
Available online 19 September 2014

Keywords:
Combustion stability
Swirl-cup combustor
Ignition
Lean blow-out
Spray pattern

ABSTRACT

An experimental study on both spray and combustion were carried out in order to investigate the effects of gap of nozzle shroud on combustion stability and correlate the spray characteristics with some of combustion performances in a swirl-cup combustor, such as flame pattern, ignition and lean blow-out performances. The performances of ignition and lean blow-out were evaluated in a three-sector combustor in which only the middle dome is operated. Spray analyses were conducted on test sets in a quiescent open-air environment, with measurements of spray pattern by kerosene planar laser induced fluorescence (Kerosene-PLIF) and droplet size by Fraunhofer diffraction techniques. The optimum gap of nozzle shroud for ignition performance is obtained. Based on the droplets spatial distribution in the combustor with recognition of multi-phase nature of the ignition process, the phenomenon that the gap of nozzle shroud has a great impact on the ignition performance was analyzed. Meanwhile, one also analyzed the lean blow-out performance associated with the droplets spatial distribution. By tuning the fuel mixture from ignition condition to the near lean blow-out condition, one found that the lean blow-out performance is less sensitive to the gap of nozzle shroud. Furthermore, CFD simulation results of the flow field under the typical combustor operation conditions were presented and discussed to provide insight into the interaction between air streams from anti-carbon apertures and primary swirler.

1. Introduction

One of the primary requirements of a gas turbine combustor is that combustion must be maintained over a wide range of operating conditions [1,2]. This is especially true for the aircraft combustion chamber which may be operated at low temperatures and pressures, and at fuel/air ratios that lie well beyond the normal limits of flammability for hydrocarbon/air mixtures. In military and commercial aircraft engines, blow-off avoidance during sudden changes in throttle setting is a major design consideration. During rapid decelerations, the fuel flow rate drops very quickly, while the slower airflow transient rate is controlled by the rotational inertia of the compressor. In addition, the unfavorable conditions of low temperature and pressure at high altitudes make relight after a blow-off event very difficult. Emission legislations have motivated current lean, premixed combustor designs, which enhance the risk of lean blow-off.

Swirling flows have been commonly used for a number of years for the stabilization of high intensity combustion processes [3]. The primary role of the swirler is to create an internal recirculation zone, which constructs low velocity regions where the flame can be anchored [4]. The recirculation zone is known to have several beneficial effects to improve the fuel/air stream mixing and increase the turbulent flame speed by augmenting the level of turbulence.

Swirl cup combustor basing on swirl-stabilized combustion has been utilized extensively in modern aero-engine due to its larger

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http://dx.doi.org/10.1016/j.fuel.2014.08.072
0016-2361/

Nomenclature

LBO	lean blow-out	D_{32}	Sauter mean diameter
PLIF	planar laser induced fluorescence	Φ	equivalence ratio
PLS	planar laser scattering	ΔP_{f}	pressure differential of fuel
PTU	programmable timing unit	v_{rf}	the mean velocity across the plane of the maximum cross-sectional area of the casing
CCD	charge-couple device		
FAR	fuel/air ratio		

operating conditions [5]. In the past decades, its excellent combustion performances draw a great number of attentions. Many researchers have focused their studies on the flow field, spray and combustion performance of swirl cup combustors. Wang et al., Fu et al., and Colby et al. studied the effects of geometry parameters on the flow field, including flare geometry, confinement, and swirl angle [6–9]. Becker and Hassa [10] investigated the fuel placement in a swirl cup by planar laser scattering (PLS) method. They found that the fuel placement is governed by the presence or absence of a recirculation zone inside the swirl cup. Ateshkadi et al. [11] studied the effect of swirl vane angle, swirl sense and venturi on LBO performance, and developed a new LBO correlation model accounting for heterogeneous reaction and geometry of mixer component. Stohr et al. [12] studied the dynamics of LBO of a swirl-stabilized flame in a gas turbine model combustor. Their results highlight the crucial role of the flame root for combustion stability in LBO process. They found that well-aimed modifications of flow field or mixture fraction in this region might shift the LBO limit to leaner conditions. However, little work has been undertaken to reveal the mechanisms behind LBO for the swirl-stabilized combustion. Meanwhile, no attempt has been done to study the effects of gap for nozzle shroud on LBO for such systems. There is no rule to obey that how spray characteristics influence the combustion performance for the whole operating range of gas turbine engines. Hence, relating the spray and combustion performances is vital and challenging in the development process of combustors.

The objective of this study is to explore why the gap of nozzle shroud has a significant impact on the combustion stability and flame pattern. The relationship between the spray pattern and flame pattern, combustion stability are obtained by analyzing the measurement results of the spray and combustion experiments. Furthermore, the phenomena of lean blow-out with sharply decreasing the pressure differential of fuel is well explained by variation of spray pattern in this process, which could not be predicted by the LBO correlations in the previous literature [1,10].

2. Experimental setup

2.1. Swirl-cup combustor

Fig. 1(a) schematically shows the swirl cup assembly with pressure-swirl atomizer, counter-rotating swirlers and venturi employed in this study. Pressure-swirl atomizer at the center of the assembly provides primary atomization and generates a hollow cone spray of 90°. Six elliptical tangential primary jets are used to generate the primary swirling stream and a radial secondary swirler with eight curved vanes is utilized to create a counter-rotating stream into the swirl cup. During the spray atomization, the majority of liquid droplets produced by the pressure-swirl atomizer impinge on the venturi which separate the counter-rotating airflows, and create a thin film on the inner surface of the venturi. At the edge of the venturi, the film breaks into ligaments and is immediately introduced into a shear layer generated by the interaction between the counter-rotating streams. The shear layer shatters the ligaments causing fine atomization of the liquid film. Meanwhile, the stronger secondary swirling airflow creates a toroidal recirculation zone within the swirl cup. A small portion of the droplets from primary spray directly flows out of the swirl cup without impingements on the venturi.

The axial relative position between the fuel nozzle and the swirl cup is indicated as $s1$, and the axial relative position between the exit of orifice of fuel nozzle and the swirl cup is denoted as $s2$, seen in Fig. 1(a). The gaps of nozzle shroud is termed as h, seen in Fig. 1(b). There are six anti-carbon apertures used to avoid soot formation on the fuel nozzle.

The detailed information of the test facilities for spray and combustion experiments are given in Refs. [13,14]. The spray characteristics are studied in quiescent open air environment. The combustion experiments (including the ignition and lean blow-out (LBO) performances) are carried out in a three-sector combustor in which only the middle dome is operated, as the fuel-circumferential-staging scheme is used in the ignition process for the combustor. Both of the ignition and LBO experiments are done at a fixed inlet pressure and temperature, with variation of air mass flow rate or reference velocity. Ignition data is obtained when three times of consecutive stable burning after the sparker has been switched off with the maximum sparking time of 10 s. LBO data is obtained by reducing the fuel flow rate gradually at the same air mass flow until flame extinction occurs.

2.2. Optical setup

The optical setup consists of a laser system, a image capturing and processing system, and a controlling system, shown in Fig. 2(a). The laser system with sheet optics produces laser pulses of 8 ns and a thickness of about 1 mm at a repetition rate of 15 Hz. The laser is operated with a 2nd and 4th harmonic generator to produce pulse with energy of 25 mJ and a wavelength of 266 nm. Single-excitation scheme is used for the laser and the camera in Kerosene-PLIF measurements.

The image capturing system consists of an image intensifier, a CCD camera, a lens, an interference band-pass and a long-pass filters which are used to obtain the signal with desired wavelengths, and the induced fluorescence emissions were detected with the CCD camera aligned perpendicular to the laser sheets. The camera is a 12-bit CCD with a resolution of 1376 × 1024 pixels and a framing rate of 10 Hz. In the Kerosene-PLIF setup, the CCD camera was equipped with an image intensifier, a Nikkor UV lens (f = 105 mm), a 266 nm long-pass filter for detecting the induced LIF signals which consist two separated bands respectively in the 270–310 nm and in the 310–420 nm spectral regions. The gate width in the kerosene-PLIF experiments was set to 50 ns.

The whole system is controlled and synchronized by a PC via a programmable timing unit and a software. An intensified relay optics works together with PTU for setting variable exposure time and the gain of the image intensifier.

Sauter mean diameter (SMD or D32) of droplets in the spray is diagnosed by a Fraunhofer diffraction optical instruments, shown in Fig. 2(b), the results of droplet diameter is validated by a standard particle plate, with an error less than ±5%. The line of sight