Fuel 106 (2013) 639–645

Contents lists available at SciVerse ScienceDirect

Fuel

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

Combustion characteristics of swirl coaxial injectors at kerosene-rich conditions

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HIGHLIGHTS

- We studied kerosene-rich, oxygen combustion at chamber pressures up to 6.9 MPa.
- We applied three different bi-liquid swirl coaxial injectors.
- The flow discharge coefficients under combustion are less than the cold flow ones.
- The low-frequency waves around 150 Hz are excited at oxygen subcritical conditions.
- The inherent flow pulsation from the injectors triggers the low-frequency waves.

ARTICLE INFO

Article history:
Received 1 June 2012
Received in revised form 23 October 2012
Accepted 30 October 2012
Available online 15 November 2012

Keywords:
Kerosene
Jet A-1
Fuel Rich
Swirl
Combustion

ABSTRACT

Static and dynamic characteristics of fuel-rich combustion burning Jet A-1 and liquid oxygen have been experimentally studied in the present study. The combustion chamber pressures were varied up to 6.9 MPa with mixture ratios ranging from 0.25 to 0.36. Liquid fuel and oxygen are atomized using bi-liquid swirl coaxial injectors. Flow discharging through the injectors under combustion environment is hindered by flame anchoring at the exit of the oxidizer injector and it can be improved by the increase of the axial momentum of the oxygen flow. The space formed between the fuel and the oxidizer flows significantly affects flow discharging and dynamic characteristics of fuel-rich combustion. At the chamber pressures less than the critical pressure of oxygen, pressure waves at a frequency of 150 Hz are excited and their phases are identical in the combustion chamber. Their excitation is triggered by the inherent low-frequency pulsation of the oxidizer swirl injector with the contraction chamber and eventually, a pressure wave coupled to the Helmholtz mode of the combustion chamber becomes sustaining.

1. Introduction

A power generation system such as a turbopump assembly and an auxiliary power unit requires a subsystem of gas generation for driving the turbines. One of practical approaches for generating high-pressure driving gas is to make combustion take place at a fuel-rich condition. Combustion gas cooled by excessive fuel can satisfy the upper bounds of the temperature limitations withstood by the blades of the turbines. For aerospace application, liquid fuels are used and gas generation devices usually operate at a high temperature greater than the critical temperatures of fuel and oxidizer. Fuel-rich gas generation devices typically consist of a fuel injection device, a mixing chamber and a connecting duct [1]. The mixing chamber associated with the fuel injection device provides unique combustion dynamic characteristics with a relatively high energy density compared to conventional combustion devices. The enclosed chamber space preventing the dissipation of the acoustic energy in the devices also promotes the complexity of combustion dynamic characteristics [2].

Previous studies on the dynamic characteristics of combustion at fuel- or oxidizer-rich conditions are scarce on the public domain. One of a few available literatures about fuel-rich combustion was reported by Dennis and Sanders [3]. They stated that RP-1(kerosene)-rich combustion happened to reveal low-frequency combustion instability when the combustion device operated at low-power levels and elevated mixture ratios (MR, defined as the ratio of the mass flow rate of oxidizer to that of fuel). In the very same experimental setup, Nesman and Dennis [4] observed high-frequency combustion instabilities coupled to the longitudinal resonant mode of the chamber at a chamber pressure of about 3.7 MPa and a mixture ratio of 0.30. They also found that this acoustic coupling was eliminated by the change of the feed line. Mah [5] found the similar results in the experimental work using a gas generator burning nitrogen tetroxide and 50% hydrazine + 50% unsymmetrical dimethyl hydrazine. It was observed that pressure oscillations increase with a decrease of a mixture

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0016-2361/$ - see front matter
http://dx.doi.org/10.1016/j.fuel.2012.10.078

Nomenclature

A	cross sectional area, m^2
a	acoustic speed, m/s
C_d	discharge coefficient
d	diameter, m
f	frequency, Hz
G	geometric constant
l	length, m
$\dot{m}$	mass flow rate, kg/s
n	number of tangential entries
p	pressure, Pa
Δp	pressure difference, Pa
R	radius, m
U	velocity, m/s
V	volume, m^3
Π	transfer function
ρ	density, kg/m^3

Subscripts

c	combustion chamber
cr	critical condition
h	Helmholtz
i	injector post
inj	injector
f	fuel
n	nozzle
o	oxidizer
r	recess
s	swirl chamber
sa	swirl arm
t	tangential

ratio and the low limit of a mixture ratio without pressure fluctuations gets decreased with an increase of a chamber pressure. The recent experimental investigation by the authors of the present paper [6] revealed that Jet A-1 combustion of the fuel-rich gas generator exhibited spontaneous, self-excited, high-frequency combustion instabilities occurring in the vicinity of 330 Hz, which corresponds to one of the longitudinal modes sustaining across both branches of the turbine manifold connected to the combustion chamber of the generator. Flandro et al. [7] also observed steep-fronted waves closely corresponding to the first longitudinal resonant mode of the liquid rocket engine hydrogen-rich preburners and concluded that the waves have characteristics much similar to shock waves.

Fluid dynamic characteristics of bi-liquid swirling cold-flow spray sheets from coaxial injectors have been extensively investigated by Sivakumar and Raghunandan [8]. They experimentally found that a self-sustained periodic process occurs involving the formation and separation of swirling liquid sheets at the low flow rates of the outer sheet. Fu et al. [9] have derived the theoretical modeling for an open-end swirl injector and used the conductance method for experimentally measuring instantaneous volume flow rates out of the injector. They found that the phase difference between the flow fluctuations and the pressure pulsation becomes increased with an increase of the excitation frequency of the flow. Kenny et al. [10] have conducted cold flow tests using a high-pressure vessel and water as a working fluid, and concluded that increase of backpressure, i.e. chamber pressure increases the film thickness inside of the swirl injector and eventually increases its discharge coefficient.

A recent study by Seo et al. [11] showed that combustion efficiency of bi-liquid swirl coaxial injectors highly depends on the recess length of the center oxidizer post, l_r (as described in the right of Fig. 1), and low-frequency pressure fluctuations around 200 Hz were measured when liquid oxygen and kerosene were burning at the mixture ratio of 2.5. The intensities of pressure fluctuations decreased along with the decrease of the recess length. Whether the first impinging location between oxidizer and fuel stays inside of the injector or not dominantly affects the dynamic characteristics identified through the measurement of pressure fluctuations in the chamber. Other results from bi-liquid swirl, fuel-rich combustion burning liquid oxygen and kerosene [6] showed that the dynamic characteristics are greatly differed by whether the chamber pressure is above the critical pressure of oxygen or not. At subcritical conditions, low-frequency fluctuations around 128 Hz appear and dissipate as the chamber pressure increases. Sivakumar and Raghunandan [12] also concluded that the recess length is one of the critical design parameters determining the spray atomization from the cold-water tests. As reviewed so far, the literature on the research of combustion dynamics associated with bi-liquid coaxial injectors especially combusting at fuel-rich conditions is rather scanty even though the information on the liquid fuel/oxidizer interaction and dynamic combustion characteristics with excessive fuel is very crucial for the development of high-pressure gas generation systems required for various power devices.

The objectives of the present study are like the following. First, the flow discharging characteristics of swirl coaxial injectors under kerosene-rich combustion are experimentally investigated with variations of injector dimensions and their operating conditions. Combustion dynamics at nonequilibrium conditions is carefully observed and its behavior is analyzed by help of the measurement of pressure fluctuations to ultimately identify the relations between injector flow dynamics and combustion-induced pressure excitations at chamber pressures around the critical pressure of oxygen with excessive fuel flow three times greater than that of oxidizer.

2. Experiments

2.1. Setup

The experimental combustion device used in the present study consists of the injector head, the combustion chamber and the choking nozzle as shown in the left of Fig. 1. The combustion chamber has an inner diameter of 74 mm and a cylindrical length of 146 mm. The nozzle has a conical shape with a throat diameter of 21 mm. The injector head becomes the most important component of the device since it injects and atomizes the propellants for

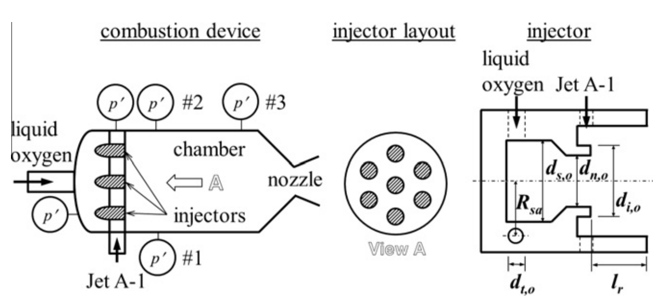

Fig. 1. Cross sectional, schematic views of the chamber (on the left) and the injector, and injector layout (in the middle).