Energy 89 (2015) 158–167

Contents lists available at ScienceDirect

Energy

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

Flameless compact combustion system for burning hydrous ethanol

Cláudia Gonçalves de Azevedo*, José Carlos de Andrade, Fernando de Souza Costa

Associate Combustion and Propulsion Laboratory, Brazilian Space Research Institute, Cachoeira Paulista, São Paulo, CEP 12630-000, Brazil

ARTICLE INFO

Article history:
Received 17 November 2014
Received in revised form
25 June 2015
Accepted 7 July 2015
Available online 6 August 2015

Keywords:
Flameless combustion
Alternative liquid fuels
Biofuel
Hydrous ethanol

ABSTRACT

Environmental concerns and uncertainties in oil supply motivate the development of new combustion technologies using biofuels. Flameless combustion is a promising technology capable of operating with high thermal efficiency, reduced pollutant emissions and low operational costs. This work presents an experimental study of a flameless compact combustion system for burning hydrous ethanol, 96% v/v using a blurry injector to atomize the fuel. Relatively uniform sprays with small droplets and narrow cone angles were obtained, favoring the operation of the flameless combustor. The flameless combustion regime was observed under several operational conditions, through the determination of temperature profiles and flue–gas composition. For a 2 kW thermal input, the flameless regime occurred with excess air coefficients 1.65–2.45, temperatures 690–921 °C, NO_x emissions 2.55–3.08 ppm and UHC (unburned hydrocarbons) emissions 1.43–1.10 ppm. For a 4 kW thermal input, the flameless regime occurred with excess air coefficients 1.21–1.80, temperatures 810–1002 °C, NO_x emissions 1.98–2.16 ppm and UHC emissions 1.53–2.25 ppm. The temperature profiles measured during the flameless regime were relatively homogeneous inside the combustion chamber with very low emissions, compared to the conventional flame regime.

1. Introduction

In the last decades the use of biofuels has had an increasing interest aiming to reduce the environmental impact of combustion processes and the replacement of fossil fuels. Although market demand currently favors the use of pure ethanol and its mixtures with fossil fuels mainly for internal combustion engines [1–4] recently there has also been a growing interest in power generation industry, specially, gas turbines for renewable power generation [5–8]. Gas turbine driven cogeneration plants using bio-fuels can be located close to energy consumption sites, especially for remote areas of developing countries where grid power is not available [9,10].

The interest in improving the performance of power generation systems, aiming to reduce costs, increase operating efficiency and reduce pollutants emissions has driven the combustion community to work on new combustion technologies. Flameless combustion [11], also known as HiTAC (high temperature air combustion) [12,13], MILD (moderate or intense low oxygen dilution) combustion [14] or CDC (colorless distributed combustion) [15], is an effective new combustion technology to obtain high process efficiency for enhancing heat transfer combined with the advantages of low pollutant emissions and low noise combustion.

The technique is based on high internal flue gas recirculation by high momentum injection of the reactants [16–18]. The flue gas recirculation reduces the oxygen concentration in the flame zone, due to previous mixing between the oxidizer and the combustion products, and increases the temperature of the fresh reactants, creating a mixture in ignition condition distributed throughout the volume of the combustor [19]. This reduces the rates of the oxidation reactions, providing spatially wider distributed heat release and avoiding high peak temperatures. When the local temperature is above the auto ignition temperature of the mixture, a diluted homogeneous volumetric combustion mode is established, with the reaction zone almost invisible and uniformly distributed throughout the volume of the combustor [20,21]. The highly distributed reaction zone eliminates hot spots, resulting in a heat release spread out and at the same time in a far more uniform temperature distribution throughout the combustion region. Flameless combustion technology has been demonstrated to provide significant benefits for industrial and power systems, such reduced fuel consumption, stable and efficient combustion, reduced pollutant emission, homogeneous temperature field, low

* Corresponding author.
E-mail address: claudia@lcp.inpe.br (C.G. de Azevedo).

http://dx.doi.org/10.1016/j.energy.2015.07.049

noise combustion and reduced species concentration gradients [11,22–25].

Several studies have been performed to evaluate performance of gaseous fuels for flameless combustion applications [11–28], but little attention was given on the behavior of liquid fuels combustion in flameless condition [29–36], despite a significant number of industrial combustors being operated with liquid fuels. The development of specific flameless combustion systems for burning liquid fuels presents additional technological challenges, since the combustion of liquid fuels involves many complex processes such as atomization, dispersion and vaporization of the fuel and mixing of the fuel and gaseous oxidizer [37].

This paper describes a flameless biofuel combustion system with 2 and 4 kW thermal inputs (based on fuel mass flow rate and LHV (lower heating value)) for burning hydrous ethanol, 96% v/v atomized by a blurry injector. This novel twin fluid atomization technique exploits the advantages of internal and external mixings, and presents several advantages over other injectors, such as formation of a relatively uniform spray, high atomization efficiency, robustness, excellent fuel vaporization and mixture with air [38,39]. The flameless regime was characterized by measurements of spatial distributions of temperatures and flue–gas composition (UHC (unburned hydrocarbons), CO_2, NO_x and CO).

2. Experimental setup

Fig. 1 shows a schematic diagram of the combustor and dimensional details of the burner and blurry injector. The combustion chamber is a stainless steel cylinder with inner diameter of 101 mm and length of 330 mm, with a vertical Robax© ceramic glass window (35 × 200 × 5 mm) to optical access, allowing visualization of the chamber interior and verification of changes in the reaction zone, thus indicating the formation of a visible flame or, with the additional support of temperature distribution and flue–gas composition measurements, the existence of the flameless regime.

As seen in Fig. 1, the burner has an injection section (detail B) where the blurry injector (detail A) is located. The injector has exit orifice and fuel tube diameters of 0.5 mm and the distance from the fuel tube tip to the exit orifice is 0.125 mm. The fuel and atomization air are supplied to the injector by concentric tubes. Atomization air and fuel mix within and at the exit of the fuel tube before exiting through the orifice plate to form the spray downstream.

The injector is surrounded by 8 orifices of 1.5 mm inner diameter each, through which the combustion air is supplied. These orifices are concentrically positioned around the central jet fuel on a circle with inner diameter of 30 mm (detail B). The combustion air is preheated by recovering heat from the flue gases that pass through 8 orifices of 12 mm at the top of the injection section, by a coil tube (section A–A) at the injection section, yielding inlet air temperatures up to 530 °C, which are monitored using a type K thermocouple installed at the entrance of the burner. The burner is placed at the bottom of the combustion chamber and the flue gases are extracted at the top of the chamber through a duct with diameter of 45 mm and length of 100 mm. During the tests, the combustion chamber was insulated with a 30 mm thick ceramic blanket to minimize the heat losses to the environment.

Fig. 2 shows a schematic diagram of the experimental apparatus. Liquid fuel (hydrous ethanol) is stored in a pressurized steel tank at 5 bar. A ball inlet valve and a calibrated rotameter with an accuracy of ±5% and repeatability of ±0.5% were used to control the fuel mass flow rate. Compressed air supplied by a high-pressure cylinder was used to atomize the fuel. A needle valve and a calibrated flow meter with accuracy of ±1.5 slpm were used to control the air mass flow rate.

The combustion air was supplied by an air compressor. The combustion air flow rate was controlled by a manual valve and was measured upstream of the combustor by a rotameter with an uncertainty of ±2% slpm. Supply pressure in the fuel and air combustion lines were measured using pressure transducers at locations depicted in Fig. 2. The combustor was initially ignited by a spark-plug and run with hydrous ethanol-air mixture, establishing a stable flame with rich conditions. At the beginning of the experiments the combustion chamber was preheated for about 1 h and 40 min, operating in the conventional visible flame mode. The flameless burning regime transition occurred when the chamber temperature was above the self-ignition temperature of the fuel–air mixture, from about 635 to 735 °C, for a 2 kW power input, and from about 655 to 790 °C, with 4 kW power input, for the different air excess coefficients.

Flue–gas composition data (CO_2, UHC, CO, and NO_x) were withdrawn at the exhaust duct using an iso-kinetic, water-cooled stainless steel probe. Exhaust gas composition was determined using paramagnetic analyzer for O_2 measurements (0–20% range, 0.2% accuracy), non-dispersive infrared gas analyzers for CO_2 (0–20% range, 0.2% accuracy) and CO (0–1% range, accuracy ±0.001%) measurements, a flame ionization detector for UHC measurements (0–300 ppm, ±3% accuracy) and a chemiluminescence analyzer for NO_x measurements (0–100 ppm, ±0.5% accuracy). Several ports for temperature measurements were available along the height of the combustion chamber, in order to obtain the axial and radial temperature profiles inside the chamber. Temperature measurements were made with type K mineral insulated thermocouples (diameter 1.5 mm), with maximum measured temperature range of 1300 °C (accuracy ±0.1%). Continuous online measurements of the sample gas composition and temperatures were carried out during tests.

3. Results and discussion

3.1. Spray characteristics

The combustion of liquid fuels depends on the effective atomization in order to promote vaporization, mixing and combustion with maximum efficiency within the chamber volume and produce low emissions. Besides, in the case of flameless combustion of a liquid fuel it is necessary to obtain a rapid and uniform vaporization and mixing of fuel and oxidant, therefore it is important to determine the characteristics of hydrous ethanol sprays produced by a blurry injector. For the current experiments the blurry injector described by Ref. [39] was used, since it produces a relatively uniform spray with small droplets and the number of geometric parameters influencing the droplet formation is limited. The flameless combustion system was tested for 2 and 4 kW thermal input (based on fuel mass flow rate and LHV) and heat release densities of 0.76 and 1.52 MW/m^3, respectively. A laser diffraction system (Malvern Spraytec©) was used to measure the mean droplet diameter with accuracy of ±1% of full scale. In combustion technology, the average diameter most commonly utilized to characterize liquid fuel sprays is the SMD (Sauter Mean Diameter). Measurements were taken along the centerline of the spray cone at a distance of 50 mm below the exit of the injector, since the characteristic diameters were approximately constant from 40 to 70 mm. Table 1 presents the spray characteristics for the test conditions used in this study.

The droplet size distribution in sprays is needed for analysis of the transport of mass, momentum and heat in combustion systems [40]. The Rosin–Rammler size distribution is given by Ref. [41]: