Applied Energy 88 (2011) 2925–2933

Contents lists available at ScienceDirect

Applied Energy

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

Combustion characteristics of a swirling inverse diffusion flame upon oxygen content variation

H.S. Zhen, C.W. Leung *, C.S. Cheung

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China

ARTICLE INFO

Article history:
Received 6 September 2010
Received in revised form 28 February 2011
Accepted 28 February 2011
Available online 25 March 2011

Keywords:
Inverse diffusion flame
Induced swirl
LPG/air combustion
Oxygen enrichment
Oxygen depletion

ABSTRACT

The combustion characteristics of a swirling inverse diffusion flame (IDF) upon variation of the oxygen content in the oxidizer were experimentally studied. The oxidizer jet was a mixture mainly composed of oxygen and nitrogen gases, with a volumetric oxygen fraction of 20%, 21% and 26%, and liquefied petroleum gas (LPG) was used as the fuel. Each set of experiment was conducted with constant oxygen content in the oxidizer. When the oxygen was varied, the changes in flame appearance, flame temperature, overall pollutant emission and heating behaviors of the swirling IDF were investigated. The swirling IDFs with different oxygen content in the oxidizer have similar flame structure involving a large-size and high-temperature internal recirculation zone (IRZ) which favors for thermal NO formation, and the thermal mechanism dominates the NO production for the swirling IDFs. The use of nitrogen-diluted air (with 20% oxygen) allowed the IDFs to operate at lower temperature with reduced NO_x formation, compared to the case of air/LPG combustion (with 21% oxygen). Meanwhile, an increase in CO emission is observed. With oxygen-enriched air (26% oxygen), the increase in temperature and $EINO_x$ under lean conditions is more significant than under rich conditions. With 26% oxygen in the oxidizer stream, the IDF produces: (1) a shorter and narrowed navy-blue flame ring located closer to the burner exit, (2) highly luminous yellow flame extending into the central IRZ and above the blue flame ring, (3) a low CO emission, especially under lean conditions, (4) an increase in temperature at low Φ while a decrease in temperature at high Φ, and (5) an increase in $EINO_x$ at all Φ. The heating test using the swirling IDFs in flame impingement heat transfer reveals that the heating rate can be monotonically increased as oxygen content in the oxidizer jet increases under the lean condition ($\Phi = 1.0$). The oxygen enrichment does not contribute to the heating rate under the rich condition ($\Phi = 2.0$), because for the non-premixed combustion of an IDF, the enrichment in oxygen means a lower oxidizer jet Reynolds number and thus less complete combustion occurs as a result of reduced amount of entrained ambient air.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The increasingly stringent air quality rules have pushed research efforts towards development of combustion devices with low pollutant emission and reduced fuel consumption. Unfortunately, the lean and ultra-lean premixed combustion burners developed for this purpose suffer from the delicate issues related to flashback and flame stability [1,2]. These two issues could be overcome by using swirling flows in inverse diffusion flames (IDFs). Due to the absence of air/fuel mixing upstream of the reaction zone in an IDF, there is no danger of flashback and the swirl-induced recirculation provides regions where the flow velocity and the flame speed can be matched, hence the flame stability could be improved [3].

For gas combustion, the primary environmental concerns are related to NO_x emission and CO emission [4]. NO_x is a pollutant which could result in acid rain and depletion of ozone in the stratosphere, while CO is a pollutant which presents a hazard to human health. Miller and Bowman [5] provided a comprehensive review of the mechanisms that affect NO formation, and showed that for fuels without bound nitrogen, the three most important pathways for NO formation are: the thermal or Zeldovich mechanism, the prompt or Fenimore mechanism and the N_2O-intermediate mechanism. However, in non-premixed combustion of hydrocarbons, the first two mechanisms are responsible for the majority of NO formed [6]. As for CO emission, it is generally accepted that CO is an intermediate combustion product which will get oxidized into CO_2, provided enough oxygen is available at relatively high temperature [4]. There have been some studies performed on NO_x and CO emissions of non-swirling IDFs [7,8] while those on swirling IDFs are scarce [9]. The study [9] investigated a highly swirling IDF and revealed that the thermal mechanism plays a leading role in NO_x formation because the presence of a large-size and high-temperature internal recirculation zone (IRZ) favors thermal NO

* Corresponding author. Fax: +852 23654703.
E-mail address: mmcwl@polyu.edu.hk (C.W. Leung).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.02.041

Nomenclature

Re	Reynolds number	$\dot{q}$	local heat flux, kW/m^2
Φ	jet equivalence ratio	R	radial distance from the burner axis, m
Z	vertical distance from the burner rim, m	$\dot{Q}_{fuel}$	volumetric flow rate of LPG, m^3 s^{-1}
H	nozzle-to-surface distance, m	ρ_{fuel}	density of LPG, kg m^{-3}
EI	emission index, g/kg	LHV_{fuel}	lower heating value of LPG, J kg^{-1}

production. In comparison with the non-swirling IDF, the swirling IDF is superior in the flame stability and has much lower NO_x emission under lean combustion condition. The study [9] pointed out that strong swirl and lean combustion are the two key factors for reducing NO_x emission of the swirling IDF, but the reduction in NO_x emission is inevitably associated with an increase in CO emission. Since the study on the emission characteristics of swirling IDFs is so few, therefore this study, as the continuation of the former paper [9], aims to investigate where and under which conditions nitric oxide is being formed in the swirling IDF when the oxygen content in the oxidizer jet is varied.

Oxygen-enhanced combustion (OEC) has been widely used as a useful energy-saving technology in industrial combustion systems. The benefits of OEC over conventional air-fired combustion include increased temperature and thermal efficiency, reduced fuel consumption and improved flame stability [10]. Beltrame et al. [11] examined an oxygen-enriched counter-flow diffusion flame and reported that oxygen enrichment significantly enhances the flame temperature and changes the relative contributions of the thermal and prompt mechanisms in NO formation. Wu et al. [12] studied the influence of 21–30% oxygen concentration on the heating rate, emissions, temperature distributions, and fuel consumption for a non-premixed flame. They observed a more rapid heating rate and less fuel consumption as the oxygen concentration increases. Higher oxygen concentration yields higher flame temperature and hence the NO_x emission is increased. Moreover, the NO_x emission is more sensitive to the excess oxygen at higher oxygen levels. There are still other studies on non-premixed systems utilizing OEC [13–15]. However, most of the previous studies are on non-swirling flames and no effort has been made to understand the oxygen-enhanced combustion characteristics of swirling flames. Keeping this in mind, the effects of oxygen enrichment on a swirling IDF burning LPG will be experimentally investigated in this study. On the other hand, for the purpose of taking full advantage of swirling IDFs in combustion devices to achieve low pollutant emission and reduced fuel consumption, it is required to understand the combustion characteristics of swirling IDFs when the oxygen content in the oxidizer jet is smaller than that in air-fired combustion. Therefore, three swirling IDFs with oxygen content of 20%, 21% and 26%, respectively, are utilized in this work to investigate their combustion characteristics. At different oxygen content, the changes in flame appearance, flame temperature and overall pollutant emission are examined. The heating test is made by the application of the three IDFs in flame impingement heat transfer and the differences in the heating behaviors of the IDFs are also studied.

2. Experimental apparatus and techniques

Details of the burner for generating the swirling IDFs in this study are well documented in Ref. [9] and thus only a brief description is given here. Fig. 1 shows a schematic of the swirl burner, which consists basically of a swirl chamber, followed by a contracted throat and ending in a divergent outlet. Oxidizer gas enters the swirl chamber from two tangential inlets to induce a rotational motion. The swirling oxidizer gas then flows into the contracted throat and finally ejects out of the divergent outlet. The burner has a geometrical swirl number of 9.12. The 12-mm-diameter oxidizer port is evenly surrounded by twelve 2.4-mm-diameter fuel ports. The main feature of the swirling IDFs produced on this burner is the presence of an internal recirculation zone (IRZ) [9]. Standard liquefied petroleum gas (LPG: 70% C_4H_{10} and 30% C_3H_8) available in Hong Kong is used as the fuel. The jet equivalence ratio (Φ), based on the supplied fuel and oxidizer flow rates is adopted and the oxidizer jet Reynolds number (Re) is used to feature the aerodynamics of the flame.

The experimental setup is shown in Fig. 2a. The fuel and oxidizer flows were stabilized and monitored by calibrated flowmeters. The burner was placed on a 3-D positioner which could locate the burner at any position in space. A digital CCD camera with a shutter speed of 1/60 s was employed to record the visible flame in a dark background. A visualization technique was used to observe the flow field [9]. It was achieved by inserting a small, thin wooden rod into the flame to dye the fluid color to yellow. The small yellow blaze introduced by combusting the rod followed the mainstream and acted as streaklines. Thus, the local flow fields were visible to the naked eyes and the direction of the local flow could be identified.

An uncoated type B thermocouple was used to measure the flame temperature. The thermocouple wires have a diameter of 0.25 mm and their joint bead is smaller than 0.5 mm in diameter. Such size is small enough to reduce the error caused by thermal conduction but big enough to keep the rigidity of the thermocouple. The swirling IDF is axis-symmetrical, thus along the flame centerline and at five axial distances of Z = 6, 12, 30, 60 and 96 mm above the burner rim, a total of five temperatures were obtained for each operating condition of the flame. All the recorded temperatures were corrected according to the bare-bead thermocouple model of Blevins and Pitts [16]. The maximum value in correction is 150 °C at the directly measured temperature of 1634 °C.

The overall pollutant emission was acquired by flue gas measurement. The emission indices of NO_x and CO were calculated from the measured data. A stainless steel hood of 15 cm base-diameter and 15 cm in height was used to collect exhaust products in the post-flame region. Water vapor was condensed and removed

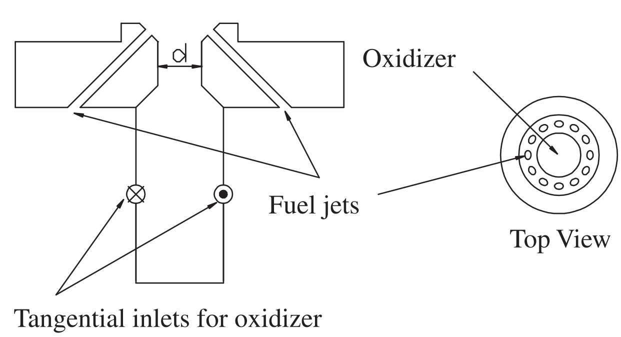

Fig. 1. Swirl burner.

Download English Version:

https://daneshyari.com/en/article/243763

Download Persian Version:

https://daneshyari.com/article/243763

Daneshyari.com