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Effects of oxidizer flexibility and bluff-body blockage ratio on flammability limits of diffusion flames

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HIGHLIGHTS

- Experiments on air, O_2-enriched-air and oxy-flames anchored over bluff body.
- Stability limits, visual appearance and extinction limits of these flames are quantified.
- Effect of blockage ratio on flammability limits are presented for the three oxidizers.
- Emissions are characterized for the three different flames.
- Experiments were performed considering wide ranges of operating parameters.

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ABSTRACT

Concerns about global warming have encouraged the interest in hydrocarbon combustion techniques that allow easy capture of carbon dioxide. One technique for achieving this objective is through the use of pure oxygen instead of air for combustion or what is called oxy-combustion carbon capture technology. The main goal of the manuscript is to study flammability limits, visual flame appearance and exhaust emissions of diffusion flame stabilized over a bluff body over ranges of operating and design conditions. The operating conditions include flow Reynolds number, equivalence ratio and oxidizer composition. The design parameter considers the change of blockage ratio (BR) of the bluff body namely, BR = 0.36, 0.5, 0.67 and 0.82. Based on this, three sets of experiments were performed utilizing compressed natural gas (CNG) as a fuel to be burned with three different oxidizers including air, oxygen-enriched-air and oxy-fuel mixtures (O_2 plus CO_2 with a controlled oxygen fractions, OF). The three sets of experiments were performed to identify ranges for stable flame operation considering different oxidizers under different operating conditions. Stability limits, visual flame appearance and extinction limits of these flames are quantified and analyzed. Furthermore, three different regions were observed; precisely, jet flames, central-jet dominated flames and recirculation zone flames, depending on the ratio between oxidizer and fuel momentum. The flame color changed from yellow for air combustion, to bright white for oxygen-enriched-air combustion and finally to blue with yellow tips for oxy-combustion. The flame length was the highest for air combustion, then lower for oxy-combustion and the lowest for oxygen-enriched-air combustion. This was attributed to the effect of oxygen-enrichment which results in increase in the flame speed making flame length shorter. For the sake of comparison, the flammability limits of the three sets were reported and the results revealed that oxygen-enriched-air-flames have higher stability than air-flames and oxy-flames, respectively.

1. Introduction

The use of oxy-combustion technology for CO_2 capture is a promising technique to reduce CO_2 emissions. In this technique, pure oxygen can be used as an oxidizer rather than air to avoid nitrogen in the combustion chamber [1]. This technique enables

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Nomenclature

CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
HC	hydrocarbons
D_1	burner inner diameter
D_2	burner outer diameter
D_3	bluff body outer diameter
BR	blockage ratio, the ration between the outer diameter of the bluff body and the outer diameter of the burner body
D_4	confinement diameter
O_2	oxygen
OF	oxygen fraction, percentage of oxygen in the oxidizer mixture of O_2 and CO_2
R_o	confinement outer radius

the exhaust stream to be separated into concentrated CO_2 and water vapor. The water vapor can be removed by a simple condensation process leaving a high concentration CO_2 stream that can be easily captured. However, burning pure oxygen is unpractical due to the resulting extremely high flame temperature [2]. For this reason, the oxygen is normally diluted with a steam of CO_2 in order to control the flame temperature. One of the advantages of this combustion technique is the expected significant reduction in thermal NOx emissions. Fuel NOx, however, may not decrease if the fuel has significant nitrogen content [3]. This technique has been proposed for slight modifications of existing gas turbine combined cycles [4] or completely new concepts [5,6]. A review by Yin and Yan [7] was conducted on the fundamentals and modelling of the oxy-fuel combustion of pulverized fuels. The review illustrates the promising importance of the pulverized fuels for CO_2 capture from power plants and discussing the concerns, developments and recent studies in the past years. Tan et al. [8] examined an oxy-fuel circulating fluidized bed combustion as an alternative technology to oxy-fuel pulverized combustion that has many advantages that can exceed the prediction of the normal oxy-fuel pulverized technology for CO_2 capture. They reported results of stable oxy-fuel combustion up to 90% of CO_2 introduced in the combustion process on a dry basis. Hu and Yan [9] investigated the characterization of flue gas in oxy-coal combustion process for CO_2 capture. The economic effective and technical viability for CO_2 capture process by using characterization of the flue gas recirculation, FGR, was conducted for an oxy-coal combustion process. The study showed that increasing the O_2 (oxidizer) from 20% to 35% by Volume results in reducing the FGR rate by approximately 58%. Furthermore, the FGR rate changes linearly with the oxygen concentration. The results revealed some useful references for existing power plants efficient optimization and for future designed power plants. In a further numerical study conducted by Hu et al. [10], the heat transfer characteristics in utility boiler of oxy-coal combustion was investigated. They highlighted that the O_2 concentration of 33% in oxy-coal combustion acts in a similar manner to the air–coal combustion cases in terms of achieving the same highest flame temperature and total heat transfer rate through boiler walls. In addition, it was shown that the increase of the moisture content in flue gas has a small impact on the flame temperature.

The current work investigates the combustion characteristics of confined diffusion CNG flames under different oxy-combustion conditions (different mixtures of CO_2 and O_2) and compares the results with the cases of combustion using other oxidizers including pure air and oxygen-enriched-air. The work covers flame appearance and stability limits. It should be noted that $CH_4/O_2/CO_2$ (oxy-combustion) flames are characterized by slower chemical kinetics than methane–air flames. Equilibrium CO emissions in CO_2 diluted systems are much higher than in corresponding air systems. In addition, pipeline specifications in carbon sequestration applications impose limitations on CO and O_2 levels [11]. In the context of CO emissions, Oh et al. [12] studied the effect of CO addition on the flame characteristics of a non-premixed (diffusion) oxy-methane flames in a lab scale furnace. This experimental study showed that, as the CO concentration decreased, the more the flame is stable, the flame length becomes higher as CO is diluted. Yewn et al. [13] compared the structure of three diffusion flames utilizing natural gas (NG) as a fuel with three different oxidizers including oxidizer A (air, 21 vol.% O_2 and 79 vol.% N_2), oxidizer B (28 vol.% O_2 and 72 vol.% CO_2) and oxidizer C (enriched air, 28 vol.% O_2 and 72 vol.% N_2). The study showed the variation of centerline temperature with distance from the burner tip for all oxidizers. The results revealed that the temperature of enriched air flame is higher than other flames. Also, it was indicated that the concentrations of NO and CO in O_2/CO_2 flame are lower than other flames. Nemitallah et al. [14–16] studied experimentally and numerically diffusion oxy-combustion flames in different combustors. They reported that the stability of oxy-fuel combustion flames is adversely affected when the operating oxygen fraction reduced below 25%. Ramadan et al. [17] studied the stability of $CNG/CO_2/O_2$ flames and compared the results with CNG/air and $CNG/air/O_2$ flames anchored over a bluff body under atmospheric conditions. They observed no lower limits of the flammability due to the use of non-premixed flames. They quantified and explained the dependence of the upper flammability limit on oxygen fraction, fuel and oxidizer momenta and bluff body blockage ratio. The characteristics of oxy-oil combustion in an existing furnace were experimentally investigated by Chi and Lin [18]. This experimental study examined the operability of an existing 300 kW air–oil furnace to be adapted with oxy-oil combustion. They investigated the effect of oxygen enrichment in the range from 21% (air) up to 100% while using the FGR system in the retrofitted furnace. They claimed that the existence of air leakage to the systems would decrease the CO_2 concentration in the flue gases. The study reported that the CO_2 concentration increases as the oxygen fraction increases from 13% to 34.4% at the atmospheric pressure and from 14.7% to 61.1% for the pressurized combustion. The shifting from air to oxy-fuel did not bring adverse effect to the flame stability.

A recent experimental investigation by Rashwan et al. [19–21] studied the combined effect of flame premixing and oxy-combustion on flame stability and compared the results with the cases of normal air combustion. They reported a range of oxygen fraction, from 29% to 40%, over which the flames are stable. Also, they reported that the air–fuel combustion has wider range of flame stability than oxy-fuel combustion due to the adverse effect of introducing the CO_2 into the combustion process. Furthermore, they claimed that increasing the oxygen fraction compensates the negative effect of CO_2 until the burner could work similar to air–fuel combustion at oxygen fraction of 42%. Ditaranto and Hals [22] revealed from their experiment that oxy-combustion requires