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Combustion characteristics of methane–oxygen enhanced air turbulent non-premixed swirling flames

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ABSTRACT

Application of oxygen-enhanced combustion to existing fossil fuel energy systems to facilitate CO_2 capture presents several challenges. This work investigates the combustion characteristics of methane oxygen enriched air turbulent non-premixed swirling flames. It focuses on the stability of flames, NO_x, CO_2 and CO emissions and the flow field dynamics. The burner configuration consists of two concentric tubes with a swirler placed in the annular part for the oxydant. The experiments are conducted using a 25 kW water cooled combustion chamber. The exhaust gas compositions are measured using gas analyzers. OH chemiluminescence experiments are conducted to investigate the structure and the stability of the flames without and with oxygen enrichment. Flame liftoff heights, fluctuations of the flame base and flame lengths are determined. Particle Image Velocimetry is used to analyze the dynamics of swirling flows. The measurements are performed for oxygen concentrations ranging from 21% to 30% by volume, with swirl numbers from 0.8 to 1.4 and global equivalence ratios from 0.8 to 1. The results show that the addition of oxygen to air, while keeping the oxidant flow rate constant, enhances the combustion efficiency and flame stability. It is observed that increasing oxygen concentration leads to lower lift-off heights and reduces flame height fluctuations. Increasing the swirl number significantly improves the flame stability. The results demonstrate that the CO_2 emissions in the exhaust gases linearly increase with increasing O_2 content in the oxidant. The CO emissions are shown to decay exponentially, whereas the NO_x emissions, mainly produced through the thermal pathway, increase strongly with oxygen enrichment. The PIV results illustrate that increasing the swirl intensity increases the reverse flow velocities close to the burner exit. The decay of axial velocity presents favorable flow patterns for the stabilization of the flame.

1. Introduction

Accounting for roughly 80% of the world primary energy production, fossil fuel combustion results in the emission of large quantities of CO_2 such that it is a significant source of global warming and climate change. Fossil fuels will remain dominant in the global energy mix for the next two decades [1]. According to the International Energy Agency (IEA), no more than one-third of proven reserves of fossil fuels should be consumed prior to 2050 in order to limit global warming to less than 2 °C [2]. As a result, the power and heat generation industry is under increasing pressure to cut its CO_2 emissions. Improvement in combustion efficiencies and switching from coal to natural gas could be possible short term measures to reduce CO_2 emissions. However, numerous Carbon Capture and Sequestration (CCS) strategies and technologies should be widely deployed to reduce the greenhouse gases in the long term. Basically, three major CO_2 capture concepts can be identified: post-combustion capture, oxy-combustion processes and pre-combustion decarbonisation processes [3–6]. Realistic oxy-combustion systems integrated into industrial systems, such as Natural Gas Combined-Cycle (NGCC) plants, where power consumption for oxygen generation imposes a total thermal efficiency penalty up to 10 points [7]. An alternative less energy consuming approach is oxygen enrichment of air which refers to oxygen concentrations ranging from 21% to 90% [8].

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One of the promising applications of oxygen-enriched air combustion is to increase the CO_2 concentration in burned gases and subsequently to improve the efficiency of CO_2 capturing physical processes as described by Favre et al. [9]. The authors assessed a simulated hybrid process combining an oxygen enrichment step, and a CO_2 capture step by membrane permeation. It is shown that the hybrid process can lead to a 35% decrease of the energy requirement compared to oxy-fuel combustion. Another important effect of oxygen enrichment is to increase flame temperature which is beneficial to enhance radiative heat transfer in flames for industrial process applications. Wu et al. [10] observed a decrease of 26% fuel consumption rate when oxygen enrichment varies from 21% to 30% while keeping the furnace temperature constant around 1220 °C. But Zhou et al. [11] reported that oxygen enrichment significantly enhances the thermal NO_x formation as mentioned also by Song et al. [12].

Swirling flow burners are not only used in gas turbines, but also in industrial furnaces because of their significant beneficial influences on flame stability [13–15], combustion intensity [10,16], local mixing [17,18], and pollutant emissions as the NO_x [19–22]. Cozzi and Coghe [18], studied a burner configuration including a swirler for the air flow and examined the influence of air staging on NO_x formation. They compared an axial and a radial fuel injection into the secondary air. They concluded that a radial injection allows a faster centrifugal mixing. Cheng et al. [23] observed that increasing the level of premixing by a swirler decreases the flame length in the case of partially premixed swirling flames. They also noticed a minimum of NO_x and CO emissions for a given optimum level of premixing in swirling flames.

Few works investigated the combustion characteristics of methane combustion in oxygen enhanced air for turbulent non-premixed flames in a practical burner configuration including a swirler. For instance, Zhen et al. recently studied the characteristics of oxygen enriched inverse diffusion swirling flames [24]. They investigated the changes in flame appearance, flame temperature, overall pollutant emission and flame impingement heating rate for a LPG flame. Li et al. [19] studied a low swirl burner, swirl number of 0.4, with oxygen enrichment conditions from 21% to oxy-fuel flames with CO_2 dilution. They measured O_2, CO, and NO_x emissions in the exhaust gas. They found NO_x emissions sharply increase with O_2 addition and reach more than 300 ppm for 35% of O_2 in the oxidizer. From the fuel saving aspect, they found that oxy-fuel burners should be run with a global equivalence ratio of less than 0.95 for $CH_4/CO_2/O_2$ flames. Some studies included the characterization of non-reacting and reacting swirling flow fields to better understand the interactions between rotating flows and the flame [25–30]. For instance, Kremer et al. [29] investigated in details the turbulent velocity field above the TECFLAM burner with a swirl number of 0.95. They observed that the internal reverse flow zone acts as an intensive turbulent mixing process, favorable for the mixing of recirculating hot burned gas products and possible non-stable intermediate products of the reaction. Olivani et al. [25] emphasized the influence of radial or axial fuel injection into a swirling air flow on the mixing close to the burner exit.

The objective of the current investigation is to characterize the effects of oxygen enrichment on the combustion characteristics of methane–air turbulent non-premixed swirling flames. The OH chemiluminescence technique is used to indicate the instantaneous flame reaction zone and thereby to characterize the flame stability. Lift-off position and flame length for several configurations of burner are measured. The study of dynamic field is carried out by the PIV technique for non-reacting flow. Pollutant emission measurements, such as CO, CO_2 and NO_x, are performed by gas analyzers using a sampling probe.

2. Experimental setup

2.1. Burner, combustion chamber and operating conditions

The burner configuration consists of two concentric tubes with a swirler placed in an annular part for the oxidant flow (air or oxygen–air) as shown in Fig. 1. The central tube delivers the methane through eight holes symmetrically distributed on the periphery of the pipe, just below the burner exit plane. The radial injection of fuel is used to enhance mixing at the near field of the burner exit.

The degree of swirl for rotating flows is usually characterized by the nondimensional swirl number S_n. S_n represents the ratio of the axial flux of tangential momentum G_θ and axial flux of axial momentum G_x [31]:

$$S_n = \frac{G_\theta}{G_x R} \tag{1}$$

Eight guide vanes are designed with various vane angles to induce swirl intensity variations. The geometrical swirl number S_n related to this configuration is defined as [31]:

$$S_n = \frac{1}{1-\psi} \cdot \left(\frac{1}{2}\right) \cdot \frac{1-(R_h/R)^4}{1-(R_h/R)^2} \tan\alpha_0 \tag{2}$$

where ψ is the blockage factor and α_0 is the vane angle, R and R_h are nozzle and vane pack hub radii respectively. The swirler position above the burner exit plane is indicated by h.

The experiments are conducted with a square cross-section 25 kW chamber of $48 \times 48\ \text{cm}^2$ and 1 m in height (Fig. 2) operating at atmospheric pressure. The walls of the combustion chamber are water cooled on the outside and refractory-lined inside. It is noticed that increasing oxygen enrichment from 21% to 30% in burning conditions increases the flue gas temperature from 450 °C to 650 °C at the chamber exit. The chamber ends with a convergent section of 20 cm height and a final circular section of 10 cm diameter in order to limit the air intake from the top. Six windows are placed in each face of the chamber, allowing optical access to all the potential flame zones.

A global equivalence ratio, Φ, can be defined as the molar ratio of methane and oxidant at injection to the molar ratio of methane and oxidant in stoichiometric conditions, as:

$$\Phi = \left(\frac{V_{CH_4}}{V_{O_2,\text{oxidant}}}\right) \bigg/ \left(\frac{V_{CH_4}}{V_{O_2,\text{oxidant}}}\right)_{\text{stoichio}} \tag{3}$$

where V is the volumetric flow rate.

An oxygen–air mixture is employed as the oxygen-enriched oxidizer flow. Mass flow rates of air, oxygen and fuel are regulated by thermal mass flow controllers (Brooks SLA5851S).

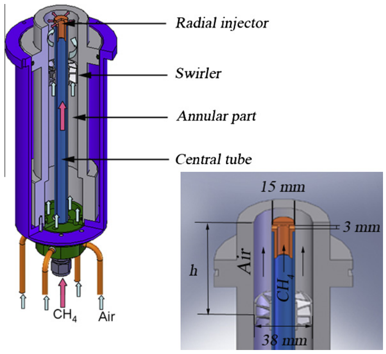

Fig. 1. Coaxial swirl burner.