Combustion of a hydrogen/carbon monoxide/carbon dioxide mixture in hot and diluted streams

A Cardona-Vargas1, D Valencia2, C E Arrieta3, and A Amell4
1 Grupo de Investigación de Materiales Avanzados y Energía, Instituto Tecnológico Metropolitano, Medellín, Colombia
2 Facultad de Ingeniería, Universidad de Antioquia, Medellín, Colombia
3 Grupo de Investigación en Energía, Universidad de Medellín, Medellín, Colombia
4 Grupo de Ciencia y Tecnología del Gas y Uso Racional de la Energía, Universidad de Antioquia, Medellín, Colombia

E-mail: arleycardona5670@correo.itm.edu.co

Abstract. This work presents an experimental investigation on the combustion behavior of a mixture of hydrogen, carbon monoxide and carbon dioxide in hot and diluted streams, like those obtain under flameless combustion regimes. A jet in a hot coflow burner was used to carry out the experiments. This burner consists of a central fuel jet surrounded by a combustion products stream, which comes from a premixed flame under lean conditions. In this way, it is possible to obtain high temperature and low oxygen concentration in the jet flame. Here, a mixture of 40% H2, 40% CO and 20% CO was issued through the jet nozzle. This composition corresponds to a renewable fuel known as syngas. Three oxygen composition in the oxidant stream were evaluated: 2.0%, 4.7% and 6.9%. Temperature and species concentration values were measured along axial and radial lines under a fix Reynolds's number. The results suggest that when oxygen concentration increases, CO and NO emissions of the total process decreases.

1. Introduction
Efficient and low emission combustion systems development is the combustion research main target, besides the combustion equipment manufactures. Modern combustion systems must be accepted and adopted in the industrial field to attenuate energetic resources waste and relieving environmental damage generated by pollutant emissions [1,2]. The above can be solved employing utilizing low calorific value fuels, dilution by massive steam injection, or intense exhaust gas recirculation (EGR). Cavaliere et al. [3] defined, reactive mixture initial temperature is higher than autoignition temperature and their increase, due to the combustion process, is less than preheat temperature under moderate or intense low-oxygen dilution (MILD) condition. This regime shows lower temperature fluctuation, less noise production, emissions, and fuel consumption. It also presents wider, well distributed, and more interactive reaction zones, a self-sustained process with autoignition, a more uniform temperature field and effective combustion control.

Nowadays, based on pollution generated by greenhouse gases, it becomes necessary to increased fuel use from alternative sources, such as biogas, biomass, or syngas [4–8]. Synthesis gas (Syngas) is a several gases mixture composed mainly of H2, CO, some inert gases, and hydrocarbons [9,10]. This alternative fuel's relevance has been discussed along with many studies [10–13], which point out that Syngas implementation drives energy supply diversification and improves some combustion properties.
as laminar and turbulent combustion velocity, expand flammability limits under lean combustion condition. Furthermore, carbon dioxide (CO₂) and other polluting emissions decrease significantly compared to traditional fuels; this can be explained by hydrogen content in the mixture and cleaning methods after gasification. In addition to what was mentioned above, hydrogen combustion, which is a syngas component, has distinctive characteristics as high reactivity and diffusivity, as well, high free radical concentration such as O, H and OH in the flame. Hydrogen has a high laminar combustion velocity and commonly very thin thickness flames; likewise, it can cause unwanted flame and hydrodynamics instabilities. In contrast to traditional hydrocarbons, hydrogen content in syngas will induce turbulence-chemistry interactions under this combustion regime [10].

A jet burner type in a hot coflow consists of a central fuel jet surrounded by a combustion products stream (coflow), which comes from a premixed flame under lean condition. Hence, high oxygen content in the gases current is generated [14]. The amount of oxygen in coflow is up to how lean conditioned is the premixed flame, allowing it to obtain different oxygen concentrations besides controlling the coflow temperature efficiently. Inside this type of burner, strong combustion gas recirculation can be simulated by disengaging the complex flux structures present in practical combustion devices. In this case, intense recirculation in the reaction zone is emulated via coflow at high temperatures and low oxygen concentration. The fuel jet is injected through the coflow centre and fuel autoignition is automatically achieved due to coflow high temperature, such as on flameless combustion regime [14–19].

The present study aims to evaluate the emissions performance of a jet burner type in a hot coflow using a syngas jet, for this purpose average temperature profile, CO, and NO emissions were measured. The highly diluted zone will be varied to three different oxygen concentrations, corresponding to 2.0%, 4.7%, and 6.9% oxygen in the hot jet coflow. Results show, in general when oxygen concentration increases, CO and NO emissions of the total process decreases.

2. Methodology

Volumetric composition of the gas used in this study was 40%H₂+40%CO+20%CO₂ used to emulate a syngas composition; as can be observed, the gas has a high H₂ content. For the mixtures' preparation, high purity certified gases were used; besides, rotameters calibrated explicitly for each gas were used to ensure the percentage desired in the fuel mixture. Experiments were carried out under the following atmospheric conditions: 1550 m.a.s.l, 0.849 atm and 295 ± 2 K. The error in calibrated rotameters to emulate the fuel mixture was less than 2%. To understand the fundamentals of MILD combustion, and evaluate the emissions contaminants, a jet in hot coflow (JHC) burner was designed and proven, as shown in Figure 1.

The burner (Figure 1) consists of a central fuel jet, a secondary combustion zone or coflow zone and the cooling system. Hot coflow temperature was, on average, 1100 K at the central jet nozzle. Reynolds's number was fixed at 6500 to all the experiments. Hot air flow is provided from hot combustion products of a secondary burner aiming to achieve composition and temperature required in the output plane of the JHC burner. Measurements were carried out for a Syngas with 2.0%, 4.7% and 6.9% oxygen composition in the continuous flow hot stream and these conditions are considered for the respective measurements.

Species and temperature measurements were performed on three axial points, A1, A2, A3, corresponding to Z = 0 mm, Z = 45 mm, and Z = 90 mm, respectively, as see in Figure 2. For each axial position, six radial measures are registered, see Figure 3, which come from coflow external zone (R1 = 0 mm) to coflow center (R6 = 34 mm). It is worth noting that this paper only reports experimental data for the axial position that corresponds to Z = 45 mm (A2). Oxygen and carbon monoxide species measurement is performed using a Sick Maihak s710 analyzer. Oxygen measurement. In this case, are based on paramagnetic principle. Moreover, CO measurements are based on nondispersive infrared principle. A Thermo Scientific™ Model 42i analyzer is utilized to NO measurement, based on chemiluminescence principle. The equipment precision is given for each gas and it is defined as CO 1 ppm, O₂ 0.1% volume, NO 0.001 ppm.
3. Results and discussions

Figure 4, Figure 5, Figure 6 shows the radial profile of mean temperature, CO, and NO emissions, respectively, versus radial distance at 2.0%, 4.7%, and 6.9% oxygen composition in the continuous flow hot stream. Results are presented to axial distance $Z = 45$ mm from jet discharge. Results are compared with experimental and numerical data reported by Frassoldati et al. [20], this results correspond to an axial position of $Z = 60$ mm, 6.9% oxygen composition in the continuous flow hot stream, and CH$_4$/H$_2$ fuel mixtures. Temperature results shown in Figure 4 are quite similar for three oxygen concentrations. However, the higher temperature value is given under the highest oxygen concentration, which corresponds to 6.9%. The nearest zone to the jet (34 mm) shows 834 °C, 770 °C and 820 °C to 2.0%, 4.7%, 6.9% oxygen concentration, respectively.
Figure 4. Radial temperature profile at axial position $Z = 45$ mm.

CO emissions presented on Figure 5 suggest a marked increase in the peak, corresponding to 34 mm in the axial position, which is the closest area to the syngas jet central axis; as expected, due to low oxygen concentration, CO formation because of incomplete combustion is more significant. The CO peak corresponds to 2600 ppm, 1200 ppm and 1000 ppm for 2.0%, 4.7%, 6.9% oxygen concentrations respectively. If the peak is compared for 2.0% and 6.9% oxygen percentages, a 160% CO emission decrease is noted in parts per million. In agreement with these results, it is found that, under 2.0% oxygen concentration, CO emission value is higher, which makes it the most significant concentration for CO production and consumption; instead, temperature dependence is much less apparent.

Figure 5. CO emissions profile at axial position $Z = 45$ mm.

Figure 6 shows NO emissions versus radial position under different oxygen concentrations; it can be noticed that oxygen percentage strongly impacts NO emissions. NO emissions are much higher under 2.0% oxygen condition; this NO production peak is twice greater than 4.7 and 6.9% oxygen conditions. Figure 5 and Figure 6, show CO and NO contaminant emissions. In general, contaminant emissions decrease as the percentage of oxygen in the coflow increases. Oxygen flow from the secondary burner mixes with the syngas discharge jet, enhancing the dilution of the combustion products generated in the jet and achieving complete reaction chemistry. Contaminant emission has been used as a parameter to
evaluate and compare the performance of burners in the industry, other parameters correspond to criteria of flame stability, interchangeability of gases in the burner, and operating conditions in the specific application. Furthermore, according to the results presented by Frassoldati et al. [20], the results of contaminant emissions are in good agreement with those presented in this study.

**Figure 6.** NO emissions profile at axial position $Z = 45$ mm.

4. Conclusions
Mean temperature profile, CO and NO emissions were measured using a syngas through a hot jet coflow under highly diluted condition, at an axial position equal to 45 mm and several radial points. Oxygen percentages were established at 2.0%, 4.7% and 6.9%. Results presented in this work show that oxygen concentration has an important influence on flame structure, besides in NO and CO emissions, that when oxygen concentration increases, CO and NO emissions of the total process decreases. Result obtained in this study provide a reliable and detailed database to validated chemical-kinetic mechanisms for low-temperatures and turbulence-chemistry interaction combustion models to model MILD combustion in practical system.

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