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# Experimental and numerical investigation of turbulent diffusion flames in a laboratory combustor with a slot burner

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## HIGHLIGHTS

- Investigation of turbulent diffusion flames in a combustor with a slot burner.
- OH* imaging and temperature and gas species concentrations are reported.
- Regions of highest temperatures coincided with regions with maximum OH* intensity.
- Addition of $CO_2$ to oxidizer lowered OH* intensity and suppressed NO formation.
- Model was able to satisfactorily predict the experimental data.

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## ABSTRACT

This work investigates both experimentally and numerically turbulent diffusion flames in a laboratory combustor with a slot burner. Experiments were carried out using a mixture of natural gas (75 vol.%) and hydrogen (25 vol.%) as fuel and three oxidizers with compositions of 35% $O_2$/65% $N_2$, 35% $O_2$/32.5% $N_2$/32.5% $CO_2$ and 35% $O_2$/20% $N_2$/45% $CO_2$. For these three oxidizers, hydroxyl radical chemiluminescence (OH*) imaging and spatial distributions of temperature and of $O_2$, $CO_2$, CO and $NO_x$ concentrations are reported, which enabled to identify the location and structure of the reaction zone. The regions of highest temperatures coincided with the regions where the OH* intensity was maximum. Moreover, the addition of $CO_2$ to the oxidizer forced the reaction to take place further downstream, lowered the OH* intensity and suppressed the NO formation. On the modeling side, numerical simulations were carried out using the ANSYS Fluent 15.0 commercial code. Turbulence was modeled using the $k$–$\varepsilon$ realizable model. The eddy dissipation concept was employed along with a chemical mechanism comprising 42 transported species and 167 chemical reactions. The model was able to satisfactorily predict the temperature and the concentrations of $O_2$ and $CO_2$, but discrepancies were found in the prediction of the CO concentration.
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## 1. Introduction

The excessive use of fossil fuels and their depletion along with climate change is spawning an energy crisis, as most power generation comes from fossil fuel combustion [1,2]. The concept of carbon capture has been suggested as a strategy to reduce the $CO_2$ emissions associated to the fossil fuels combustion. Oxy-fuel combustion allows for the direct capture of $CO_2$ by condensing flue gases [3], which mostly consist of $CO_2$ and water vapor ($H_2O$). This technology has the merit of decreasing the flue gas volume and increasing the energy savings when compared with conventional air combustion, since the concentration of nitrogen in the oxidizer is lower. Oxy-fuel combustion [4] is characterized by faster chemical reactions, higher adiabatic flame temperatures, and faster burning velocities as compared to those in conventional air combustion. Industrial processes have used $O_2$-enriched air to increase flame temperature and thermal efficiency [5]. However, efforts are still needed to decrease the cost of oxygen production.

The addition of $CO_2$ to the oxidizer is normally used in oxy-fuel combustion to prevent too high flame temperatures. Oxygen-enriched combustion using recirculated flue gases, rich in $CO_2$, is an effective way of controlling furnace temperature and reduce the fuel consumption [6]. In addition, the heat transferred by radiation increases due to the higher $CO_2$ concentration and soot volume fraction in the flame [7]. The increase in heat transfer by radiation is advantageous in many industrial processes, namely because it allows the establishment of a (more) uniform heat treatment during the production process of materials (e.g., steel and glass).

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Slot burners are interesting solutions for a number of industrial processes since the two-dimensional nature of the flame enables a more uniform spatial temperature distribution and, thereby, enhanced radiation heat transfer. Despite this, there are very few studies available in the literature on such burners. Oh and Noh [8–12] studied the structure of several non-premixed oxy-methane flames in a lab-scale slot burner. These authors [8] observed that the flame appearance was generally feather-shaped, with a narrow and sharp flame base, and that the oxy-fuel flame was inclined toward the fuel jet side, the slope being dependent on the global equivalence ratio and on the fuel and oxidizer mass flow rates. Moreover, the authors [8] reported that the flame length and the lift-off height increased with an increase in the fuel jet velocity, and decreased with an increase in the oxygen velocity. It was also observed that the flame stabilization was enhanced when the distance between the fuel and the oxygen slots decreased [8]. Physically, this distance behaves as a dump plane that affects the mixedness of the fuel and oxidizer jets. Boushaki et al. [13] investigated the influence of the separation distance between the fuel jet and the oxygen nozzles on the flame length and lift-off height and found that the separation distance affects the mixedness of fuel and oxidant, which influences the flame behavior.

Oh et al. [9] reported that the flame stabilization broadened and the flame length decreased by adding hydrogen to the fuel jet. Hydrogen-enriched fuel allows smaller combustors to have wider operational range, because the flame is smaller and the flame stabilization is enhanced in comparison with non-enriched fuel. The authors also observed that the measured temperature distribution contours were similar to those of the OH* images and that the chemiluminescence intensity and luminosity of the flame was highest near the center of the reaction zone, which was coincident with the region of maximum temperatures.

The effect of addition of carbon monoxide to the fuel jet in a slot burner was investigated by Oh et al. [10]. This study was motivated by the current need of CO post-combustion in industrial furnaces [14]. A similar study was concerned with the addition of $CO_2$ to the fuel jet [11]. It was found that the flammability region of the flame decreased and the reaction zone became narrower with the increase of the $CO_2$ concentration in the oxidizer. The maximum and lower temperatures in the lab-scale furnace increased with the decrease of $CO_2$ in the oxidizer. The maximum temperature is strongly influenced by the oxygen mole fraction in the oxidizer, but the mean temperature is less sensitive, due to the production of $CO_2$, which has higher specific heat than the reactants. In practical combustors, the $NO_x$ emissions are still a concern because the complete elimination of nitrogen ($N_2$) from the reaction zone is impossible. The use of flue gas recirculation with $CO_2$ is effective in reducing $NO_x$ emissions because the addition of $CO_2$ to an oxy-fuel flame decreases the flame temperature [15].

A recent study investigated the influence of the fuel and oxidizer compositions on the structure of a non-premixed oxy-methane flame for a slot burner [12]. The flame stabilization was enhanced by increasing the $H_2$ and CO concentrations and by reducing the $CO_2$ concentration in the fuel, in agreement with previous works. The literature also reports numerical and experimental studies in laminar and turbulent premixed flames in slot burners [16–18].

Against this background, further investigations are necessary in order to improve the existing knowledge of the combustion process in slot burners. This paper investigates, both experimentally and numerically, turbulent diffusion flames in a laboratory combustor with a slot burner. Specifically, this work intends to examine the impact of the oxidizer composition on the flame structure from both the chemiluminescence emission of the OH* radical, and spatial distributions of temperature and of $O_2$, $CO_2$, CO and $NO_x$ concentrations.

## 2. Experimental

Fig. 1 shows a schematic of the combustor used in this study. The burner consists of two parallel rectangular slots separated by 9 mm from each other. The slots used to feed the fuel and the oxidizer have 1 mm and 2 mm width, respectively, and 20 mm length. The burner is confined by quartz plates to prevent external disturbance and allow for optical access. Each plate is placed at a distance large enough from the burner to prevent flame wall interactions.

The experimental techniques used in this study are fully described elsewhere [19]. Local mean temperature measurements were obtained using 76 μm diameter fine wire platinum/platinum–13% rhodium (type R) thermocouples. The uncertainty due to radiation heat transfer was estimated to be less than 7% by considering the heat transfer by convection and radiation between the thermocouple bead and the surroundings.

The sampling of the gases for the measurement of local mean $O_2$, $CO_2$, CO and $NO_x$ concentrations was achieved using a stainless steel water-cooled probe. The analytical instrumentation included a magnetic pressure analyzer for $O_2$ measurements, a non-dispersive infrared gas analyzer for $CO_2$ and CO measurements and a chemiluminescent analyzer for $NO_x$ measurements. Quenching of the chemical reactions was rapidly achieved upon the samples being drawn into the central tube of the probe due to the high water cooling rate in its surrounding annulus. No attempt was made to quantify the probe flow disturbances. On average, the repeatability of the gas species concentration data was within 10% of the mean value.

Both the temperature and the gas species probes were inserted into the quartz-glass combustion chamber through the top end of the combustor. The analog outputs of the thermocouple and of the analyzers were transmitted via A/D boards to a computer where the signals were processed and the mean values computed.

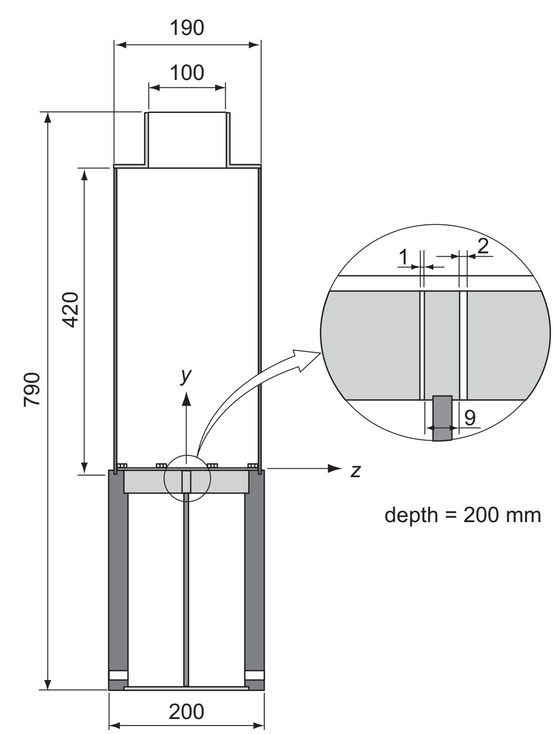


**Fig. 1.** Schematic of the combustor with the slot burner.

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