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Chemiluminescence and Structure Characteristics of a H₂/O₂ Downward Inverse Diffusion Flame

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Abstract

An experimental study was performed to investigate the effects of the burner geometry on the heat released and on the structure of multi-fuel-jet inverse diffusion flames (MIDF). Two different burner configurations were compared at different equivalence ratios and jet velocities using direct visualization and OH* chemiluminescence. Two downward burners were used, with H₂ and O₂ as fuel and oxidizer, respectively. A post-processing of the OH* chemiluminescence data was carried out with the Abel deconvolution through Matlab®. OH* emission intensities show a dependency on the burner geometry, as well as flame structure characteristics.

Introduction

Diffusion flames are widely used in different practical combustion systems due to their safety, and wide operating range as compared to premixed combustion [1]. Diffusion flames can be classified as normal diffusion flames (NDF), where oxidizer jet surrounds the fuel jet, and inverse diffusion flames (IDF). IDF are characterized by an oxidizer jet located in the center of the flame and surrounded by fuel jets [2]. This configuration conserves the flame stability and adjustable flame length of a NDF, as well as its safety since the central oxidizer jet creates a negative pressure, nevertheless it affects the flame shape, OH distribution, emission, and temperature distribution [3]. Furthermore, high temperatures with low soot emission can be obtained due to the location of unburned oxidizer and fuel mixing zone [3]. Hence, IDF is becoming more and more widespread in industrial applications such as processes of coal gasification and coke oven gas autothermal reforming technology [4]. However, the comprehension of its behavior still requires more detailed research varying the fuels and design aspects of the burner (such as its geometry), and on how these features will affect the process performance [3,5–7].

Several researches have studied IDF and their thermal behavior. One particular type of IDF that have been analyzed because of its high heat transfer [5], is the multi-fuel-jet inversion diffusion flames (MIDF), that consists in a larger central circular oxidizer jet surrounded circumferentially by a number of smaller circular fuel jets. One parameter has been the nozzle length and its effects on the air-pollutant emission and noise-radiation behaviors. Zhen et al. [5] studied two different nozzle length under the same air/fuel supply conditions (Re_{air} and ϕ). They found significant differences in the flame appearance, flame centerline temperature, CO/CO₂ concentrations and the noise radiation. The nozzle length influences the development of the jets and hence interaction between the air/fuel jets including their mixing process. Further investigations found that the MIDF, compared to the traditional IDF, is able to operate

stably at Reynolds number lower than 1000, when fuel jets are separated at an appropriate distance from the air jet, allowing the fuel entrainment. Its mix of air/fuel was also found to be more intensive [6,7]. The influences of the air-jet Reynolds number, overall equivalence ratio (Φ) and nozzle-to-plate distance on the local and average heat flux of the impinging MIDF have been also examined [8,9]. It was found that the flame shape and structure are mainly dependent on the air jet velocity and the ratio of the air and fuel velocities [8]. The area-averaged heat flux increased with either Re_{air} or Φ , and at higher Re_{air} and at higher Φ , the heat transfer efficiency decreases. [9]

As it can be seen, there have been researches that reported the differences between NDFs and IDFs in terms of soot formation characteristics, flame temperature, and flame topology. Nevertheless, few efforts have used flame chemiluminescence characteristic, which allows characterizing flame reaction zones, global flame structure characteristics, and process parameters [4]. Furthermore, chemiluminescence has proved to be a good optical technique that allows to relate the intensities of chemiluminescence radicals with the release of heat [10,11]. Lauer proved that the use of chemiluminescence imaging is able to determinate the heat released distribution in turbulent flames [10]. Clark et al. showed that measured chemiluminescence signals on the fuel-flow rate at constant equivalence ratio have a linear dependency with the equivalence ratio, and the reaction kinetics of chemiluminescence is identical for laminar and turbulent flames [11].

Regarding the above, speed injection of fuel and oxidizer, and geometry of the burners has shown to be important features that affect the flame thermal behavior and its characteristics; in addition, the chemiluminescence has shown to be a suitable non-inclusive technique to analyze them. This research aims to analyze the effects of burner geometry on the thermal behavior and flame structure characteristics of a H₂/O₂ downward multi-fuel-jet inverse diffusion flame changing the jet velocities of fuel

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and oxidizer, and equivalence ratios. Because oxyhydrogen flames have particularly high temperatures (higher than 2000°C), traditional techniques of temperature measurements are difficult to use on this research, direct visualization and the OH* chemiluminescence are techniques that suit with the complex setup of this study.

Experimental Setup

Direct visualization and OH* chemiluminescence are performed on this study. Two equivalence ratios were used for two burner geometries, different jet velocities of fuel and oxidizer were also tested; these correspond to an industrial application, which have proved a stabilized flame. Table 1 shows the equivalence ratios, which were the same for both cases and the velocities obtained with each geometry per jet

	ϕ	V_{H_2} [m/s]		V_{O_2} [m/s]		
		B ₁	B ₂	B ₁	B ₂	
					Central	Peripheral
1	1.50	3.91	11.00	5.99	5.87	1.47
2	1.50	4.10	11.54	6.28	6.16	1.54
3	1.35	4.96	13.94	8.43	8.26	2.06
4	1.35	5.15	14.49	8.76	8.59	2.15

Table 1. Experimental Conditions. Velocity per jet (V) in m/s. Φ = equivalence ratio.

The direct visualization allows spotting global flame structure characteristics. It is used principally for observation purposes. OH* chemiluminescence permits to compare qualitatively the heat released by the two type of flames and their characteristics, it also permits to have a qualitative approach of the reaction zone location.

The experimental setup used is showed on Figure 1. It has two main zones: one is the burner, which has the injection of O₂ and H₂, and the other one is the insulation zone, a confinement that contains the flame.

Two types of burner geometry were used and called Burner 1 (B₁) and Burner 2 (B₂) that are shown on Figure 1. A central jet of oxygen is done for the two configurations; its exit is positioned at the oxygen nozzle. The O₂ injection of B₂ configuration is divided in two, one central jet and several peripheral O₂ jets. The supply of hydrogen for both cases is peripherally and more external. It exits at the hydrogen nozzle, which is a perforated ring to have multi-fuel-jets, H₂ nozzle encloses the O₂ nozzle, the amount of H₂ jets on B₂ is twice B₁. The diameters of the O₂ and H₂ jet is different for each burner. The contact between the hydrogen and the oxygen occurs in the burner exit, ceramic part around the O₂ and H₂ nozzle.

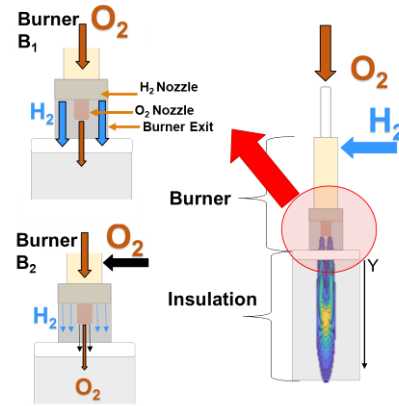


Figure 1. Experimental Setup

To perform measurements in direct visualization, a camera Canon EOS 650D with a Canon Lens EF 100mm 1:2 was used and for the OH* chemiluminescence a Photon SA4 Fast Camera coupled with an OH* FWHM (Full Width at Half Maximum) filter of 320 nm \pm 20 nm.

Direct visualization and OH* chemiluminescence were performed at the same time. Figure 2 shows a typical image capture by direct visualization and OH* chemiluminescence, an image post-processing was performed with Abel deconvolution using Matlab (MathWorks, Matlab R2018b). The results obtained are discuss on the next section.

Results and Discussion

Flame appearance

Luminosity photos of one experimental condition tested is presented on Figure 2. On the top, configuration B₁ is presented, which has one O₂ central jet surrounded by H₂ jets. On the bottom is configuration B₂ that has one O₂ central jet surrounded by O₂ jets and outer H₂ jets. Image with the direct visualization is on the left side, on the right is OH* chemiluminescence and the post-processed image. Images show a black part on the flame due to optical obstacles that belong to the experimental setup.

These flames report three zones (Figure 3): a flame neck (nozzle exit), an inner reaction cone (dark blue) and an outer flame layer (combustion products outer flame layer), which have a similar structure reported by Dong et al. [8] and Zhen et al. [5]. However, the present flames have a downward arrangement and the nozzle exits are not at the same height, hence the flame base is not reported on these flames as on the other studies.

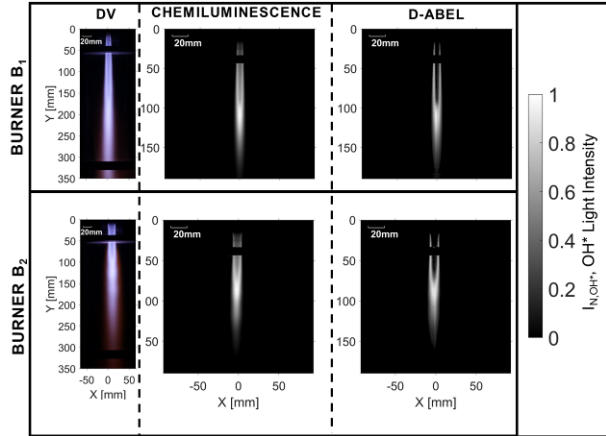


Figure 2. Results for point 1, DV (Direct Visualization), Chemiluminescence and Abel's deconvolution (D-Abel)

Regarding the effects of the double injection of O_2 , with constant Φ , the flame neck of the single O_2 jet is thinner; its reaction cone appears to be longer as well as the outer flame layer. Increasing the number of O_2 and H_2 jets affects clearly the shape of the flame, making it wider and shorter. At this configuration, the oxidizer velocity per jet decreases. Besides, the outer flame layer shows some red zones for both configurations that are related with the radiation of the combustion products and their interactions with the materials of the insulation. Furthermore, this seems to be more visible with the increase of the fuel jet number, where the flame is wider. The same behavior was reported for the other conditions tested.

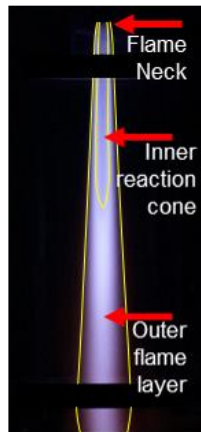


Figure 3. Flame zones

OH^* Emission Intensities

In H_2/O_2 flames OH^* radicals can be easily recognized due to its spontaneous emission of light [12]. There are two paths to produce excited radicals in flames, thermal excitation and chemical excitation, thermal excitation is related to flame temperature and the number of ground state radicals. Chemical excitation results from chemical reactions as other reactions produced ground state radicals, from which the radiation is called chemiluminescence [4]. The thermal excitation way of OH^* at temperatures above 2800K is more prominent

[12], thus the probability of thermal excitation way effecting OH^* formation is small, which can be excluded. Nevertheless, Lauer et al. [10] concluded that due to the simultaneous influence of the equivalence ratio on the integral heat release and vice versa, no direct proportionality between any chemiluminescence signal and heat release can be determined. Even though chemiluminescence can be used to monitor the integral heat release of turbulent flames if an empiric correlation between chemiluminescence and heat release can be obtained.

This study is restricted to analyze the distribution of OH^* emission in order to compare qualitatively the flames obtained by the two geometries. Normalized intensity of OH^* emissions at different conditions were determined from the post-processed images with the following equation:

$$I_{N,OH^*} = \frac{\text{Local } OH^* \text{ Emission Intensity}}{\text{Maximum } OH^* \text{ Emission Intensity}} \quad (1)$$

OH^* distribution has been used as an indication of flame reaction zone [4], and where the maximum OH^* emission is where the reaction is the most vigorous (flame-front). From the nozzle exit to the position of maximum OH^* emission, fuel and oxygen are mixed depending on the action of interdiffusion and reach the stoichiometric proportion at the position of maximum OH^* emission.). Concerning the position of maximum OH^* emission, the total flame has two regions along the y-axis: nozzle exit to the position of maximum OH^* emission (Region I, initial reaction zone), the position of maximum OH^* emission to the end of the flame propagation (Region II, further oxidation zone) [4]. After the maximum OH^* emission position, some few unburned fuel passing the flame- front, and going on burning in the flame downstream region, where is the further oxidation zone (Figure 4).

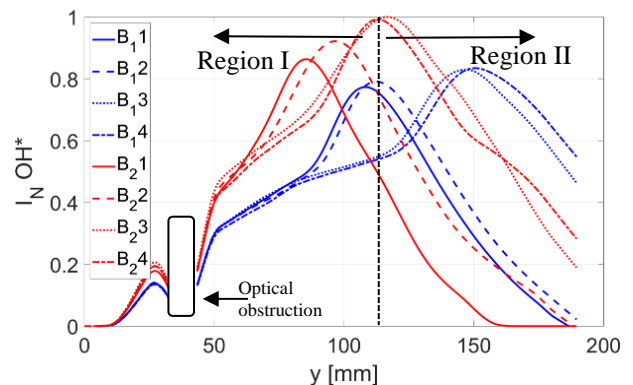


Figure 4. Local intensity of OH^* emission along y-axis

Figure 4 shows the results of the obtained normalized intensity of OH^* emissions, it is represented the integral respect to x, which indicates the quantity of OH^* emissions at certain point on y, hence the OH^* emissions

produce with the two configurations. This allows comparing qualitatively, the flames and their local heat released and the influence of the burner geometry.

Using the same configuration with constant Φ and different fuel and oxidizer jet velocities, OH^* generated is basically the same, and only more fuel is consumed along the flame propagation direction until the maximum OH^* emission position, causing the originally position of the stable flame- front moves downstream.

OH^* radical emissions are higher locally with the double injection of O_2 , which also has higher fuel velocities and lower oxidizer velocities, the highest intensities were found for the highest fuel velocities. The OH^* generated in configuration 2 is significantly more than configuration 1, and the distributing area is wider, as a result of more fuel and oxygen involved in the reaction. Hence, the local heat released is expected to be more significant with a double injection of O_2 and more fuel jets.

The location of the flame-front was analyzed on Figure 5, the fuel injection velocity has shown to influence the location of flame [13]. The maximum OH^* emissions emitted along the y-axis moves downstream with the increase of jet velocity (fuel and oxidizer).

It was found that at constant Φ and different jet velocities (H_2 and O_2), the flame-front is located almost at the same distance from the nozzle exit. Besides, the value of the maximum intensity does not vary significantly. However, it can be observed that with a single O_2 injection, higher O_2 jet velocities and lower H_2 jet velocities, it moves downstream.

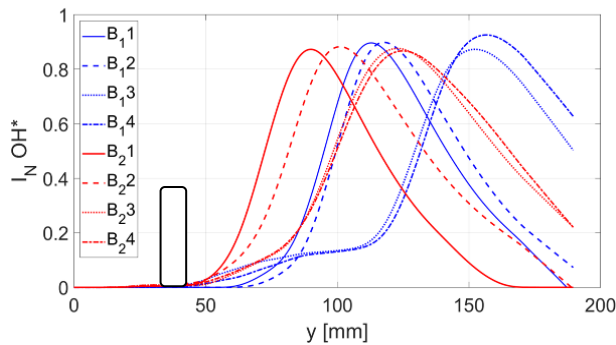


Figure 5. Intensity of OH^* Emission along y-axis

Flame structure characteristics

Flame characteristics were defined from the post-processed image of OH^* chemiluminescence, such as flame length and thickness. The flame length is defined as the distance between the burner exit ($y = 0$) and the intersection point y-axis and $\text{OH}^*_{\text{isoline,max}}$ (Figure 6), this line will constitute on this study the internal boundary of the reaction zone as well as the maximum emission of OH^* radical. The flame thickness, will be the length between the borders of the OH^* isoline highlighted on

Figure 6, this isoline was chosen because it showed to be clear and stable for both configurations.

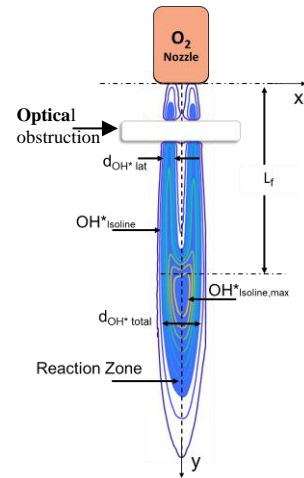


Figure 6. Flame Characteristics

Both the inlet air momentum and the inlet fuel momentum affect the shape of an IDF. With the increase of oxygen jet velocity, the difference in the momentums of the two jets increases, leading to entrainment of some fuel into the central oxygen flow[4], which will define the flame structure characteristics.

Flame thickness (Figure 7) allows identifying the location where the widest point of the flame is situated, the biggest zone of OH^* emissions. Wider flames were found when the amount of jet increases as for fuel and oxidizer, and increasing fuel and oxidizer velocities. At constant Φ the value of the thickness does not vary increasing the velocities (fuel and oxidizer).

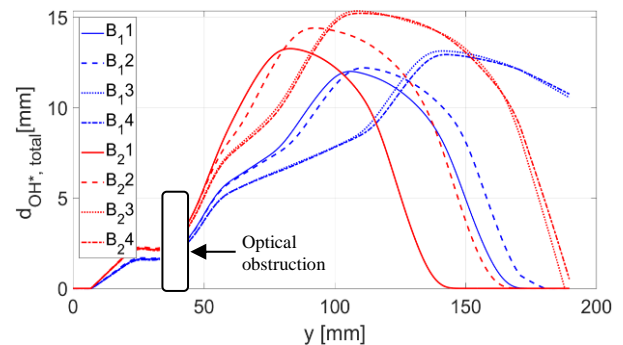


Figure 7. Flame Thickness ($d_{\text{OH}^*,\text{total}}$).

L_f allows identifying the maximum emission and the length of the inner reaction cone zone. Figure 8 shows that longer flames are obtained with lower quantity of jets with the higher fuel and oxidizer jet velocities; this last behavior is similar to the highest emission intensities on Figure 4. Besides, flame length shows to depend more on Φ than on fuel velocities. These results agree with the ones obtained by Dong et al. [8], where the flame height showed to depend on Φ more than on Reynolds number (Re). Configuration with more jet of fuel and oxidizer

shows to be more sensible to the change on Φ and Re at lower fuel and oxidizer jet velocities.

A wider and shorter flame indicates that the mix fuel/oxidizer is relatively faster with the double injection of O₂.

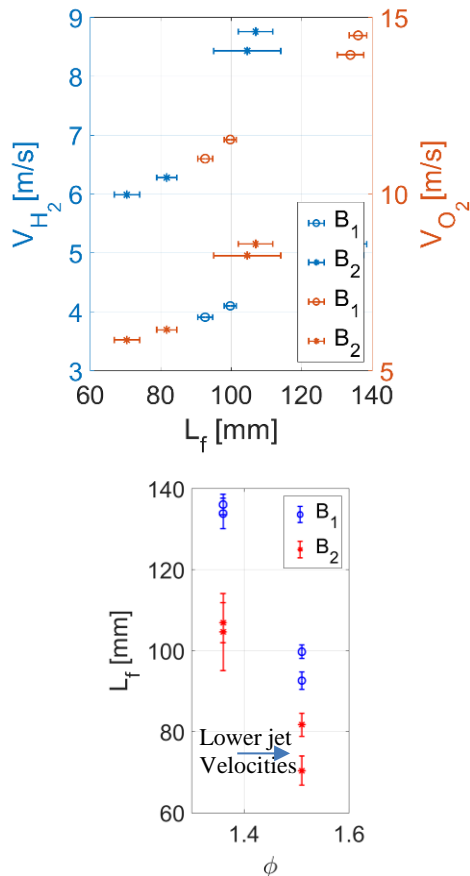


Figure 8. Flame Length (L_f).

Conclusions

Chemiluminescence distribution of excited OH* radicals of a MIDF was compared with two different burner geometries at different equivalence ratios and jet velocities, using H₂ and O₂ as fuel and oxidizer, respectively.

Direct Visualization of the flame reveals a dependency of the flame shape on the burner geometry. This means that interaction of O₂/H₂ jets and their mixing vary based on the burner geometry.

The influence of burner geometry on the thermal behavior of a diffusion flame was analyzed, owing to the location of OH* intensity levels. Therefore, the highest heat released zones could be identified. It shows to be higher for a double injection of O₂, lower O₂ jet velocities and higher H₂ jet velocities. Besides, the equivalence ratio shows to affect more the heat released than Reynolds number, nevertheless the maximum overall heat released seems not to be influenced by neither equivalence ratio nor Reynolds number.

The study shows that the structure of the flame is highly depending on the burner geometry as well as the number of jets (fuel and oxidizer); a dependency on H₂/O₂ ratio is also recognized.

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