18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0769
STABILITY LIMITS OF NON-PREMIXED INVERSE TURBULENT DIFFUSION FLAMES WITH O2 ENRICHMENT

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Abstract. *An experimental study was conducted to investigate the effect of oxygen enrichment on the stability limits of non-premixed turbulent inverse diffusion flames. The experimental set up was composed by a jet of oxidant spread into a chamber filled with gas to form an inverse flame with a coaxial burner. Many combinations of flow rates were tested, and the oxidant flow rate was increased until the flame blow-out occurred. The results are presented in terms of the oxidant velocity and the O2 percentage. It was observed that oxygen enrichment expanded the stability limits, reaching oxidant Reynolds over 2300 and fuel Reynolds number of 3863, representing a turbulent regime for the external flow. Therefore, in the present work it was possible to stabilize inverse diffusion flames in a turbulent fuel atmosphere by means of oxygen enrichment.*

Keywords: *inverse diffusion flames, oxygen enrichment, stability limits*

1. INTRODUCTION

Flames are categorized in two groups, the premixed flames, and the non-premixed flames. The non-premixed are also called diffusive flames. They are used in different applications due to their great stability and wide operation ranges (Choi et al., 2015). The non-premixed flames show less heat release than premixed flames and more soot formation (Kaplan and Kailasanath, 2001). On the other hand, the premixed flames present high heat release and less soot formation. However, it is difficult to stabilize a premixed flame and there is a low range of applications for this kind of flames (Patel and Shah, 2018).

There is a type of non-premixed flames, called inverse diffusion flames (IDF), that present intermediate characteristics between premixed flames and normal non-premixed flames. In the case of normal diffusion flames (NDF) the fuel is injected through a burner port into an oxidant atmosphere, which is generally air, whereas in the case of IDF the oxidant is injected through the burner port into a fuel environment. This kind of flame is being studied because of its promising features like reduced soot production (Elbaz and Roberts, 2014) and reduced NOx formation (Sze et al., 2006).

In IDF's, the soot forms in a fuel rich region at the top of the flame sheet, and the path line of its particles passes through the higher speed region of the flame, resulting in a low residence time. Therefore, there is short time for soot formation (Mahesh and Mishra, 2008).

Some works show that the IDF's can be used in the production of carbon nanotubes (Wu and Essenhigh, 1985) and in heat transfer applications (Rabee, 2018). Nevertheless, the studies about its applications are still very recent. The IDFs are not so commonly used because they are difficult to stabilize, especially the turbulent inverse diffusion flames. IDFs have reduced stability limits as experimentally observed for a CH_4/air co-flow flame in a confined chamber (Xu et al., 2006). Also, in the experimental work carried out by Arthur and Napier (1955) the IDFs did not reach the turbulent regime.

In previous studies IDF's were mainly produced with coaxial jet burners (Sze et al., 2006). The same burner type is used for the experiments in the present work. The burner consists of two concentric tubes, where the middle tube supplies the oxidant and the outer tube the fuel. A study written by Sobesiak and Wenzell (2005) tested ten different diameter relations for coaxial jet burners. In that article it was shown that, for smaller inner air jet diameters the flame length decreased faster for variations of the air to fuel velocity ratio larger than the ratio of diameters. According to Wu and Essenhigh (1985) Inverse diffusion flames have reduced soot luminosity.

Regarding the combustion of IDFs produced with oxygen enriched air, It has been reported that the increased O_2 promotes the generation of OH and CH radicals in the flame (Zhang et al., 2013), producing changes in the soot formation process (Mahesh and Mishra, 2010). Also, the flame stability limits are expected to extend due to oxygen enrichment. It is expected that a turbulent regime could be reached in that manner. Another possibility for increasing the IDFs stability limits is by using a bluff-body burner. Thus, creating a recirculation zone. This recirculation zone serves as a continuous ignition source for reactants traveling to the shear layer of the bluff-body through the vortex (Kostka et al., 2012), therefore, improving flame stabilization.

2. EXPERIMENTAL SETUP

The experimental setup used in the present work for the characterization of inverse non-mixed turbulent flames is illustrated in Figure 1. The main parts of the experimental apparatus are the oxidant supply line, the fuel supply line, the combustion chamber, the video camera, the exhaust system and the ignition system.

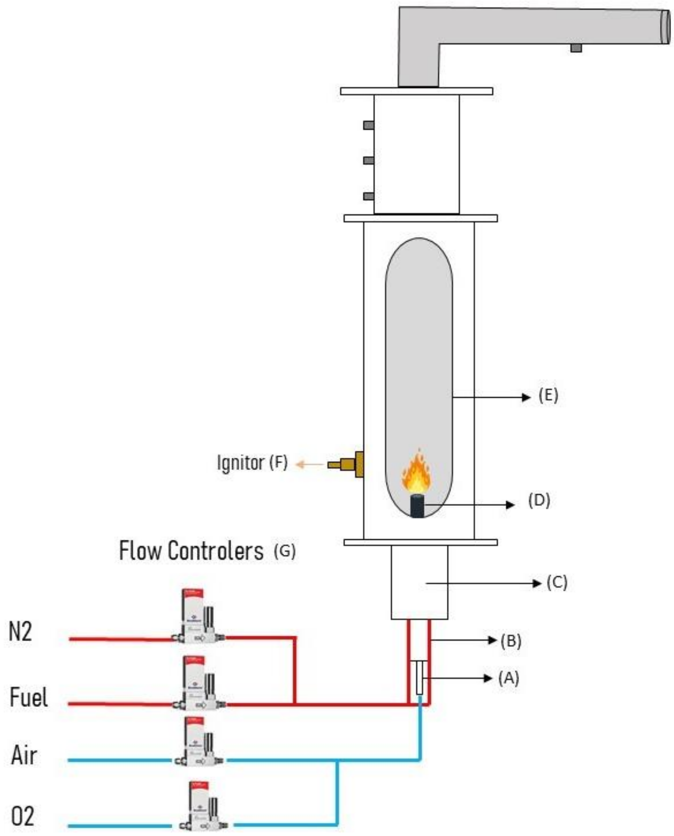

Figure 1. Experimental setup for the inverse diffusion flame experiments.

Experiments were carried out with natural gas as fuel and atmospheric air or oxygen enriched air as the oxidants, the natural gas presented the following volumetric composition: 90,8% of CH_4, 6% of C_2H_6, 1,2% of C_3H_8, 0,5% of CO_2 and 1,55% of N_2.

The volumetric flow rate the fuel was measured with an electronic flow mass controller [G] Bronkhorts F-201CV-10K with an uncertainty of ±0.5% of the displayed measurement and ±0.1% of the full scale. The flow mass controller operated within a range of 0.01 l/min to 15 l/min. The volumetric flow rate of the oxidant was measured with a flow mass controller OMEGA FMA-2600A series with an uncertainty of ±0.8% of the displayed measurement and ±0.2% of the full scale. The burner [D] was specially designed for this experiment. A circular cross-section area stainless-steel tube carried the oxidant [A], concentrically positioned inside a stainless-steel square tube that carried the fuel [B]. At the entry cross section of the square tube a honeycomb [C] was allocated with the objective of straightening the fuel flow. The walls of the square tube expand longitudinally, forming the combustion chamber [E]. This chamber provides visual access through two Borosilicate windows of 200 mm x 40 mm.

The ignition system [F] was designed so it would not interfere with the flow conditions. The flame ignition was accomplished by moving the ignitor near the oxidant burner position and creating an electric discharge, which provided the ignition. Afterwards, the ignitor was returned to its original position.

The experimental procedure consisted in setting the mass flows of fuel and oxidant through the mass flow controllers and increasing those flows to observe the flame behavior. In the case of tests with oxygen enriched air, two mass flow controllers are used to obtain an enriched air with the desired oxygen concentration. Another two mass flow controllers were used to control nitrogen and fuel mass flows. The nitrogen was used to purge the line and to create an inert environment prior to the tests. The fuel flow is maintained constant during the combustion experiments while the air or oxygen enriched air flows were varied.

The oxidant flow was increased until the flame reached the blow-out limit. The velocity data was used to calculate the Reynolds numbers and verify the flow regime. The ideal gas model was used to calculate the oxidant and fuel densities while the methodology presented in Wilke (1950) was used to calculate the viscosity. The different experimental conditions tested in the present work are presented in Tables 1 and 2. In order to perform the experiments with safety, a normal diffusion flame was established outside the test region to consume the excess natural gas that was not burned at the experiments. The stability limits of this normal flame determined the experimental limit within the laboratory. This is because any further increase in the fuel flow rate would mean the liberation of unburned natural gas into the laboratory.

Table 1. Experimental conditions for fuel flow at 150 lpm (Re=2898)

%O2	Flow rate (lpm)	Vox (m/s)	Viscosity (Pa.s)	Density (kg/m^3)	Reynolds
21.00	Not stabilized	-	-	-	-
22.75	Not stabilized	-	-	-	-
24.50	Not stabilized	-	-	-	-
26.25	Not stabilized	-	-	-	-
28.00	8.70	3.61	1.85743×10^{-5}	1.1315	1568
29.75	13.90	5.76	1.86213×10^{-5}	1.1214	2477
31.50	17.10	7.09	1.86684×10^{-5}	1.1113	3012
33.25	21.30	8.84	1.87154×10^{-5}	1.1011	3709
35.00	25.70	10.66	1.87624×10^{-5}	1.0910	4423
36.75	Not stabilized	-	-	-	-
38.50	Not stabilized	-	-	-	-
40.25	Not stabilized	-	-	-	-

As it is observed in Table 1, for a fuel flow rate of 150 lpm the IDF was not stabilized for O2 concentrations of 21%, 22.75%, 24.50% and 26.25%. Starting from O2 concentrations of 8.70% and until a concentration of 25.70% the IDF was stabilized. However, for O2 concentrations between 36.75% and 40.25% it is again not possible to stabilize the flame.

The data presented in Table 2 corresponds to a fuel flow rate of 200 lpm. In this case the IDF was not stabilized for O2 concentrations of 21%, 22.75%, 24.50%, 26.25%, 28.00% and 29.75%. Once the concentration of O2 reached 31.50% the flame was stabilized, and it was possible to keep it stable up to a O2 concentration of 40.25%.

It is important to point out that in order to carry out tests with these high fuel flow rates (150 and 200 lpm) it was necessary to have an auxiliary normal non-premixed flame that consumed the unburned fuel which was exhausted from the test chamber. Therefore, the data for O2 concentration of 42.00%, labelled as Lab. Limit in Table 2, actually corresponds to the blow-out limit of the auxiliary normal non-premixed flame.

Table 2. Experimental conditions for fuel flow at 200 lpm (Re=3863)

%O2	**Flow rate (lpm)**	**Vox (m/s)**	**Viscosity (Pa.s)**	**Density (kg/m^3)**	**Reynolds**
21.00	Not stabilized	-	-	-	-
22.75	Not stabilized	-	-	-	-
24.50	Not stabilized	-	-	-	-
26.25	Not stabilized	-	-	-	-
28.00	Not stabilized	-	-	-	-
29.75	Not stabilized	-	-	-	-
31.50	14.90	6.18	1.86684×10^{-5}	1.1113	2625
33.25	20.70	8.59	1.87154×10^{-5}	1.1011	3604
35.00	24.70	10.25	1.87624×10^{-5}	1.0910	4250
36.75	29.70	12.32	1.88094×10^{-5}	1.0809	5051
38.50	33.50	13.90	1.88564×10^{-5}	1.0707	5630
40.25	38.10	15.81	1.89033×10^{-5}	1.0606	6326
42.00	Lab. Limit	-	-	-	-

3. RESULTS

In the present section, the results obtained in the experiments will be presented. It is important to notice that in the following results the attached flame state is defined as the state at which the flame is still attached to the exit port of the burner and the blow-out state is defined as the oxidant velocity at which the flame is extinguished due to an excessive and abrupt separation from the burner top. No lifted stable flames were observed in the experiments performed. Therefore, there is not a lifted flames region indicated in the maps that will be presented in this section.

All the tests were performed in atmospheric pressure conditions. The flame stabilization map consists of the attached flame region and the blow-out region. The combustion stability limits of inverse diffusion flames were measured in order to identify the effect of oxygen enrichment under various fuel and oxidant velocities. In the present study it was not possible to stabilize an inverse diffusion flame for the aforementioned external flow conditions and using air as an oxidant. Therefore, oxygen enrichment was necessary to stabilize the flame.

According to Choi et al. (2015), it is expected that the enrichment of the air with O2 widens the stability limits of the inverse diffusion flames. The stability map shown in Figure 2, is the result of the stability tests performed with natural gas as fuel and an oxidant mixture consisting of 28% O2 and 72% N2 in volume. The experimentally obtained extinctions velocities are depicted as red squares in Figure 5.

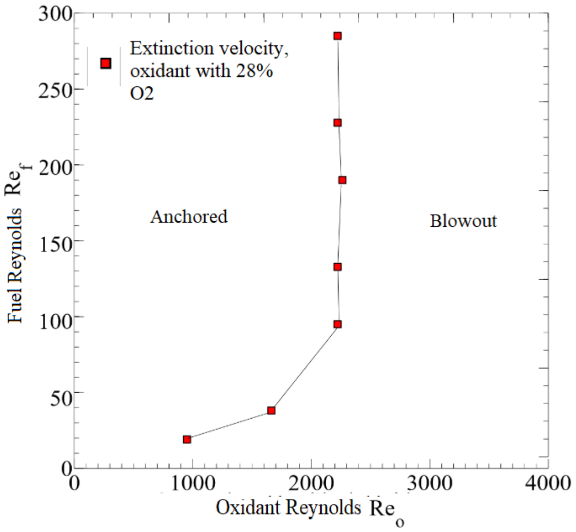

Figure 2. Stability map with 28% of oxygen concentration in the oxudant.

The results shown in Figure 2 corroborate the statement given by Choi et al. Flames with low fuel velocities present a monotonic increase of the oxidant extinction velocities with the increase of the fuel velocity. However, there is a critical fuel velocity starting from which the oxidant extinction velocity becomes independent of the characteristics of the external flow. This is shown by the almost vertical line in Figure 2. The oxidant extinction velocity corresponding to this critical condition is in average 40 m/s and this represents an oxidant flow average Reynolds number of 2300.

The stabilization of flames with different concentrations of O2 in the oxidant with a fixed fuel flow rate (150 lpm), that allowed for a turbulent regime in the external flow (Re=2898), was also studied. The results of those experiments are presented in Figure 3. The experimentally obtained extinctions velocities are depicted as red squares in Figure 3.

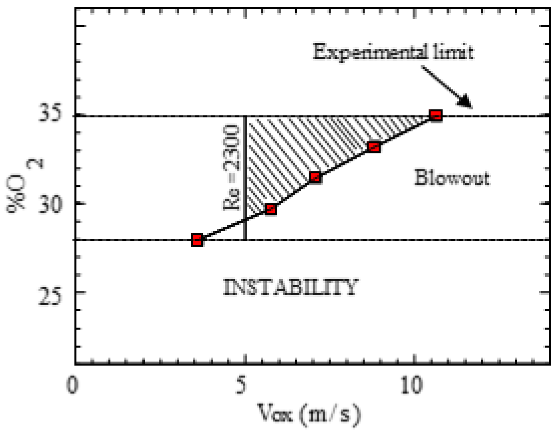

Figure 3. Stability map for fixed fuel flow of 150 lpm and different concentrations of O2 using a simple burner.

It is observed that the increase in the O2 concentration in the oxidant increases the oxidant extinction velocity obtained for a given fuel velocity. The shadowed area in Figure 3 means that it is possible to stabilize an inverse turbulent diffusion flame for conditions that fall inside that area. The higher extinction velocity reached with this configuration was 10.66 m/s for an O2 concentration of 35%.

Increasing the fuel velocity to 200 lpm (Re=3863) made possible to study a higher range of O2 concentrations, all the way to 40.25% of O2 at the oxidant. The results of those experiments are presented in Figure 4. The experimentally obtained extinctions velocities are depicted as red triangles in Figure 4.

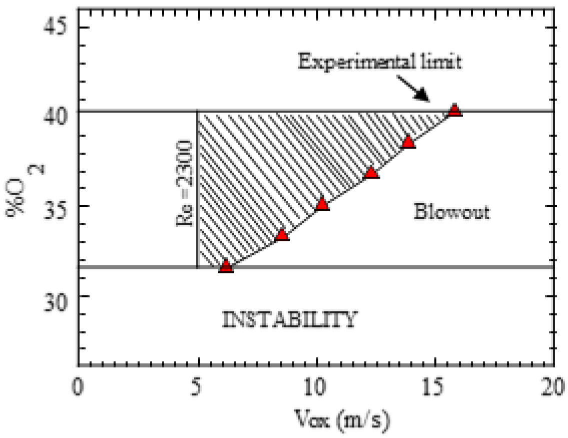

Figure 4. Stability map for fixed fuel flow of 200 lpm and different concentrations of O2 using a simple burner.

In the same manner, it is observed that the increase in the O2 concentration in the oxidant increases the oxidant extinction velocity. The shadowed area in Figure 4 represents the area where it is possible to stabilize an inverse turbulent diffusion flame. The higher extinction velocity reached with this configuration was 15.81 m/s for an O2 concentration of 40.25%. A comparison of the results presented in Figures 3 and 4 shows that higher O2 concentrations (31.5%) are necessary to stabilize the flame for higher fuel flow velocities.

Finally, a bluff-body burner was used in order to study the flame stability at higher oxidant velocities. The O2 percentage was increased in intervals of 10%, starting at 50% until 100% O2 was reached. The stability limits for an oxidant velocity ranging from 14.3 m/s to 74.2 m/s and a fuel flow rate of 200 lpm (Re= 3863) is depicted in Figure 5. The experimentally obtained extinctions velocities are depicted as red triangles in Figure 5.

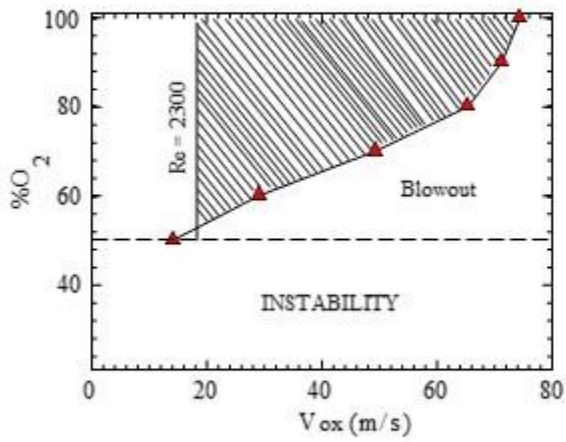

Figure 5. Stability map with fixed fuel flow for different concentrations of O2 using a bluff-body burner

It is also observed in Figure 5 that for a fixed fuel velocity which created a turbulent flow regime (Re=3863) the stability limits increased with the increase of O2 concentration in the oxidant. The experimental conditions that fall within the shadowed area represent points for which a turbulent inverse diffusion flame can be stabilized by using a bluff-body burner.

For O2 concentrations below the 50% the flame was not stable, therefore, higher oxidant velocities, due to the use of the bluff-body burner, required higher O2 concentrations in order to attain flame stabilization. It is important to observe that the 50% O2 blowout point does not represent a turbulent flame regime. It can be observed that the oxidant velocity at the stability limits increases monotonically with the increase of the O2 percentage. That observation agrees with the results obtained by Sobiesiak and Wenzell [15] for experiments with Reynolds numbers above 100.

4. FINAL CONSIDERATIONS

In the present work the combustion stability limits of inverse diffusion flames were determined for different external and internal flow velocities. It was observed that the stability limits increased with the increase of the O2 concentration in the oxidant. A coaxial burner and a bluff-body burner where used in the experiments.

The enrichment with O2 allowed to obtain stabilized turbulent inverse diffusion flames. Moreover, stability maps were constructed, and they represent the main contribution of the present experimental research.

The results showed good agreement with Sobiesiak and Wenzell (2005) experiments for Reynolds numbers above 100. The velocity of the external fuel flow also affected the stability limits. It was observed that there is a minimum O2% which allows the stabilization of inverse diffusion flames when a turbulent external flow is stablished.

The increase in fuel velocity from 1.03 m/s to 1.37 m/s resulted in a relative decrease of the oxidant extinction velocity between 3 to 4%. This also increased the minimum O2% concentration necessary to stabilize the flame from 28 to 31.5% for the simple burner tests. In the case of the bluff-body burner the minimum O2% that allowed to stabilize the flame was 50%.

5. ACKNOWLEDMENTS

The authors are grateful to PETROBRAS – Petroleo Brasileiro S. A. for support of this work through Project 2017/00622-2.

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