

ENC-2022-0728

EXPERIMENTAL STUDY OF THE GAS ATMOSPHERE EFFECTS ON A STOICHIOMETRIC PREMIXED FLAME

Rafael Trintinaglia Perin^{a,*}

Lucas Güenter Fernandes^{a,*}

Andrés Armando Mendiburu Zevallos^{a,*}

Fernando Marcelo Pereira^{a,*}

Paulo Roberto Pagot^b

^a UFRGS – Universidade Federal do Rio Grande do Sul – 425 Sarmiento Leite Street – Historic Center, Porto Alegre – RS – Brazil

^b CENPES – PETROBRAS, Petróleo Brasileiro S.A., Rio de Janeiro, RJ, Brazil

rafael.perin@ufrgs.br

fernando.pereira@ufrgs.br

Abstract. *This study investigates the gas atmosphere effects on the behavior and stability limits of stoichiometric premixed flames of methane and air. A stoichiometric premixed flame has a complete mixture that allows a complete combustion, however the influence of the gas atmosphere in which the flame burns are not an easy answer to find on the literature, therefore, this study tries to explain how different atmosphere gases affect a stoichiometric premixed flame. The experimental measurements were performed using a closed chamber with windows, allowing the visualization of the experiment. The gases were adjusted using mass flow controllers, allowing a precise control of the gases and the evaluation of the stability limits. The results show that although the premixed flame have a stoichiometric proportion, the gas atmosphere around it have a significant influence on the flame stability, affecting it through edge mixing effects, secondary air relevance to the premixed flame and by participation of the gas atmosphere on the combustion.*

Keywords: *Premixed flame, gas atmosphere, flame stability.*

1. INTRODUCTION

The efficient use of controlled flames for industrial purposes dates back to the 19th century with the rise of the First Industrial Revolution, which became precursor to the technological advancements we have today. In the academic field, flames are studied before their physical and chemical characteristics, accordingly to the interaction between the present gases. While diffusive flames occur when the fuel and oxidant are apart, premixed flames present a mixture between the components before the ignition of the reaction, being a stoichiometric mixture the perfect amount of oxidant and fuel, allowing a complete combustion.

Although premixed flames are very well studied in the literature, the effects that the gas atmosphere, in which the flame resides, and the explanation for its influence on premixed flames are not so easy to find. The work of Edmondson et al. (1970), evaluated the burning velocity of methane and air using a flat flame in different gas atmospheres and found significant differences for each atmosphere. The gas atmosphere effects were associated with edge mixing under convective entrainment. On the work of Claesson et al. (1983), using a bunsen burner, a premixed flame of methane and air were studied varying the proportions of nitrogen and oxygen on the gas atmosphere synthetic air. The authors observed that the oxygen on the gas atmosphere have a significant influence on the flame, even when it is a stoichiometric premixed flame.

With the few works where this theme is studied, this work's objective is to evaluate the effects of the gas atmosphere on a Bunsen type stoichiometric premixed flame, expanding the previous works by evaluating fuel atmospheres of methane, that characterize an inverse flame atmosphere.

2. METHOD

2.1 Experimental setup

For the evaluation of the gas atmosphere influence on a stoichiometric premixed flame, a closed chamber was used, allowing the stabilization of a confined flame with a coflow of any selected gas. The experimental setup (Figure 1) is, therefore, composed of a chamber with borosilicate glass windows allowing the visualization of its interior, a burner for the stabilization of the studied flame, a gas feeding system, for both the coflow and flame mixture, and a camera to record the image of stable flames.

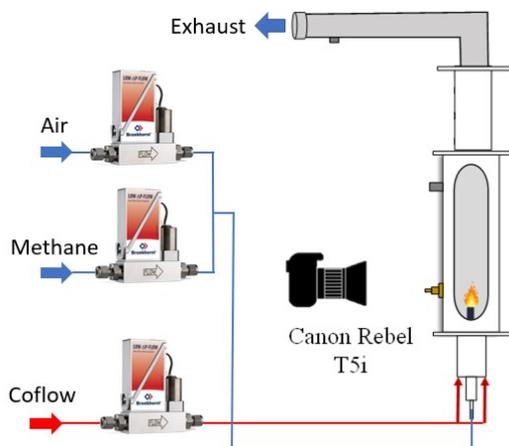


Figure 1 - Experimental setup

Two burners were used for the stability evaluation, first a normal strait tube burner and later an ORCA Labor Bunsen burner (Figure 2), that due to its configuration produces a stabler flame than a normal strait tube burner. Both burners have similar area for the gas to flow through. The camera used is a Canon Rebel T5i. Both the coflow and flame mixtures were controlled using thermal mass flow controllers from Bronkhorst model EL-Flow F-201CV, calibrated using a MesaLabs DryCal Defender 530+, allowing a precise control of the gas flows. The gases used were stored in gas bottles, except for air that was obtained from the atmosphere. The experiments were performed at 1 atm and 300 K.



Figure 2 - ORCA Labor Bunsen burner

2.2 Experimental procedure

The experiments were performed using a stoichiometric premixed methane/air flame ($\phi=1$), stabilized at the burner on the center of the chamber while varying the gas atmosphere that surrounds the flame (coflow), its flow rate, and the flame's mixture flow rate. Through the variation of these parameters, the stability limit of a stoichiometric premixed methane/air flame at different gas atmospheres were investigated. The gases were selected for the surrounding atmosphere in this study so that the variation of a number of gas properties could be evaluated in the stability of the central flame. Table 1 shows the gases selected for the surrounding atmosphere and their properties.

Table 1. Properties of the surrounding atmosphere selected gases.

Gases ⁽¹⁾	Molar mass	Density	Cp	Cp	Lambda	Alpha
	kg/kmol	kg/m ³	kJ/kg.K	kJ/kmol.K	W/m.K	mm ² /s
Air	28.970	1.169	1.004	29.086	0.0262	22.323
N ₂	28.013	1.130	1.042	29.071	0.0260	22.081
CO ₂	44.010	1.775	0.842	37.198	0.0168	11.241
CH ₄ (NG) ⁽²⁾	16.043	0.648	2.254	36.161	0.0341	23.347
Ar/CH ₄ (50/50%)	27.996	1.131	1.017	28.467	0.0260	22.618

⁽¹⁾ measured at 25°C, ⁽²⁾ natural gas.

The gases for the surrounding atmosphere have similar and different properties, allowing the evaluation of different properties on the flame stability. Air was selected as the first gas, allowing for the base configuration of a normal flame atmosphere. Being air composed of 79% nitrogen, the second selected gas, nitrogen, have very similar properties to air with the difference that it is an inert gas. The third gas, carbon dioxide, have a high heat capacity and very different properties to the other two gases. When using methane as the gas atmosphere, it characterizes an inverse flame atmosphere, which is focus of several studies in the literature. For the methane atmosphere, natural gas was used, being composed of over 90% methane. Lastly, a mixture of argon and methane (50/50%) allows the evaluation of a gas atmosphere with properties very similar to air, but still being an inverse flame atmosphere.

For each atmosphere gas, three experiments were performed, evaluating the limit flow rate for the central flame's mixture before the blowoff. 1) using the normal strait tube burner with a coflow of 10 lpm (liters per minute), 2) using the normal strait tube burner with a coflow of 50 lpm, 3) using the ORCA Labor Bunsen burner with a coflow of 90 lpm. All the flames presented in this study are premixed flames with an stoichiometric equivalence ratio ($\phi=1$), however, for practical purposes, the mass flow rate presented in the text represents the air portion of the mixture.

3. RESULTS AND DISCUSSIONS

3.1 Air atmosphere

With Air as the gas atmosphere a base line for comparison is determine since this is the conditions of a normal flame. For this atmosphere, using the strait tube burner with a 10 lpm coflow of air ($Re=220$), the flame's maximum flow rate was 5.5 lpm ($Re=1075$), figure 3a. While for the second test, with a coflow of 50 lpm of air ($Re=1102$), the flame's flow rate limit was 4.8 lpm ($Re=940$), Figure 3b.



Figure 3 - Flames with a coflow of air, 10 lpm (a) and 50 lpm (b).

The third experimental test (Figure 4) shows that for a coflow of 90 lpm ($Re=2140$), the maximum flame flow rate was higher than 30 lpm ($Re=5840$), and was not evaluated further because of equipment limitations. The tests using air as the surrounding atmosphere presented the higher flow rate values for the flame, being the most stable atmosphere for the premixed flame in study.



Figure 4a - Coflow of air using the ORCA Labor burner.



Figure 5b - Coflow of air using the ORCA Labor burner.

3.2 Nitrogen atmosphere

Evaluating nitrogen as the gas atmosphere, the flame's mixture flow rate limit for the first test was 3 lpm ($Re=590$), with the 10 lpm nitrogen coflow ($Re=220$). The second test, with a coflow of 50 lpm ($Re=1102$), presented a mass flow rate of the flame's mixture of 2.8 lpm ($Re=550$), Figure 5.



Figure 6 - Flames with a coflow of nitrogen, 10 lpm (a) and 50 lpm (b).

The third test, with the ORCA Bunsen burner and the coflow of 90 lpm of nitrogen ($Re=2140$), the central flame remained stable up to 17 lpm ($Re=3325$), Figure 6. Here it can be noticed that, although the properties of the surrounding atmosphere gas, nitrogen, are almost identical to air, the maximum flow rate value for a stable flame were substantially lower, showing that the oxygen present on air have a significant role on the flame stability, even with a stoichiometric premixed flame ($\phi=1$), agreeing with the work of Claesson et al. (1983), that states about the oxygen on the coflow are responsible for the formation of free radicals, affecting the flame through diffusion to the flame.



Figure 7 - Coflow of nitrogen using the ORCA Labor burner.

3.3 Carbon dioxide atmosphere

The flames with carbon dioxide as the gas atmosphere presented a flow rate limit of 2.1 lpm ($Re=410$), for a coflow of 10 lpm of CO_2 ($Re=320$), and a limit of 1.7 lpm ($Re=330$), for a coflow of 50 lpm of CO_2 ($Re=2160$), Figure 7. For the third test, with a coflow of 90 lpm ($Re=3890$) and the ORCA Labor Bunsen burner, the maximum flow rate for the flame's mixture was 16 lpm ($Re=3130$), Figure 8.



Figure 8 - Flames with a coflow of carbon dioxide, 10 lpm (a) and 50 lpm (b).



Figure 9 - Coflow of carbon dioxide using the ORCA Labor burner.

With these experiments it is possible to observe that, although the gas properties are very different from the tests with nitrogen as gas atmosphere, the results were not so different. As stated by Edmondson et al. (1970), the gas atmosphere around the premixed flame can affect the flame through edge mixing, partially diluting the flame. The difference between the experiments with nitrogen as atmosphere, could be explained due to the high heat capacity of the carbon dioxide, that decreases the flame temperature, decreasing its stability limit, as well as the fact that the carbon dioxide is not an inert gas and participates on the chemical reactions (Nonaka and Pereira, 2016).

3.4 Methane atmosphere

When methane is the atmosphere gas, the conditions for the premixed flame are the opposite of air as the atmosphere gas, since here the atmosphere is composed of fuel instead of oxidant. The first and second tests resulted in 2 lpm ($Re=390$) and 1.5 lpm ($Re=290$) for the maximum flow rate in coflows of 10 lpm ($Re=224$) and 50 lpm ($Re=1121$), being the smaller values in all the atmosphere gases tested in this study, Figure 9.

The third test with methane as the atmosphere gas, coflow of 90 lpm ($Re=2018$), presented a maximum gas flow rate of 11 lpm ($Re=2150$) for the flame's mixture, also smaller than all the tests made with the other gas atmospheres (Figure 10).

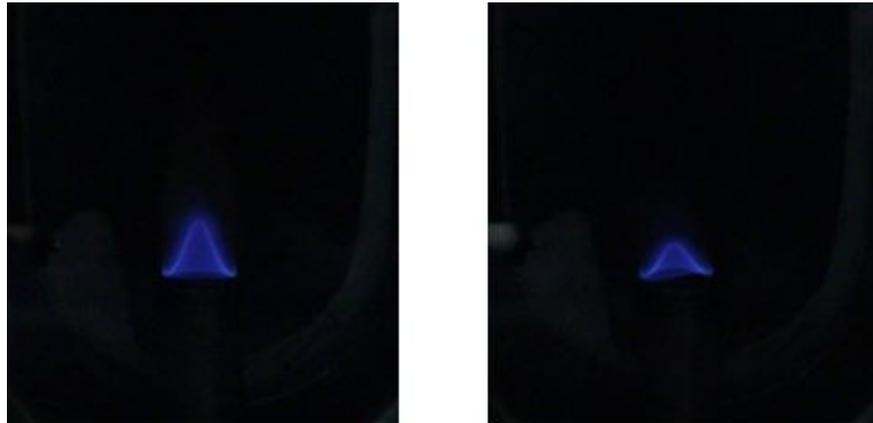


Figure 10 - Flames with a coflow of methane, 10 lpm (a) and 50 lpm (b).



Figure 11 - Coflow of methane using the ORCA Labor burner.

3.5 Argon/Methane atmosphere

Finally, the last atmosphere tested on this study is a mixture of argon and methane with a volumetric ratio of half each. The purpose of this mixture is to maintain a fuel atmosphere but with the same gas properties of air (Table 1), where argon, being an inert gas, acts as a diluent.

For the tests with the strait tube burner, the limit flow rate was 2.7 lpm ($Re=530$) with the coflow of 10 lpm ($Re=244$). The second test, with the atmosphere coflow of 50 lpm ($Re=1120$), resulted on a maximum flame flow rate of 2 lpm ($Re=390$), Figure 11.



Figure 12 - Flames with a coflow of argon/methane, 10 lpm (a) and 50 lpm (b).

The third test, with the ORCA Labor burner and 90 lpm of coflow ($Re=2200$), resulted on a maximum flow rate of 13.5 lpm ($Re=2640$) before the flame's blowoff (Figure 12). Comparing these results with the previous ones with pure methane as atmosphere, the limit flow rate of the flame was greater, showing that although the results presented a better range of stability, the atmosphere gas properties have not represented a big difference when compared to the results of air and nitrogen that have similar property values.



Figure 13 - Coflow of argon/methane using the ORCA Labor burner.

These results also shows that the methane atmosphere affects the flame through participating and interfering in the chemical reactions, since due to the high temperature of the flame and to the edge mixing effect the methane on the atmosphere can react and steal radicals from the flame. Therefore, when the methane is mixed with argon, an inert gas, this effect is diminished, resulting in a larger stability limit for the flame.

4. CONCLUSIONS

Through the evaluation of a stoichiometric methane/air premixed flame stabilized on different gas atmospheres, the influence of the surrounding gas atmosphere was studied. The atmosphere gas that presented the flame with the highest stability limit was Air, followed by nitrogen, carbon dioxide, the mixture of methane/argon and then methane (GN). Through the analysis of the experiments and the literature, the following conclusions can be drawn.

- 1) The gas atmosphere surrounding a stoichiometric premixed flame influence the flame stability, affecting it by edge mixing. Depending on the gas of the atmosphere the edge mixing effect can influence the flame by diluting the flame's mixture or having an influence over the combustion reactions.
- 2) The relevance of oxygen on the atmosphere gas are significant and easily noticeable. Air promotes a much larger stability limit than nitrogen, even though their properties are almost identical and that air is composed of 79% nitrogen. This corroborates with Claesson et al. (1983), that stated about the secondary air role in producing free radicals that help to sustain the flame.
- 3) Gas atmospheres containing methane are the ones that most affect the flame, this probably occurs due to dilution but also because the methane in the atmosphere when close to the flame are subjected to high temperatures, making the methane to react and stealing radicals from the flame.

5. REFERENCES

- Claesson, O., Noda, S., & Yoshida, H., 1983. ESR studies of Bunsen-type methane-air flames. I. Effects of the entrainment and diffusion of secondary air on the chemical reactions in the flame. *Bulletin of the Chemical Society of Japan*, v. 56, n. 9, p. 2559-2561, 1983.
- Edmondson, H., Heap, M. P., & Pritchard, R., 1970. "Ambient atmosphere effects in flat-flame measurements of burning velocity." *Combustion and Flame*, v. 14, n. 2, p. 195-201.
- Nonaka, H. O. B., & Pereira, F. M., 2016. "Experimental and numerical study of CO₂ content effects on the laminar burning velocity of biogas." *Fuel*, v. 182, p. 382-390.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.