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A STUDY OF GAS INTERCHANGEABILITY IN HIGH-POWER BURNER USING BY-PRODUCT OF THE STEEL MAKING PROCESS

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Abstract. *The steel industry produces a considerable amount of waste gases during its production process, such as the gas from the basic oxygen furnace (BOF). These waste gases, if properly utilized, can be a valuable source of energy and help reduce the industry's overall carbon footprint. The use of a burner that utilizes these gases can present some difficulties for the industry. These difficulties can be attributed to the chemical composition of the gas, which is a byproduct of the steelmaking process and is toxic overall due to its high carbon monoxide content. In the present work, we have developed a burner that uses only BOF and air to heat the steel ladle, which can carry 350 tonnes of molten steel. The difficulty in using a burner that uses BOF is its fluctuating composition, which has a great influence on the low heating value (LHV). The chemical composition of BOF can vary depending on several factors, including the quality of the raw materials used in steelmaking and the steelmaking process itself. The fluctuating composition can lead to different combustion characteristics, which can affect the stability and efficiency of the burner. In addition to the aforementioned challenges, conducting operational tests of the burner is also critical, as this type of fuel is not available on the general market. In this study, in addition to developing the burner for use with BOF, a test facility was developed to simulate BOF with LPG and air. The experimental plant consists of mixtures of LPG and air to study the interchangeability of gases by Wobbe index and multiple Weaver indices. Numerical simulations were performed using FLUENT to directly predict the combustion of BOF and simulate BOF. The Reynold stress model was used for the turbulence model and non-premixed combustion with non-adiabatic chemical equilibrium was used for the chemistry. Measurements of temperatures and chemical species were then made and used for comparison with the numerical results. The results show good agreement between the simulation and experimental data. The burner developed here is used to heat steel ladles in a steel mill capable of producing more than 5 million tons of steel per year. This work has a significant impact on steel production, mainly by reducing the consumption of other fuels in the plant, such as natural gas. The result is that the byproduct, which was waste, is used as the main fuel, reducing the carbon footprint.*

Keywords: *Basic Oxygen Furnace (BOF), High Power Burner, Interchangeability, Wobbe Index, FLUENT ANSYS*

1. INTRODUCTION

Steelmaking is a complex process that involves several steps, from the preparation of raw materials to the production of the final product (Turkdogan, 1996). During this process, several combustible gases are produced, which serve as a source of energy for the operation of furnaces, heat generators, and other industrial equipment. These gases are the result of chemical reactions and decomposition processes that occur during steel production, and their use contributes to the energy efficiency and sustainability of steel mills.

The main gases produced during steelmaking are coke oven gas (COG), blast furnace gas (BFG), and basic oxygen furnace gas (BOF). Coke is a solid fuel obtained by heating hard coal in the absence of air. During its production, volatile gases such as methane, ethane, propane and hydrogen are released. These gases are captured and used as an energy source in steel mills. Coke gas is normally burned in ovens or boilers to produce heat and steam which can be used to drive turbines and generate electricity.

Another important fuel gas is blast furnace gas. During iron ore reduction to produce pig iron, gases such as carbon monoxide (CO) and hydrogen (H_2) are produced as byproducts. These gases are captured and used as fuel in various steel mill equipment. Blast furnace gas is primarily used as a fuel in reheating furnaces, where steel is heated to high temperatures to facilitate rolling and forming.

In addition to COG and BFG, other fuel gases are produced during steel production, such as steelworks gas. It is also known as converter gas, LDG (Linz-Donawitz gas) or BOF and is produced in the refining stage of pig iron for steel production. In this step, oxygen is injected into the molten pig iron to remove impurities and adjust the chemical composition of the steel. As a result of this reaction, combustible gases such as carbon monoxide and carbon dioxide are released. These gases are captured and used as fuel in various industrial processes.

The use of these fuel gases from the steelmaking process provides significant benefits to steelmakers. First, the use of these gases as an energy source reduces dependence on traditional fossil fuels such as coal and oil, thus contributing to the reduction of greenhouse gas emissions and environmental sustainability. In addition, the use of these fuel gases helps optimize energy consumption in steel mills, resulting in higher energy efficiency and lower operating costs.

However, the major challenge in using such gases is their low calorific value and chemical composition. Table 1 shows the average composition of byproducts gases (Costa, F. C., 2010). These chemical compositions vary during the process, which also changes their LHV (Low Heating Value). These byproducts undergo purification treatment, which is almost always not very effective and allows impurities and moisture to pass through, making their use as fuel a major challenge. In addition, as can be seen, BFG and BOF contain a large amount of inert species, which justifies their low LHV and makes their combustion even more difficult. One of the techniques used for their use as fuel is to blend them with gases with higher calorific value, such as COG (Coke Oven Gas), NG (Natural Gas), LPG (Liquid Petroleum Gas) or even biomethane, if available. Another option is to enrich the combustion air with oxygen (23 to 30%) or even to burn the gas with a high oxygen content (above 92%) in a process known as oxyburning, as reported in Costa (2010).

Table 1 – Properties of by-products gases.

	O_2	CO	H_2	CO_2	N_2	CH_4	C_nH_m	LHV (kcal/Nm^3)	Theoretical flame temperature (ºC)	Theoretical amount of air (Nm^3/Nm^3)	Gas density (kg/Nm^3)
BFG	0.4	20 - 36	1.5 - 8	3.5 - 13	55 - 61	-	-	~800	~1300	~0.61	~1.34
COG	1.0	7.5	59.1	2.6	6.2	21.5	2.1	~4300	~2130	~4.50	~0.45
BOF	trace	65 - 80	-	5 - 7	25 - 35	-	-	~1900	~1900	~1.61	~1.34

On the other hand, steel gases are very difficult to be used in heating due to the impurities contained in them and due to fluctuations in their respective chemical compositions, which also reflects on their LHV, besides large amount of humidity. In heating processes, where it is necessary to maintain temperatures within a previously determined curve, this is a serious problem, as in addition to the chemical composition affecting the LHV, it also affects the equivalence ratio, which is intrinsically linked to the flame temperature. Therefore, it is often preferable to incinerate these types of gases in flares, without direct use in industry, which is extremely harmful to the environment, as it increases emissions of polluting gases into the atmosphere. BOF is typically produced at a rate of 80 – 100 m^3/t molten iron produced Ludick (2018).

In short, fuel gases from steel production, such as cited before, are valuable resources that can be used as an energy source in steel mills. Their use contributes to energy efficiency, reduced emissions and the sustainability of steel operations. The use of these gases is an important step in the search for more sustainable steelmaking processes and in the transition to a cleaner and more efficient steel industry. Caillat (2017) reports on the main applications of the use of by-product fuel gases in reheat furnaces and annealing lines equipped with tens and hundreds of burners, respectively, below 200 kW power. In this work, he points out the main difficulties in the use of these fuel gases, such as variations in composition, humidity and impurities. (Bruna et al., 2020) studied the economic impact of using combustible gases from by-products in the steel industry as a means of meeting natural gas shortages in Europe. According to (Zhao et al., 2021), the use of these alternative fuels has a great impact on reducing CO_2 and increasing the efficiency of industrial processes, thus reducing productivity costs.

In order to use these gases from steelworks production, combustors are required that can burn them with a high degree of efficiency. The development of burners for this purpose is an extremely difficult and demanding task, as several parameters must be considered in order for them to function safely. As you can see, these gases have a high concentration of carbon monoxide, a very dangerous and deadly gas. When building burners, especially industrial burners, extensive testing is required to avoid accidents of any kind. In addition, and no less important, the burner's operating intervals must be evaluated by varying the air and fuel flow rates. For such an evaluation of industrial burners, as developed in this work, large gas flows are required. As these gases are only available in industrial plants, it is practically impossible to carry out preliminary tests to determine the operating range of these burners for reasons of safety of the operating personnel and the plant itself. One way of testing would be to simulate the chemical composition of each gas using storage cylinders containing the relevant chemical species. However, this is not economically feasible either, as it is a burner with a high thermal load and large quantities of each type are required, as well as their respective control by several flow and pressure meters and a good mixer, which also increases the operating risks.

Costa et al. (2015) investigated mixtures of LPG and air to simulate natural gas. Due to interruptions in the natural gas supply in some cities, the ratio between these gases was studied so as not to affect productivity in the different industrial sectors. They point out that the devices can operate safely if the gas mixture remains within ± 5% of the Wobbe index of the fuel for which it was designed. They also report on the various difficulties in using these mixtures, not only because of the performance of the devices, but also because the various measuring devices, such as flow meters, are calibrated directly for natural gas. In addition, to obtain the Wobbe index of natural gas, a volume mixture of 51.3% LPG and 48.7% air must be used, which means that 1 m^3 of synthetic natural gas is equivalent to 1.49 m^3 of natural gas, which can cause problems with the combustion gas velocities in the appliances to be used. In this work, the use of a bench containing a mixture of LPG and air is proposed to simulate the properties of these steel gases, in particular BOF. To do this, it is necessary to use the Wobbe index and several Waever indices so that the mixture of these gases is as close as possible to the gas to be used.

2. THE BURNER

The burner used was idealized, designed, built and patented by Veríssimo and Passos (2021). The burner is designed to achieve high power rates using combustible gases produced as a byproduct of steel production (BOF). The burner's heat requirement is 5,000,000 kcal/h (five million kcal/h) and requires a thorough study of all physical and chemical aspects, i.e. thermal, aerodynamic and mechanical design. BOF gas is a gas with an extremely low PCI, since this value is about 1/4 of the PCI of natural gas and its chemical composition is essentially carbon monoxide and inert substances. Generally, this type of gas is burned in flares at remote locations in a steel mill, and when it is used for other purposes, it is burned together with oxygen. With the aim of using only the BOF, the proper aerodynamic configuration was studied to achieve effective anchoring of the flame without lifting or flashback.

A project of this type is of enormous complexity, since it is necessary to solve several aspects related to the gas and the final heating for which it will be destined, divided into the following steps: Determination of the thermal load of the burner, evaluation of the variation of the chemical composition of the gas, the humidity of the gas, the pollution of the gas and the requirement of applicability, in the case of heating steel ladles and their respective heating curves.

The output speeds of the burner are of the order of 100 m/s, with the aim of heating well the lower parts of the steel ladle. A schematic drawing and a picture of the burner are shown in Figure 1. The burner consists of three swirlers, the outermost of which contains the combustion air, the inner one the fuel and the middle one the pilot burner. The air inlet has a diameter of 12 inches (304.8mm), the fuel inlet has a diameter of 8 inches (203.2mm). The length of the burner body is 800 mm and its total length is 1500 mm.

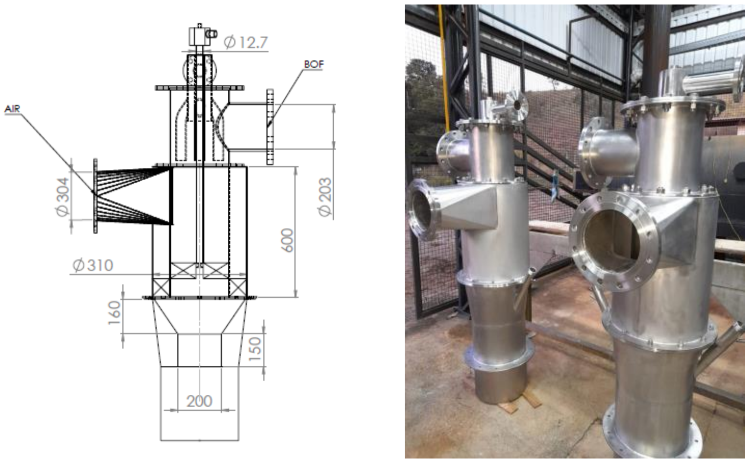
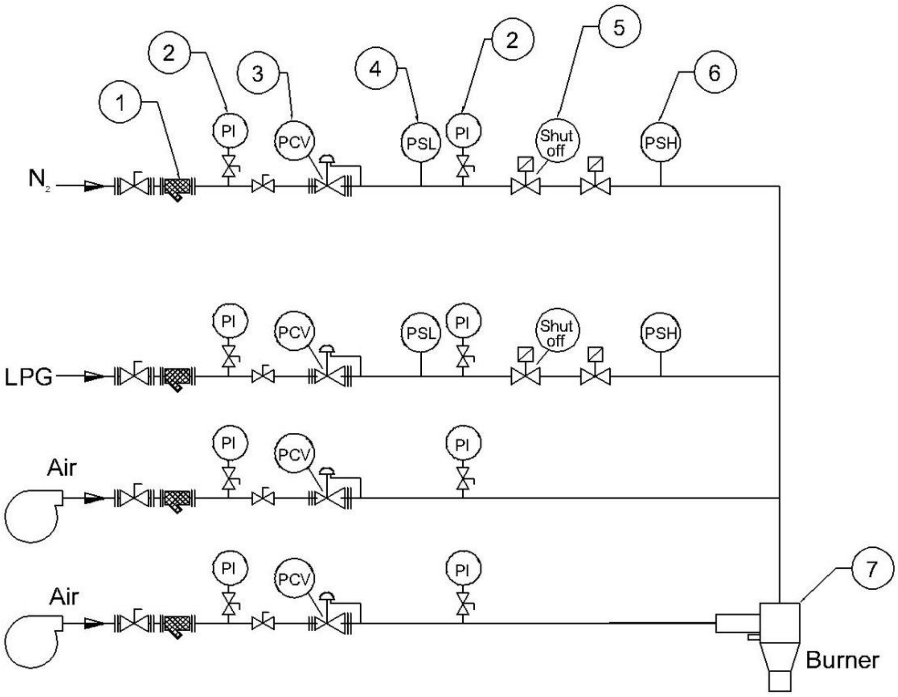


Figure 1 – BOF burner for heating steelworks ladles. The dimensions are in millimeter.

3. EXPERIMENTAL SETUP

A test rig was set up to carry out tests with the gas mixture to simulate BOF. The diagram to make the blending of the gases is shown in Figure 2 and consists of an airline fed with a variable speed centrifugal blower to control the air flow, LPG with a needle valve and a nitrogen line for purging. The flow rate of the gases was measured using mass flow meters manufactured by FOX, model FT-2.



1	Filter
2	Pressure indicator
3	Pressure control valves
4	Pressure switch low
5	Shut off
6	Pressure switch high
7	Burner

Figure 2 – Representation of the mixing line to simulate by-product gases.

A natural gas-fueled pilot burner was used for a safe start, strategically positioned to ensure a smooth start of the main burner. This is an optional item but has proven effective when the fuel line contains a lot of moisture. Figure 3 shows an image of the experimental setup.

Figure 3 – Experimental arrangement. Left side instrumented burner. Right side with pilot flame.

Due to the thermal load, it was used to perform the tests with maximum load. The image of the test with half nominal load and with full load is shown in Figure 4. In both cases, the flame showed a yellowish color. The temperature measurements were performed according to the excess air. A type k thermocouple, with 6mm of diameter, was used to measure the temperature. The thermocouple was located around 1.5m far from exit of the nozzle burner at the center line.

Figure 4 – Images of the burner test simulating the BOF.

4. WOBBE INDEX AND MULTIPLE WEAVER INDICES

Gas interchangeability is the ability to use different types of gases in the same combustion device without affecting the operation of the device. If two gases have a Wobbe index within a range of ± 5%, they can be considered interchangeable, Garcia (2010) and Costa (2015). The Wobbe index is obtained from Equação 1:

$$W = \frac{LHC}{\sqrt{d}} \qquad (1)$$

where W is the Wobbe index, LHC is the higher heating value, and d is the density of the gas relative to air.

The following chemical composition and some properties of BOF are listed in Table 2. This is the average chemical composition measured through a gas chromatography at the steel mill where the burner is in operation.

TABLE 2 – BOF composition to use in numerical simulation.

Component	
CO (% Vol.)	53.23
CO_2 (% Vol.)	17.34
H_2 (% Vol.)	2.71
N_2 (% Vol.)	26.72
Viscosity (cP)	0.016478
LHC (kcal/Nm^3)	1,675.8
Temp. Stoich. (ºC)	1,878
Wobbe Index (W) (kcal/Nm^3)	1,896

For the composition in Table 2, the Wobbe index is 1,896 kcal/Nm^3. Based on this, it was calculated the mixture between the LPG and air showed in Table 3. Although for practical purposes the chemical composition of LPG is estimated at 50% butane and 50% propane, it is important to use the chemical composition in more detail involving other elements such as propylene, butylene, etc., to obtain the Wobbe index as close to the real thing as possible. Using a mixture of LPG and air to evaluate the behavior of the BOF burner is very important because this byproduct is not a gas available on the network, much less in steel mills to carry out such types of tests.

Table 3 – Mixture between LPG and Air.

Species	**Mole Fraction**		
CH_4	0.000592	0.000624	0.000656
N_2	0.729300	0.726018	0.722727
O_2	0.193865	0.192992	0.192117
C_3H_8	0.020021	0.021104	0.022189
C_3H_6	0.024009	0.025307	0.026609
C_3H_4	0.003841	0.004049	0.004257
C_4H_{10}	0.015235	0.016059	0.016885
C_4H_8	0.007706	0.008122	0.008540
C_5H_{12}	0.005432	0.005725	0.006020
Sum	1.000000	1.000000	1.000000
Iw	1801.5	1896	1991.1
FUEL	7.68%	8.10%	8.52%
AIR	92.32%	91.90%	91.48%

The calculations for the multiple Weaver indices are shown in Table 4. Details of the calculations and the factors for each gas can be found in Garcia, (2013) and (Yu and Mandi, 2021). The Weaver index method includes six determination indices: the heat load index J_H, the air emission index J_A, the flashback index J_F , the lifting index J_L, the emission index CO J_I and the yellow tipping index J_Y. W is the Wobbe index; V_0 is the theoretical air volume; s is the relative density; O_2 is the volumetric composition of oxygen in the fuel gas; S_f is the flame velocity index; N is the number of carbon atoms that readily precipitate during combustion in 100 fuel gas molecules; R is the ratio of hydrogen atoms in the fuel gas to the number of carbon atoms in the hydrocarbon. The indices a and s represent the reference gas and the substitute gas, respectively.

The results of the calculations of the multiple Weaver indices for the variations of the Wobbe indices are shown in Table 5. Note that the unit thermal load is achieved when the W is 5% below the BOF W, which is evident from the percentage increase of LPG in the mixture. However, the air supply may be affected under these conditions. None of the other calculations indicate flame separation or flashback, with CO emission rates and yellow peaks remaining below the prescribed limits of the Weaver indices.

Table 4 – Multiple Weaver Indexes.

Weaver indexes		
Indexes	Calculation formula	Exchange range
J_H	$J_H = \frac{W_s}{W_a}$	0.95 ~ 1.05
J_A	$J_A = \frac{V_{0s}\sqrt{S_a}}{V_{0a}\sqrt{S_s}}$	0.80 ~ 1.20
J_F	$J_F = \frac{S_{fs}}{S_{fa}} - 1.4\frac{V_{0s}\sqrt{S_a}}{V_{0a}\sqrt{S_s}} + 0.4$	< 0.08
J_L	$J_L = \frac{S_{fs}V_{0s}\sqrt{S_a}(100 - O_{2s})}{S_{fa}V_{0a}\sqrt{S_s}(100 - O_{2a})}$	> 0.64
J_I	$J_I = \frac{V_{0s}\sqrt{S_a}}{V_{0a}\sqrt{S_s}} - 0.366\frac{R_s}{R_a} - 0.634$	< 0
J_Y	$J_Y = \frac{V_{0s}\sqrt{S_a}}{V_{0s}\sqrt{S_s}} + \frac{N_s - N_a}{110} - 1$	< 0.14

Table 5 - Results of interchangeability of mixture between LPG and Air.

	A	B	C
W (kcal/Nm^3)	1801	1896	1991
FUEL (LGP)	7.68%	8.10%	8.52%
AIR	92.32%	91.90%	91.48%
J_H (heat load index)	1.00	1.06	1.11
J_A (air emission index)	0.71	0.79	0.87
J_F (flashback index)	-0.42	-0.53	-0.63
J_L (lifting index)	1.03	1.15	1.26
J_I (emission index CO)	-0.36	-0.28	-0.21
J_Y (yellow tipping index)	-0.11	-0.04	0.04

5. NUMERICAL SIMULATIONS

To simulate the burner behavior, numerical simulations were carried out with the byproduct BOF as fuel and the corresponding Wobbe index air and LPG mixtures. FLUENT/ANSYS was used for this purpose. The mesh used for the numerical simulation of the burner is shown in Figure 5. The mesh consists of approximately 4,147,336 elements. To capture the effects of the flame at the burner outlet, a 2 m long cylinder with a diameter of 600 mm was considered. The "pressure outlet" condition was used for all surfaces of this cylinder. For the initial fuel and air conditions, 17.17 m/s @ 1.5 mmH_2O and 24.68 m/s @ 700 mmH_2O were used respectively.

Figure 5 – Mesh used for predicting burner results.

The *k-ε RNG model* was used to simulate turbulence with *Swirl Dominated Flow*, with near-wall treatment using the *Standard Wall Function*. For combustion modeling, the chemical equilibrium in the mixture fraction was used for the composition given in Table 2 for the BOF and Table 3 for the mixture between LPG and air.

Figures 6 to 8 show the results for the temperature distribution and the distribution of the chemical species carbon monoxide (CO) and hydroxyl (OH), which are all located in the center plane of the burner. Note that despite the opposing air inlets and fuel inlets, there is a certain symmetry in the distribution of temperature and chemical species. OH can be used as a good indicator of the flame front as it is present in the areas of greatest reactivity, which coincide with those of highest temperature. The oxidation of CO is slower compared to other chemical reactions, which also gives an indication of the extension of the range of chemical reactions between fuel and oxygen.

Although the LPG and air mixtures are within the acceptable range of interchangeability of the Wobbe index, they are different from the BOF simulation itself. In the LPG and air mixture, the temperatures tend to occur in the center of the burner, while the temperature distribution in the simulation of the burner itself is rather broad (Figure 6). Although the mixtures must comply with the limits of the Wobbe indices, air and LPG are mixed, giving the burner a premixed characteristic, which also justifies the higher temperatures and higher OH concentrations compared to the BOF simulation (Figure 7). Also, in Figure 7, the area with the highest concentration can be seen in a thin region representing the flame front itself. The carbon monoxide concentrations are, as expected, much higher in the case of the BOF simulation, which is due to the high concentration in the fuel (Figure 8). Looking only at the mixtures, it can be seen that the CO concentration increases with the percentage of LGP, which is to be expected due to the increased degradation of hydrocarbon molecules. In all cases, the highest concentrations are found in the center of the burner, as the flow is spiral, and the fuel is injected through the center. On the other hand, it should be noted that the burner did not exhibit any flame return or detachment predicted in the numerical simulations, which is consistent with the calculations performed with the Weaver indices shown in Table 5.

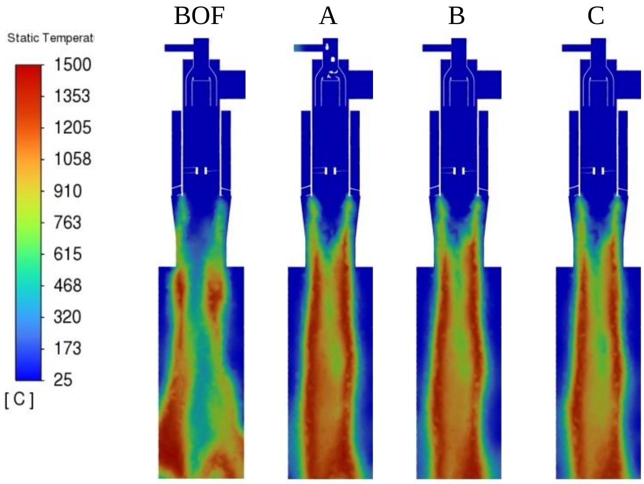


Figure 6 – Temperature distribution.

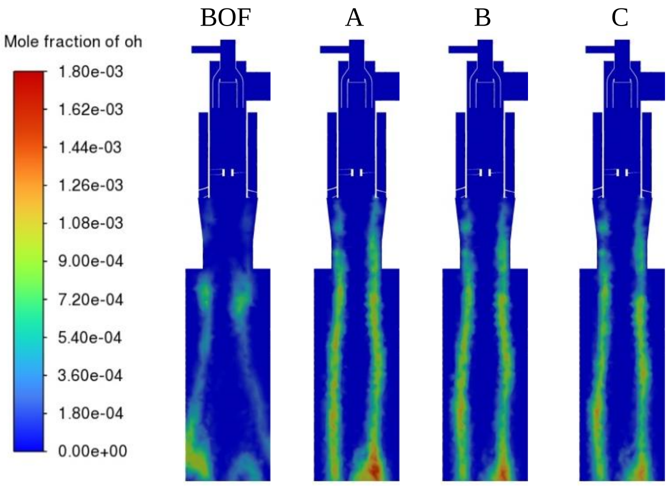


Figure 7 – OH distribution.

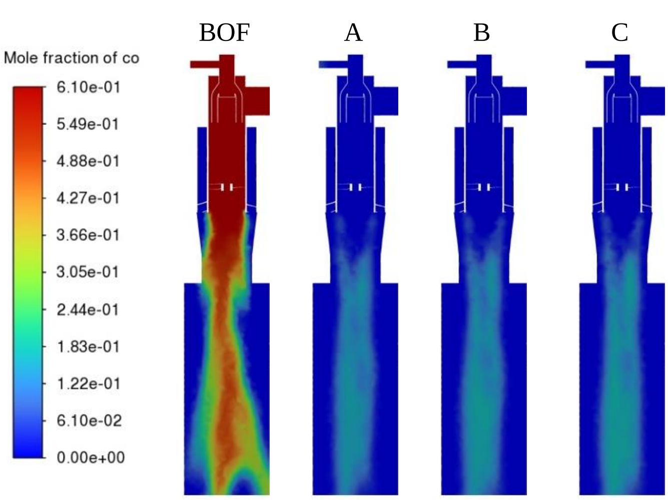


Figure 8 – Carbon monoxide distribution.

6. EXPERIMENTAL RESULTS

First, fuel modulation tests were performed to verify the stability of the combustor operations. Temperature measurements were then taken at 1 meter far from the burner exit at the center. The temperature measurements were made with a K-type thermocouple with 6 millimeters of diameter , placed at the burner outlet both for the simulation of the blended of LPG and air and steelmaking gases and during the steelwotks operation itself. The results for the temperatures measurements are shown in Figure 9. Compared to the theoretical values, they are significantly lower, as adiabatic conditions were taken into account in the calculations. The measurements were made by setting an air flow rate and varying a fuel flow rate to simulate the operating limits of the burner. Note that the temperature measurements for the case of mixture B and the combustion of the steel gas itself are below the adiabatic flame temperature. This is due to heat losses through thermal radiation at the thermocouple head and also to its size. As the measurements were carried out in an open environment, the temperatures were corrected for thermal radiation losses as described in Rocha et al. (2008). The temperature measurements were carried out for mixtures A and B, and no changes were observed in relation to mixture B. During the tests, the flame did not flashback or lifting, so the operation was maintained as expected.

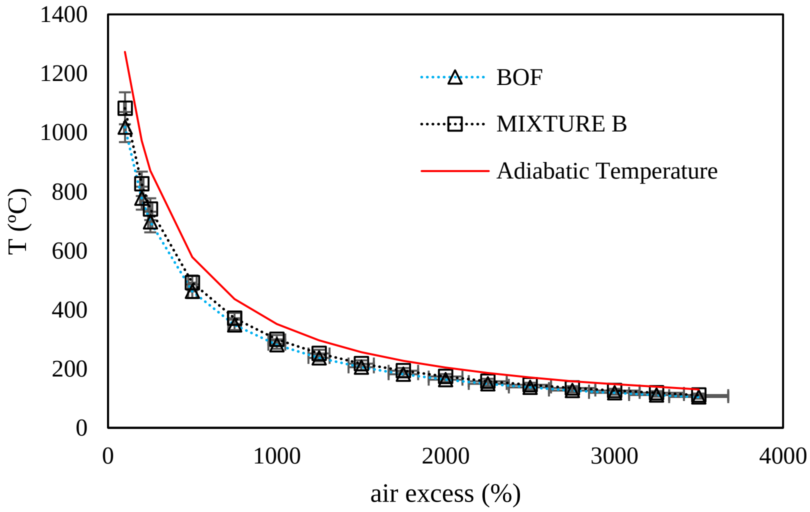


Figura 9 - Comparison between adiabatic, mixture B and BOF temperature.

7. CONCLUSIONS

The aim of this work was to test the operating limits of a burner designed for operation with byproduct gases from steel production, the BOF. Since BOF is only available in steel mills producing stainless steel, a test rig was built with a mixture of air and LPG, whereby the respective Wobbe indices of the BOF were matched with those of the mixture. The burner was also simulated by running it with the BOF only and then with a variation of the Wobbe index of the mixture in the range of ±5%. It was found that there are some distortions in the flame fronts of the fuel with which the burner was designed to operate on the fuel simulated on the test rig. This is probably since the simulated fuel contains oxygen in its composition, which gives the burner premixed flame characteristics.

The Wobbe index and the multiple Weaver indices are a good approximation for the interchangeability of gases, especially for the purpose of this work, where it is difficult to test an industrial burner because a large amount of fuel is used. However, it is essential to carry out detailed analyses of the reactive flow in its entirety, especially in the form of the flame front. However, it is essential to analyze the reactive flow in its entirety, especially in the form of the flame front, in detail. The experimental setup set up here can be used to test another type of combustible by-product such as COG or BFG.

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