EXPERIMENTAL DESIGN OF A BURNER AND FLAMELESS COMBUSTION CHAMBER FOR NOx REDUCTION

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***Abstract**: This paper presents the development of design parameters and construction of a camera model and a burner with distinguishable features used to implement a new type of combustion, named: Flameless Combustion. Flameless combustion is a system of stable combustion without the presence of visible flame, defined by the recirculation of hot products of combustion inside the chamber volume. Unlike conventional combustion processes, it is not possible to see the visible presence of flame inside the combustion volume. Burners used for this purpose usually have a complex geometry, and as a consequence, it is difficult to simplify this process. Despite being a relatively new technique and little known, it has been gaining attention in scientific circles because of the great advantages compared to conventional combustion. The main advantages are: significant reductions in forming pollutants, especially NOx and CO, increased thermal efficiency, fuel oxidation and their distribution throughout the volume; considered reducing the temperature gradient and concentration of species, etc. The main applications are: steel and glass industry, chemical industry and power generation. In this case, this paper aims to: a) know, understand and support physical and chemical phenomena of the standard behavior of this regime of combustion in laboratory scale; b) describe and present the design of a burner and a flameless combustion chamber for experimental research, c) present the results of qualitative and functional characteristics of the burner for different parameters. Finally, it is expected that this research will enable recommendations for future practical projects for thermal devices using this technology, and the experimental setup is able to achieve the needs of the project at the laboratory and serve as a reference for the study of this technique in Brazil. During the experiments, natural gas was used as fuel and preheated air as oxidant. In order to verify the functionality of the system, a gas analyzer was used to measure emissions of pollutants. The main conclusions were: a) the design of the burner and camera for this mode of combustion are relatively complex, requiring more understanding about the physical and chemical phenomena that influence the mix and the standard behavior of this combustion system; b) the final design of the set (burner and chamber) has operational features that are flexible and able to achieve the operational requirements of the technique.*

***Keywords**: 1. Combustion; 2. Flameless; 3.Burner; 4. Chamber*

1. INTRODUCTION

The development of efficient and low polluting combustion systems is the combustion researchers' and combustion equipment manufacturers' main goal. Due to scarcity of resources which adds to environmental problems arising from the utilization of energy and extraction of natural products, the concept of recovering thermal energy from combustion has expanded, and solutions have been sought through actions in energy efficiency (better usage of thermal energy with low emissions), greater insertion of biomass fuels, hydrogen usage, concerns with other gases, and greenhouse gases, such as methane and NOx.

Recently, the control of these emissions, mainly carbon monoxide (CO) and nitrogen oxides (NOx), has also become the most important target in the design of combustion chambers and industrial burners. Specifically for the NOx case, most control strategies in combustion processes are based on three variables: residence time, temperature and oxygen availability. These strategies are focused on reducing peak temperature, keeping the residence time, and low oxygen concentration at high temperature zones. However, two techniques are generally used in order to achieve these objectives: a) changing the burning process through appropriate burners, that operate in the formation mechanism of the pollutants, b) treatment of exhaust gases, acting on the mechanism of destruction of pollutants (Lefebvre,1983).

Despite these existing strategies, the growing global energy demand stimulates the development of combustion systems that are more efficient and pollutes less than the old ones.

In this scenario, a technology that has gained interest in current research as a promising technique for combustion control and minimization of emissions of NOx and other pollutants is the flameless combustion (smoldering visible). This technique is a new type of combustion that changes the characteristics of the reaction zone and consequently the formation of combustion products by process modifications.

Despite being a technique recently discovered and little known, nowadays the flameless combustion has gained attention in scientific circles because of the great advantages that offers in its use compared to conventional combustion.

The main advantages of the flameless combustion are significant reductions in forming pollutants, especially NOx and CO, increased thermal efficiency, fuel oxidation and its distribution throughout the chamber volume, considering reductions in the gradient of temperature and concentration of species etc.

Better focus on the involved phenomena during combustion is needed for practical implantation of this technology. In this case, better knowledge of the physical and chemical processes of flameless combustion could contribute significantly both to advance its application and improve its efficiency.

Based on this background, this paper presents the results of a project with aim was identifying a configuration of a burner and combustion chamber that operate accordingly to the concept of technology flameless and provide practical and dynamic operating conditions in laboratory scale.

2. FLAMELESS COMBUSTION

Flameless Combustion is a combustion technology that forms invisible flame with theoretically an evenly distributed combustion and temperature, and that generates low noise. It is reported that Flameless Combustion produces extremely low NOx emissions by utilizing high temperature inlet air and by recirculating high percentage of hot exhaust gas into the reaction zone.

Flameless Combustion is characterized by the fuel reacting with a very high temperature oxidizer with intense levels of turbulence producing a highly distributed reaction zone2. The highly distributed reaction zone eliminates hot spots and high NOx production. The turbulence levels of the Flameless Combustion are so high that if operated in the current diffusion flame combustion technology, the heat and reactive free radials would be rapidly and widely dispersed and the combustion would be unstable at lean conditions. When the oxidizer temperatures are very high, the low Damköhler number "Flameless" reactions become very stable. It is the nature of these distributed flame that lead to the term "Flameless Combustion". Through laser-optical investigation of highly preheated combustion with strong exhaust gas recirculation, Plessing *et al.* (1998) showed that the flameless oxidation takes place in the well-stirred reactor regime. The OH concentration in the flame zone of flameless combustion is lower than in non-preheated undiluted turbulent premixed flames.

According to Wunning (2004), the phenomenon was observed during experiments with recuperative burners. The experiment worked with the furnace at temperatures about 1000 ° C and air preheated to 650 ° C. It was observed that with the combination of certain input parameters (Re, Equivalence ratio, space between inlet and others) the system started reacting under different conditions from the conventional.

It was observed that when the system operated in flameless conditions, no flame could be seen and no UV signal could be detected. However, the fuel was consumed. It was also realized that the CO contained in exhaust gases decreased to below 1ppm. The emission of NOx was close to zero. Furthermore, the combustion was stable and smoothly, without the existence of instability in the flame.

During the combustion regime, air and fuel are directly injected into the combustion chamber at high velocity (extreme 'stages') helping to create a structure of carriage of burned gases. In other words, the reactants are gradually mixed with a large amount of internal recirculation gas, thereby reducing the adiabatic flame temperature of the mixture and further heating the air and fuel or air/fuel at the same time. Figure 1 show the image of system operating in flameless conditions.

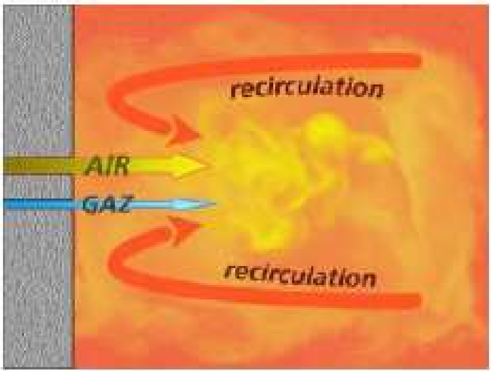

Figure 1. System under flameless conditions (Delacroix, 2005)

Wang *et al.* (2006) show that contrary to what occurs in conventional flames, an important feature of the flameless combustion is that there is no air added to the center line of fuel before the reaction. The recirculating exhaust gas is mixed in advance into the combustion air. After, this mixture reacts with the fuel injected into the center, resulting in the reaction zone. The reagents are mixed and react at a certain distance from the injection point. The flame, since then, can't be seen again, and combustion is mostly distributed through the volume of the combustion chamber. This allows a low flame temperature, low oxygen partial pressure in the reaction zone, and as a result, there will be a low formation of nitrogen.

According to Delacroix (2005), the geometry of the burner and combustion chamber, and high injection velocity are key factors to the internal recirculation of combustion products in the chamber. The high temperature of combustion products in recirculation (> 850 º C) is used to initiate and maintain stable system operation. This temperature must be above the auto ignition temperature of the mixture between air and fuel.

The stability of the flameless combustion behaves as a function of the amount of gas recirculation in the chamber volume defined as the rate of recirculation. Figure 2 shows the stability limits for different combustion modes as a function of reaction temperature and recirculating exhaust gas for methane. The gas recirculation rate is defined according to Eq (1).

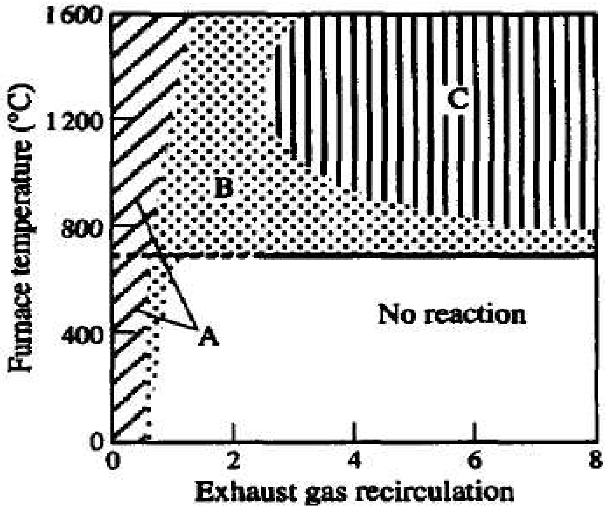

Figure 2. Stability limits (Wünning, 1997)

$$K_V = \frac{\dot{M}_E}{\dot{M}_F + \dot{M}_A} \tag{1}$$

Onde: Kv – Recirculation rate; M_E - Recirculated exhaust gas; $\dot{M} f$ – Fuel; $\dot{M}_A$ – Combustion air.

The region A (Kv <3) corresponds to the region of stability of conventional flames. The intermediate region B represents an unstable combustion (flame lift). It is the transition region to the next regime, but in case of temperatures below the auto ignition the flame moves and deletes itself. If the furnace temperature and recirculation of exhaust gases are sufficiently high (Kv> 4), the fuel reacts regularly giving rise to a stable region called C Flameless Combustion.

To Wunning (1997), the main motivation for the usage of flameless combustion is associated with the reduction of NOx emissions that is achieved by controlling the temperature of combustion products and the degree of mixture of reactions. Furthermore, most industrial operations operating in flameless regime can improve their operational performance by using preheated air. Preheated air leads to energy economy and its dilution with exhaust gases results in lower emissions of NOx, which is so important.

According to Wunning (2004) with the development and research of this technique in industry, other benefits might be found, such as: construction of furnaces to a lesser extent for the same production capacity, higher thermal efficiency accompanied by lower energy consumption, and usage of more compact burners, which facilitates the maintenance and installation.

The main applications of this technique are: in the steel and metals. The steel industry pioneered the implementation of these types of burners. Its application is at: forging and annealing lines, galvanizing, reheating pipes, production lines of silicon steel strip with recuperative burners, etc. Besides this, other applications and research are being undertaken, such as in ceramics and glass industry, chemical industry, energy generation, gas turbine combustors, the incineration of organic products, transportation, etc.

Based on this background, this paper presents an investigation and the results of a project conducted with the aim of identifying a configuration of burner and combustion chamber based on the principles of the flameless technology and is able to provide the dynamic conditions of the scheme of combustion, and that can be implemented experimentally in laboratory to verify the reduction of NOx and other pollutants during operation of the system.

3. METHODOLOGY OF THE PROJECT

In general, there are few experimental models of combustion chambers and burners flameless described in the literature, and in addition, most existing research provides few details of the design parameters and operating technique. Therefore, work and research conducted by Plessing *et al*. (1998) and Szegö *et al*. (2009) served as a guideline for the guidance of the various features and geometry of the combustion chamber and the burner used in this work.

Initially after joining as many details and important information of the operational parameters of the technique, it was defined the configuration of the chamber and burner that meets the requirements for operation of the technique in various operating conditions. These settings are shown in the following chapters.

In general, the stages of the project were as follows: a) defining the camera model, b) type definition burner, c) correctly define the main operational parameters of the configuration of the burner and camera, such as relative position between holes of air and fuel (space and angle), diameter of the holes injection of reagents, amount and form of distribution of air jets and / or fuel, equivalence ratio (Φ); power of the burner inlet temperature of air, etc.

Szegö *et al.* (2005) commented that various parameters are important for controlling the combustion dynamics and the Carriage of combustion products in the fuel lines and air before the reaction, and still asserts that the most common design parameters in the burners are momentum (amount of movement), tilt angle, and distance supply of air and fuel.

Kuo (1986) commented that the downstream recirculation zone of the burner strongly influences the burning process and hence will also affect the emission of pollutants, and still suggested that the design of combustion chambers is fundamental character of the correct sizing of the air distributor and the restraint of the flame because, as a consequence, there is an optimal fuel consumption, minimizing the production of CO and NOx control and the dynamics and dimensions of the flame.

4. RESULTS OF THE PROJECT

As mentioned, there are just few models of camera and burners used to identify the functionality of this combustion regime, being necessary to achieve a configuration of burner and camera that takes effective mixing of fuel and air with gas recirculation in a range of established operating conditions.

According to Maruta *et al*. (2000) the performance is assured based on the uniformity of the temperature profile, rate of heat release and operational flexibility. So based on these criteria and design parameters, the following results are presented as the prototype of the burner and laboratory scale chamber that will serve for the tests of this technique.

4.1. Burner

This burner is defined in a category called regenerative burners. In this type of burner the hot exhaust gases preheat the combustion air by the exchange of regenerative heat. In other words, the combustion gases are drawn through the burner itself, thereby; the combustion air is preheated by the undertow while cooling the flue gas. It differs from a conventional burner and the choice of burner influences the function of the flameless combustion regime. Szegö *et al.* (2005) said that the geometry of the burner and combustion chamber, and high-speed injection of the reactants are decisive factors for the internal recirculation of combustion products in the chamber.

The design parameters to be defined were: a) the amount and distribution form of air jets and / or fuel, b) relative position between the holes of air and fuel (space and angle), c) diameter of the holes of reagents injection; d) position of the exit of exhaust gases. Figure 3 shows the image with some measures of the burner that is designed in this study.

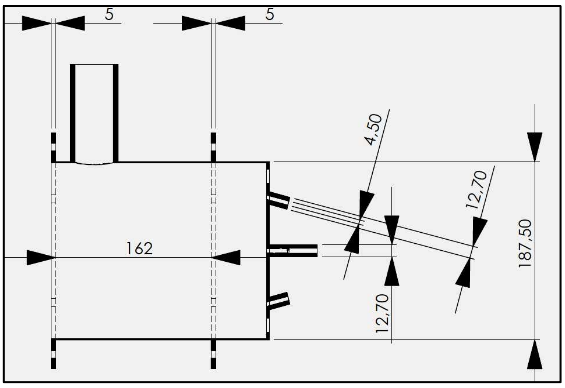

Figure 3. Characteristics and measures of flameless burner

While defining the number of jets, it was noticed that generally a large number of jets decreases the amount of motion of the air entrance. Therefore, to ensure adequate mixing of the air jet with recirculation gas, we adopted a configuration that would serve this requirement in a best way. Szegö *et al.* (2009), from numerical models, concluded that the maximum of four holes is an ideal amount of air entrances. This value favors the recycling of a bigger quantity of gas in the combustion volume.

As shown in Fig. 3 the fuel and air are injected separately. On the front face, the burner is composed of a central fuel lance and four air inlets arranged symmetrically and equidistant from the center. In each exit of reactants, there is a stretching (shoulder) of characteristic length. According to Coelho and Peters (2001) the fuel bounce promotes the release in more distant regions of the burner face, creating the necessary conditions for flameless conditions, in other words, makes the reagents mixing slower.

The space and the angles of injection vary according to the characteristics of the camera model and the burner. Szegö *et al*. (2009) used an injection angle of 15 ° in the fuel line, which resulted in the desired operations. With that angle, it was observed that there was a mixture suppression of air and fuel near the burner entrance, causing both to mix downstream of the burner. This enabled the combustion gases to have time to mingle with the fuel line before mingling with the center line of air and entering into reaction.

In this work, both the jets of air are displaced approximately 15 degrees to the central axis. The positions of each jet of air and fuel, and the displacement of the injection angle in the outlet air were determined in a way that the reagents were mixed at the central axis of the chamber in a distance of 220 mm downstream to the burner. Szegö *et al*. (2005) as previously mentioned, the high velocity of reactants entrance, the angles of injection of air injectors, and the relative distance between the nozzles are basic features to facilitate the recirculation of combustion gases.

The bounce of the fuel injector was made by the same material of the burner, and has 50 mm length and 9.5 mm inner diameter. For the air exit, 22 mm bounce, and 4.5 mm internal diameter. The external face of each shoulder is threaded, where the nozzles are placed with varying diameter.

Another important feature is the exit position of the exhaust gases. Here, the gases are extracted by the same face of entry of reagents or the body of the own burner. Figure 4 shows four outlets for combustion gases, these outlets are positioned equidistantly from the central axis of the burner (external orifices to the entrance air orifices).

It was attached a small "chimney" in the body of the burner to recover the combustion gases. In this type of operation is common for models to have gas outlet on the same side of entry of the reactants. This feature greatly facilitates the return of gas recirculation, which is needed to keep the system in operation. This also ensures a better alternative for reactants dilution in the combustion volume (Wunning, 1997).

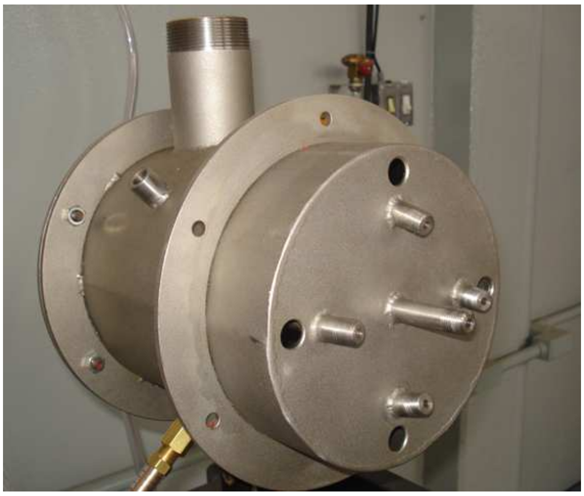

Figure 4. Flameless burner

The main characteristics of the used burner are briefly shown in Tab. 1.

Table 1. Burner characteristics

Parameters	Quantity	Units
Number of fuel jets	1	-
Number of air jets	4	-
Air jets angle	15	º
Fuel output diameter	4	mm
Air outlet diameter	5	mm
Exhaust nozzle diameter	15	mm
Distance between the central axis of air nozzle	80	mm
Exhaust nozzle diameter	40	mm

At the exit of exhaust gases a probe was installed to capture the combustion gases for the continuous analysis of its composition. The probe was positioned in the chimney 30 cm above the burner.

4.2 Combustion Chamber

For the combustion chamber, the main design parameters to be defined were: a) model and dimensions of the chamber, b) optical access, and c) thermal insulation.

The chamber was built by carbon steel plates of rectangular shape, designed to be horizontally mounted. The chamber has internal dimensions of 286 x 286 mm ² cross section and 470 mm in length and is composed by two modules.

The first camera module has a straight section, where the burner and a tapered portion are coupled. The firing mode of the chamber is made by a pilot flame and when the chamber attains a temperature higher than 850 º C, the air inlet and main fuel will be driven for the system to begin operating in flameless regime. As mentioned, high temperatures (> 850 º C) of the combustion recirculation products are needed to initiate and maintain stable the operation of the system.

The combustion chamber has nine windows for optical access (quartz windows) distributed along the cross section on three sides. Each window has a 100 x 50 mm area. The displays were installed at 200, 350, and 448 mm from the front of the chamber (measured relative to the centers of the windows). With access, it will be possible to make optical measurements in key regions of the flow and observe the changes in the reaction structure when an operating parameter is changed.

Figure 5 shows the draw with the dimensions and details of each module.

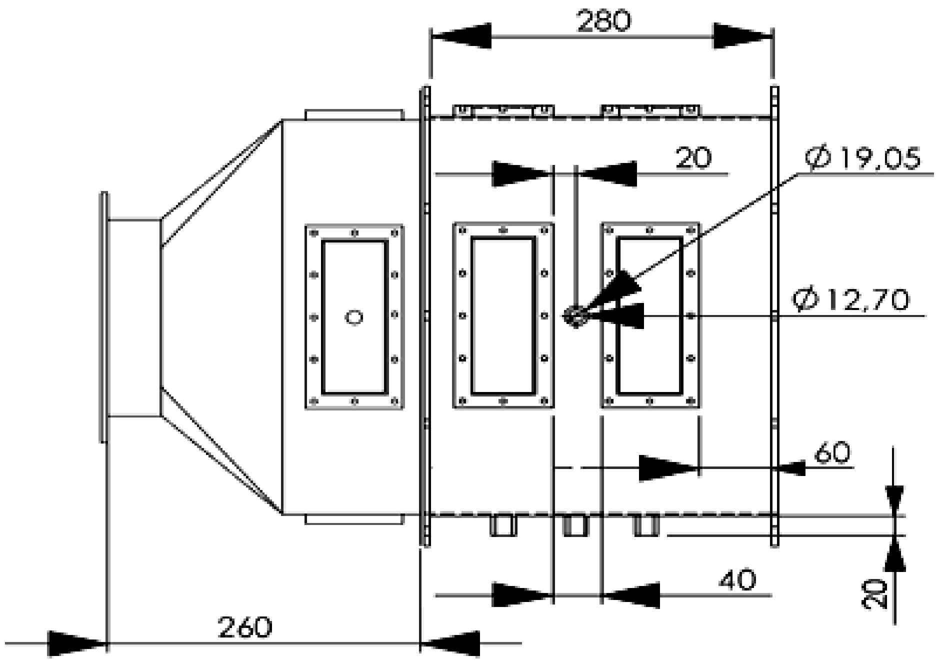

Figure 5. Dimensions and details of flameless chamber (mm).

Due to the importance of minimizing heat loss to the neighborhood, the chamber wall is coated with a 50 mm thick refractory block. It is expected that the maximum temperature in the chamber remains in the range of 1200 º C. Through the camera will be installed thermocouples for various functions. At the bottom of the camera, will be positioned nine thermocouples to analyze the temperature field throughout the chamber during operation. Others will be installed to check the temperature of combustion upstream of the burner and check the wall temperature.

4.3 Final design and preliminary tests

The result of this work involves the final assembly of the burner and chamber proposed in this research. This system was specially developed to carry out experimental laboratory tests which the aim of understanding the phenomena (physical and chemical) of flameless combustion and analyzing the reduction of NOx emissions during operation. In this paper, the stages of its design and manufacture are shown. The results presented are only preliminary tests visually observed during operation of the system.

The chamber was built at the Laboratory of Combustion and Propulsion (LCP) of the National Institute for Space Research (INPE), Cachoeira Paulista, SP, and subsequently installed in the test building of Combustion and Propulsion Laboratory of the Aeronautics Technological Institute (ITA). Figure 6 shows the image of the isometric system assembly: burner and flameless combustion chamber, and Fig. 7 show the image of the system mounted on the lab bench.

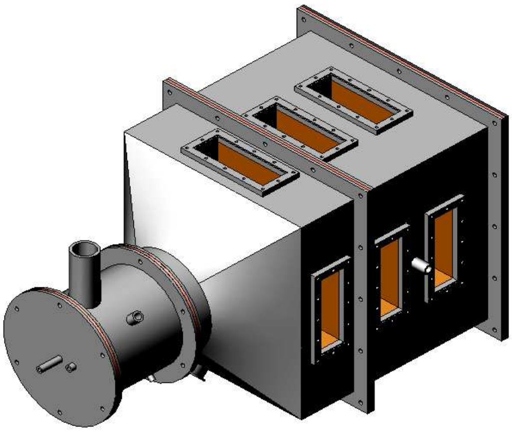

Figure 6. Burner and chamber of combustion flameless

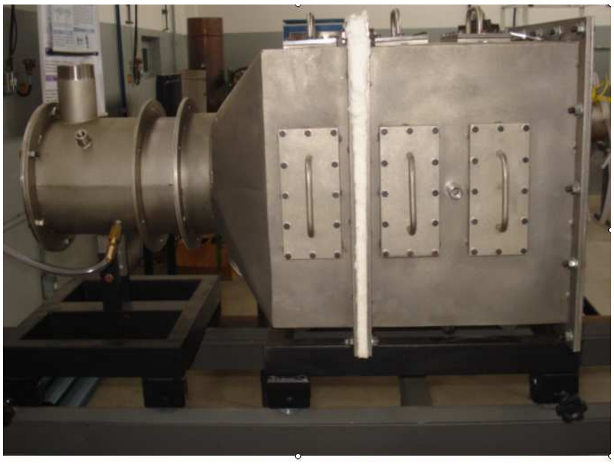

Figure 7. System (burner and chamber) mounted on the lab bench.

Figure 8 shows part of the experimental setup, which is able to meet the needs of the work. Basically the types of tests will be conducted in this study are: a) laser velocimetry for flow at low temperatures (cold velocimetry), b) analysis of the temperature field and c) analysis of pollutant emissions. The conditions of all experimental tests will be performed under ambient conditions.

Figure 8. Experimental setup

The flow field velocity will be performed by particle image velocimetry (PIV). This method (PIV) indirectly measures the flow velocity field in gaseous or liquid media. It will be added non-obtrusive particulates (follow the flow), called tracers, to the flow; and by these tracers the velocity field can detected and be evaluated if the flow is uniform inside the chamber.

For temperature measurements at fixed points of the chamber and the duct of exit of combustion gases, it will be installed commercial type "K" thermocouples with mineral insulation, insulated joint and ceramic sheath, supporting a maximum temperature of 1300º C.

The gases composition is of particular interest to assess changes in the combustion process and verify the formation of pollutants. During the experiments, it will be conducted ongoing analysis of CO, CO_2, NO, NO_2, SO_2, and specifically NOx. The capture of gases will be accomplished by a probe set in the exhaust duct of the combustor. These measures will indicate the total concentration of each gas in the combustion products.

The final steps to complement the project are going to be the bench trial with the following apparatuses: the combustion chamber, burner, data acquisition system: PIV system, pressure transducer, and the instruments of operation panel flow meters, cylinder CNG, and other instrumentation accessories.

Below are shown preliminary tests of the system. Figure 9 shows the camera operating in the conventional system and fig. 10 operating in the flameless system. There is a clear distinction regarding the presence of the flame inside the chamber. In the system flameless the flame is almost invisible. These results are only visual observation.

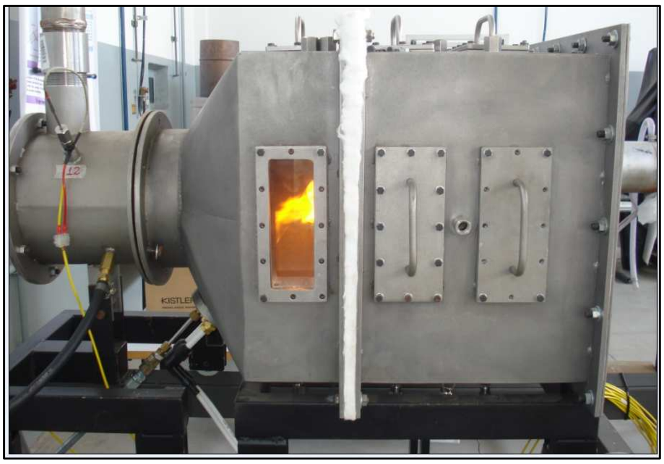

Figure 9. Visual observation in flame combustion

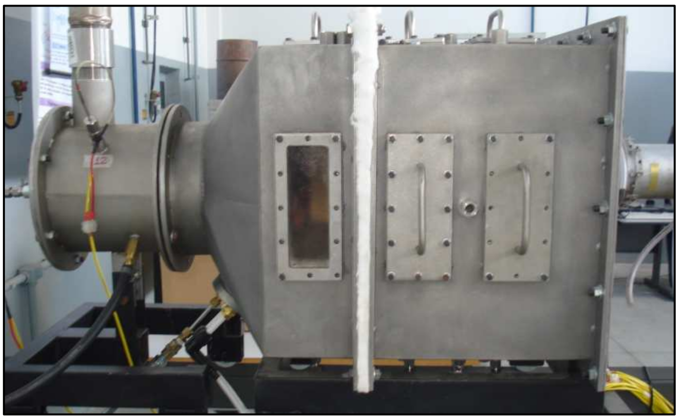

Figure 10. Visual observation in flameless combustion

The final design of the setup has features that achieve the operational requirements of the technique. The principle can be said that the system is operating under the desired conditions and meet the proposed project. The next stages of the experiment will give more accurate results of the efficiency of the flameless system.

5. CONCLUSIONS

Briefly, the main conclusions of this work are:

a) In general, we had an overview of the principles of this combustion mode, advantages about emissions and productivity of the NOx, burner and camera types that have been used and their most promising applications in various industrial sectors;

b) The designs of burner and camera for this mode of combustion have relative complexity, and deep understanding of the factors (physical and chemical phenomena) that influence the mixing and the standard behavior of this combustion regime in laboratory scale is needed;

c) The development of the experimental set (burner and combustion chamber) has a certain flexibility, enabling mobility of the design parameters (you can vary the nozzles, using various fuels, cold or preheated air, etc..) during the tests on bench trials;

d) Appropriate information is still needed to know the controlling mechanisms of flameless combustion that allow the recommendation of attitudes to practical projects of thermal devices that can use this technology;

e) This work enables the adaptation of an experimental setup, which is able to achieve the project needs at laboratory level and serve as a reference for the study of this technique in Brazil.

6. ACKNOWLEDGEMENTS

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