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BIOGAS COMBUSTION ON RECIPROCAL FLOW POROUS BURNER WITH ENERGY EXTRACTION

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Abstract. *This research has the purpose of demonstrating the effectiveness of "Filtration Combustion" (CF) to deal with fuels of low heat content, like biogas. CF is a non-conventional technology capable of producing ultra-low emissions of carbon monoxide (CO), unburned hydrocarbons (HC) and nitrogen oxides (NO_x). A reciprocal flow porous burner was experimentally utilized, constituted of ceramic spheres (alumina) that fill the combustion chamber, where heat exchangers are inserted at the porous matrix ends. The burner is equipped with a reciprocating system that provides a periodical alternation of the gas flow direction, allowing operating with several fuels and providing a stable combustion process with temperature distribution on trapezoidal profile, with temperature peaks between 1300 and 1600 K. The focus of this analysis is the fuel-air mixture flammability limit as function of CO_2 concentration and equivalence ratio, taking the technical methane as the reference gas. The results have pointed out significant benefits of the reversal on the combustion process, allowing operation in a wide equivalence ratio range ($0.10<\Phi<1$) and achieving energy extraction efficiencies above 90%, with ultra-low CO and NO_x emissions (below 1 ppm). However, when the burner operates on only flow direction, it is possible to realize a drastic reduction of the flammability limit, as the CO_2 content in the biogas composition is increased.*

Keywords: *Biogas, reciprocal flow porous burner, filtration combustion*

1. INTRODUCTION

The interest in performing this experimental investigation is related to the worry about the environmental impacts associated to great availability and to bad use of biogas, in general way. That can be summarized in two main features: i) inappropriate biogas combustion processes practiced in agro industrial facilities, with several biogas leaks and toxic gas emissions from combustion thermal systems utilized to generate electric energy or heat; and ii) high biogas release from landfills and from other natural sources with organic material degradation, in most of the cases, without any rational use or being only burned through burners of the flare type. However, few technological innovations have been directed to this kind of fuel in order to achieve lesser emission indices as well as combustion stability and efficiency, highlighting that dealing with high impurity and inert contents in the biogas composition has been a kind of challenge to be faced.

First of all, it is necessary to properly understand the effects of CO_2 addition in premixed combustion of air-methane mixtures, considering that this gas normally does exist in the biogas composition in high contents. One of the first studies in this area was conducted by Gelfand et al. (1999) with lean H_2–CO_2–air premixed flames. They used a spherical bomb experimental setup, which enabled them to collect flame velocity data at a maximum pressure of 0.5 MPa and turbulence intensity up to 10 m/s. A recent comprehensive work on this topic is that of Kobayashi et al. (2007) with CH_4–CO_2–air flames. The main results from this work are that the mean fuel consumption rate decrease with the CO_2 dilution ratio. Park et al. (2004) has shown that CO_2 dilution implies a decrease of the flame temperature, and consequently that of the thermal NO formation Another important experimental work performed by Cohé et al. (2009) analyzed CH4–CO2–air flames at various pressures, using both laminar and turbulent Bunsen flame configurations. They have attempted to characterize lean methane/carbon dioxide/air premixed laminar and turbulent flames at different pressures, studying laminar and turbulent flame propagation velocities, flame surface density and instantaneous flame front wrinkling parameters. They have confirmed that the mean fuel consumption rate decreases with the CO2 addition rate but that it increases with the pressure.

Therefore, the present work is focused on the utilization of a reciprocal flow porous burner (RFPB) as a novel technological option to be applied to a performance study about the biogas burning, which was developed through a previous paper of Barcellos et al. (2011) with base on the principles of filtration combustion (FC). In this context, the

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methane is taken as the reference gas, highlighting that RFPB has been successful with this fuel and natural gas in the obtaining of ultra-low NO_x emissions (Barcellos et al., 2003)

About the FC's fundamentals, it is possible to consider that premixed air–fuel mixtures combustion in a porous medium happens as an internally self-organized process of heat recuperation, which differs significantly from homogeneous flames (Kennedy et al., 1995). The porous medium plays the role of heat accumulator, recirculating it to the fresh mixture that comes into the reactor. The energy that would normally be released by the exhaust gases is retained by the porous matrix and recirculated in the combustion chamber, leading to an intense heat transfer process (Contarin et al., 2003a). Besides, part of the energy released from the reaction zone is absorbed by conduction and radiation in the porous medium regions upstream the flame front, and this energy is then transferred to the fresh mixture by convection, which comes into the reactor flowing in opposite direction to the heat wave propagation. On the other hand, the other part of energy released from reaction zone is transported by convection downstream, via the flue gases that go through the porous bed toward the exhaust. The presence of a high-conductivity high-specific heat solid phase enables porous combustion to occur at ultra-low equivalence ratio. Strong interstitial heat transfer leads to low degrees of thermal non-equilibrium between the gas and solid phases, allowing the thermal wave to be coupled with the combustion wave. This is characterized as the low-velocity regime, as defined by Babkin 1993). Upstream wave propagation, countercurrent to the gas flow, or the downstream propagation depends on the equivalence ratio (Φ) and the gas flow velocity (v_{gf}) employed in the reaction. It defines respectively the subadiabatic and superadiabatic operation regimes (Hanamura et al., 1993, Bingue et al., 1998, and Contarin et al., 2003b). Thus, through FC the fuel flammability limits are considerably overcome, allowing employing wide equivalence ratio range ($0.1<\Phi<10$) in the reactor operation, much beyond those one practiced at conventional burners and, still, assuring the reaction stability (Drayton et al., 1998, and Barcellos et al., 2009).

In the last years, an important engineering strategy has been applied to enhance the efficiency of FC, i.e., the technique of utilizing the gas reciprocating flow that pass through the porous medium, transforming outlet into inlet and vice-versa, periodically (Hoffmann et al., 1997). This technique has significantly favored the efficiency and emissions of the porous reactors in relation to the uni-directional flow burners. It has been utilized to develop more efficient and compact reactors that exploit a typical trapezoidal temperature profile centralized in the porous body of the burner, allowing operating it in superadiabatic regime for ultra-lean mixtures. Employing reciprocal flow filtration combustion, two reaction zones travel away from each other, towards the reactor ends, depending on the equivalence ratio and gas flow velocity applied to the operation. RFPB leads to an intense heat transfer in the vicinity of heat exchangers that are installed at the burner ends, highlighting that that is the best position to extract energy from the reaction zone. These features result in low characteristic operation temperatures (less than 1600 K) that favor the obtaining of ultralow emissions of nitrogen oxides (NO_x) and carbon monoxide (CO).

It should be highlighted that reciprocal filtration combustion have been investigated as numerically (Contarin et al., 2003b) well as experimentally (Contarin et al., 2003a, and Barcellos et al., 2005). Furthermore, some experiments in which FC has been applied to burn methane or natural gas in volumetric and radiant burners have shown low NO_x emissions. However, studies about the burning of fuels with high concentration of N_2 and CO_2 in porous reactors still demands detailed analyses to be diffused academically, concerning the principal factors that affect the NO_x formation mechanism. By adjusting the period of the cycle reversal, pseudo-steady temperature profiles can be achieved within the reactor and, therefore, the NO_x production can be decreased since the combustion temperature is low.

Any way, it is known that the reciprocal flow allows operating porous reactors on superadiabatic regime for ultra-lean mixtures with high combustion efficiency and, also, the trapezoidal temperature profile formed along the length of the burner is the resulting effect from reciprocating reaction. In the RFPB, as the direction of the gas flow is periodically reversed to confine the combustion zone in a finite length inside the burner, the transient behavior of filtration combustion is maintained. Transient combustion also favors to the burning of mixtures with ultra-low heat contents out of the conventional flammability limits. In this context, reciprocal filtration combustion is also capable to deal with fuels containing undesirable gases (impurity and inert), which have a low global heat content, like the biogas, for example.

Objectively, the present paper intends to prove that reciprocal filtration combustion is a good technical approach to deal with a biogas containing high CO_2 concentration. Through this experimental investigation it was possible to realize that high energy extraction can be obtained from biogas combustion in RFPB under a wide equivalence ratio range, maintaining ultra-low NO_x emission. Further, this article aims demonstrating the importance of the reciprocating flow in extending the flammability limit for the study fuels, methane and biogas.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

This experimental investigation treats of a comparative performance study about the RFPB burning both the fuels under analysis, biogas and methane, in which emissions, temperature profile and energy extraction at a wide equivalence ratio range were verified, through monitoring instruments. Basically, the RFPB is constituted of the following components: porous burner with heat exchangers embedded into the porous matrix ends; water-steam supply system; air-fuel mixture supply system; reciprocating electronic-pneumatic system of the water and gas flows; and data acquisition system. Figure 1 presents a whole idea about the RFPB's setup, encompassing all the instruments and accessory systems.

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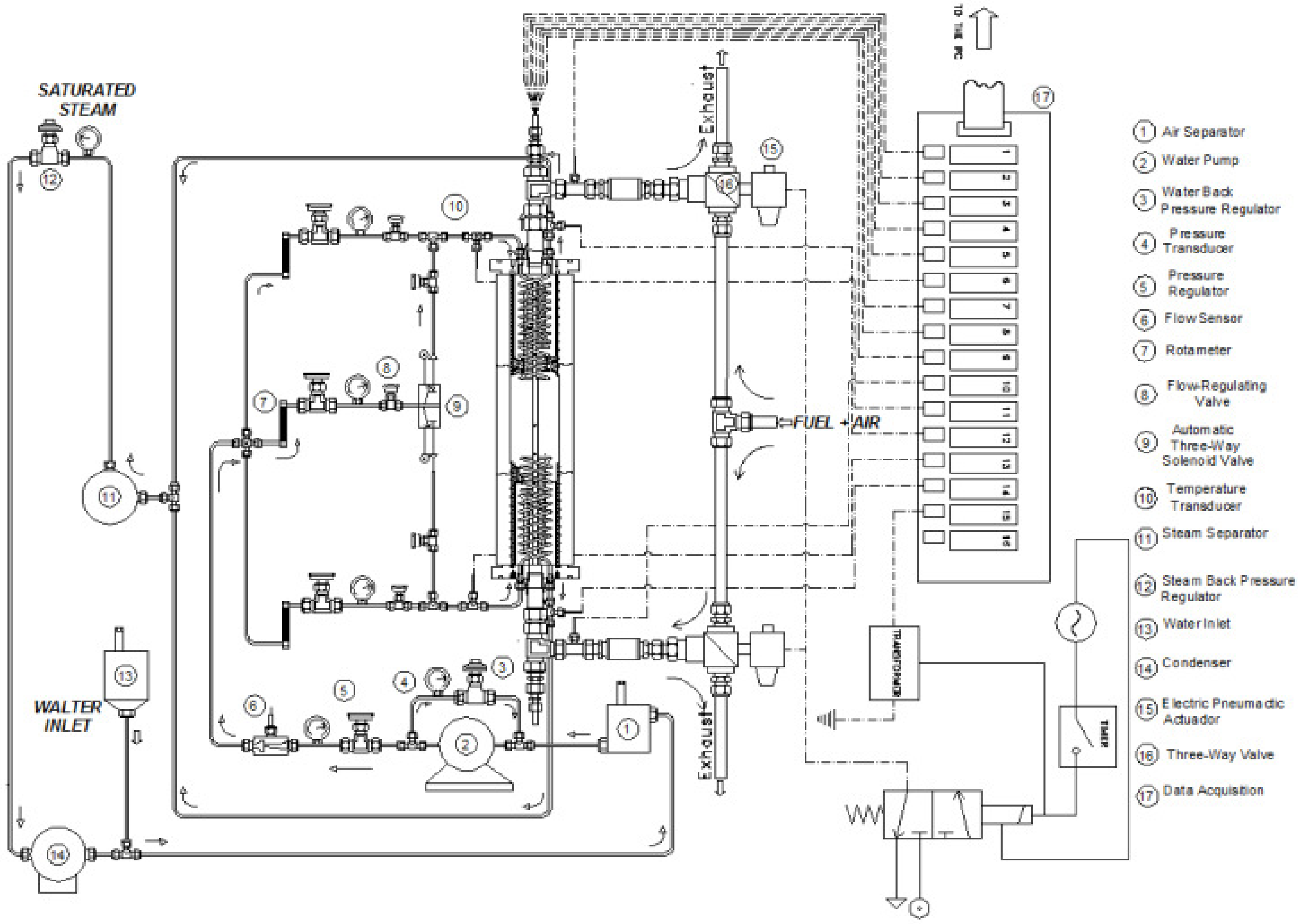

Fig. 1 – Reciprocating flow porous burner with its supply and control systems

2.1 Operation and Design Features

The core of the RFPB's burner consists of a quartz tube (L = 500 mm, ID = 76.4 mm) filled with alumina (Al_2O_3) pellets (d = 5.6 mm), creating a loose packed bed, whose porosity is approximately 40%. Thus, the alumina pellets form an inert porous medium (without catalyst) that thermally participates in filtration combustion. Two heat exchangers are embedded in each one of the burner's porous matrix ends, which are made of copper and stainless steel tubes. It should be noted that RFPB's combustion process is typically transient in which the combustion wave travels back and forth along the porous bed of the burner, so that its stroke is limited by the heat exchangers inserted into the porous matrix. Stable combustion is assured by a proper energy extraction in relation to the released heat from reaction.

The ignition of the air-fuel mixture inside the burner is done by an electrical pre-heating system employing a resistive wire, which heats the porous bed from the environment temperature up to that one proper to spontaneous fuel combustion. Or rather, the ignition takes place by detonation process via shock fronts in hot spots of the porous matrix, where the temperature is significantly higher, superior to 1200 K.

The burner is supplied with premixed air-fuel mixture in which the flow direction is periodically switched (half cycle) through an electro-pneumatic valve, which is activated by a timer to connect the rector's chamber to the compressed fuel-air line or the vent. In this air-fuel mixture reciprocating flow system, when one side of the burner is connected to the fresh mixture line the other is connected to the exhaust line, and vice-versa.

On the other hand, the water supply system of the RFPB's prototype consists of flow regulating valves and pressure regulators, in which the flow for the heat exchangers is also switched through a solenoid valve that is electronically connected to the gas flow reversal system. Thus, when the hot gases from reaction zone are flowing downstream around the bottom heat exchangers, leading to a strong convective heat transfer, a higher amount of water is supplied to these exchangers.

A number of parameters are monitored during the reactor operation, such as: the combustion temperature; the water inlet and outlet temperatures at both the burner's heat exchanger sections; the exhaust gas temperature; and NO

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and NO_2 mole fractions in the exhaust stream end. The temperature inside the burner's porous medium is measured through S-type thermocouples, at 8 linearly spaced points along the reactor axis. The housing for these eight thermocouples is provided by an 8-mm diameter ceramic (Al_2O_3) rod with eight small axial holes, positioned at the centerline of the burner.

The exhaust temperature is measured by two K-type thermocouple, constituted of a fine tip of 0.508-mm diameter in order to allow a shorter response time in the gas flow reversal region. The water temperature was measured recording small temperature fluctuations about +/-3K, and it was one of the parameters used for the burner's energy extraction efficiency calculation. Considering the narrow temperature range for intermediate positions of the water flow, a Resistance Temperature Detector (RTD) system was employed, consisting of a calibrated platinum element, whose resistance varies as a linear function of temperature.

The burner water consumption was measured through a flow transducer, which works with a water jet directed at a free running paddle wheel turbine that serves to interrupt an infrared light beam, converting it into frequency output proportional to the flow rate. Besides the transducer, water rotameters were utilized to measure the water flow at each burner section, so that it was possible to control the partial flows appropriate to the heat transfer rates at the bottom and top heat exchangers.

The NO and NO_2 emissions were measured with a chemiluminescence analyzer. The exhausts from the burner's top and bottom sections are connected to a manifold, which is coupled with a higher diameter tube to take out the burned gases. A probe from the NO_x analyzer is installed along this tube and as the gas flow is reciprocating, realistic measurements are obtained to each half cycle. A volumetric pump extracts a constant sample gas flow rate from the exhaust streams, and injects it to the analyzer. The readings of the analyzer are transformed to a standard analog signal that is digitalized by an Analog Instrument's RTI Board, displayed and recorded by a computer in a file, every 10 s.

2.2 Instruments

A number of parameters are monitored during the reactor operation, such as: the combustion temperature; the water inlet and outlet temperatures at both the burner's heat exchanger sections; the exhaust gas temperature; and NO, NO_2 and CO mole fractions in the exhaust stream end. The temperature inside the burner's porous medium is measured through thermocouples, at 8 linearly spaced points along the reactor axis. The housing for these eight thermocouples is provided by an 8-mm diameter ceramic (Al_2O_3) rod with eight small axial holes, positioned at the centerline of the burner. In the following, it is given information about all instruments used in the experiments, including details about their uncertainties: i) Temperature distribution inside the burner: Eight S-type thermocouples (0.008"- diameter), with the calibration of the conditioners through a S-Type TC simulator, in which the estimated error is of 0.25% for the full scale; ii) The temperature of the exhaust gases (or inlet gases): Two K-type thermocouple, featured with a fine tip and presenting an error of 0.75% for the full scale; iii) The water temperature: Resistance Temperature Detectors (RTD), in which the accuracy of the calibrated RTD-signal conditioner system is claimed to be of about 0.1%, resulting in an error of 0.1°C; iv) The NO and NO_2 emissions: Chemiluminescence analyzer, calibrated with 99.995%-N_2 and a mixture of N_2 + 17.6 ppm-NO, in which for the experiments the lowest scale available on the analyzer was selected: 0-20 ppm, presenting an error of ±4% for measurements lower than 125 ppm; v) Gases Flowrate: Rotameters with 7% FS-accuracy, with calibration by comparison of their readings to the ones from two primary standard instruments. Using the calibration table to fit the readings, the error of the (corrected) measurements is supposedly reduced to the repeatability of the rotameters (~1%-FS) plus the error of the primary standard instruments (~1%-FS); vi) Water Flowrate: Frequency flow transducer and rotameters - Utilizing a 5-V power supply, it yields square wave pulse outputs, in which its precision linearity is approximately of ±1.5 % of full scale over a frequency range varying from 12 to 270 Hz (from 25 to 540 ml/min, respectively). The water rotameters have a nominal accuracy of 5%-FS. After the calibration the accuracy is estimated to be around 1%. Based on the accuracy of these instruments utilized on the burner experimental investigation, the uncertainties of the temperature, specific power and energy extraction efficiency were estimated in ±0.8%, ±5.4% and ±10.1%, respectively.

About the air-fuel mixture reciprocating flow system, it is possible to mention that it is basically consisted of: i) Two inlet/outlet pipes, attached to the burner's flanges that serve as exhaust and intake, depending on the gas flow direction; ii) Two 3-ways electronic-pneumatic valves, connected to the burner's inlet/outlet tubes through one of its 3 ports; iii) A gas vent, connected to atmosphere through the second port of this valve; iv) A fresh air-fuel mixture supply tubing, connected to this valve through its third port. The two valves are simultaneously switched in opposite directions, in such a way that when one side of the burner is connected to the fresh mixture line the other is connected to the exhaust line, and vice-versa. These valves are pneumatically activated by an electro-pneumatic valve, which is switched to connect the compressed air line or the vent. This valve is controlled by a timer, in which a switching period (half cycle) is specified. A half cycle time (τ) of 100 seconds is the reference period adopted to switch the 3-way valves for all performed experiments. This switching period was the result from earlier experimental studies that attempted to conciliate some process parameters, such as: combustion process stability, uniform temperature distribution, good energy storage capability and low CO and NO_x emissions.

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3. THERMODYNAMIC ANALYSIS

3.1 Energy balance

An energy balance of the study RFPB was applied to estimate its energy extraction efficiency, obtained through practical measures with proper instruments. In principle, the efficiency depends on the methane content in the biogas and equivalence ratio applied to the burner operation. It should be mentioned that methane concentration has influence not only on the efficiency but also on emissions, as it will be shown at the result and discussion section. Basically, the power output is related to heat content of the fuel employed in the experiments. The below equations were applied to determine the balance energy in order to obtain the efficiency.

$$\dot{Q}_{Chemical} = \dot{m}_{Biogas} .[CH_4].LHV_{Methane} \tag{1}$$

$$\dot{Q}_{Chemical} = \dot{Q}_{Extraction} + \dot{Q}_{Convective} + \dot{Q}_{Wall} \tag{2}$$

$$Q_{Convective} = \sum (\dot{m}_i .h_i)_{products} \tag{3}$$

$$Q_{Wall} = \int_0^{150} \dot{q}_{top-section} .dx + \int_{150}^{350} \dot{q}_{reaction-zone} .dx + \int_{350}^{500} \dot{q}_{bottom-section} .dx \tag{4}$$

$$\dot{Q}_{Extraction} = \left(\dot{m}.c_P.\Delta T \right)_{Water} \tag{5}$$

$$\eta_{Extraction} = \frac{\bar{Q}_{Extraction}}{\dot{Q}_{Chemical}} \tag{6}$$

Where:

$\dot{m}_{Biogas}$ - Biogas flow from anaerobic biological reactors

$[CH_4]$ - Methane content in the biogas composition

$LHV_{Methane}$ - Lower heating value of the methane

$\dot{Q}_{Chemical}$ - Energy from biogas burning

$\dot{Q}_{Extraction}$ - Net energy extracted by heat exchangers from the reaction zone

$\dot{Q}_{Convective}$ - Energy lost at exhaust flow

$\dot{Q}_{Wall}$ - Energy lost through burner walls

$\dot{q}_i$ - Heat transfer rate along the burner's body on the center line

$\dot{m}_i$ - Flow rate of water or gas

h_i - Absolute enthalpy of combustion products

c_P - Specific heat to constant pressure of water

$\eta_{Extraction}$ - Energy extraction efficiency by heat exchanger per fuel consumption

3.2 Combustion process features

Filtration combustion significantly differs from conventional homogeneous laminar flame because the process occurs in the interstices of porous medium, changing considerably the thermodynamic phenomena of reaction zone, which travels freely along burner body as function of the equivalence ratio and the gas flow velocity applied. The combustion analysis

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about of the methane burning has been well studied experimentally as well as theoretically. Including, a realistic modeling have been developed to represent the combustion process in RFPB, when operated with methane under a wide equivalence ratio range for ultra-lean air-fuel mixtures.

However, little information about the predominant reaction mechanisms has been available when biogas is applied to filtration combustion. So, experimental works become interesting to understand the chemical kinetic of biogas combustion in the RFPB in order to find the flammability limits of biogas in extreme operations conditions, in terms of high CO_2 content in the biogas composition.

Therefore, this work is eminently experimental in order to learn about RFPB's combustion process and to determine not only the flammability limits, but also the emissions and efficiency features. Thereby, biogas samples were prepared to be experimented in this burner, varying its composition gradually with addition of CO_2 in CH_4-air flames to identify the main parameters of the process. To experiment the fuel blends (CH_4 + CO_2), the below global combustion reaction without irreversibility was utilized:

$$(1-\beta)CH_4 + \beta CO_2 + \frac{2(1-\beta)}{\Phi}(O_2 + 3.76N_2) \Rightarrow (1-\beta)(CO_2 + 2H_2O + 7.52N_2) + \beta CO_2 \tag{7}$$

Where "β" is the CO_2 mole fraction in the fuel, knowing that the (CH_4 + CO_2) mole fraction is equal to 1. So, "β" is defined as :

$$\beta = \frac{n_{CO_2}}{n_{CO_2} + n_{CH_4}} \tag{8}$$

Concerning CO and NO_x emissions from biogas combustion on conventional burners, it is known that the presence of CO_2 in the methane burning tends to increase CO emissions and to lessen NO_x emissions because of occurrence of incomplete combustion (Yetter and Dryer, 1991). In principle, the Zeldovich mechanism tends to stand attenuated due to the reaction temperature reduction. This mechanism has strong temperature dependence and, therefore, it is usually unimportant at temperatures below 1800 K (Zeldovich, 1947). From 70s, some researchers have begun studies about combustion of biogas to identify the predominant NO_x mechanisms. For instance, Jessen and Melvin (1977) performed experiments with natural gas, trying to deal with its physical and chemical properties and focusing NO_x emissions. They studied the burning of natural gas with addition of inert gases such as nitrogen and carbon dioxide, verifying their influences on the burning velocity and flame temperature reduction.

Recently, Matynia et al. (2009) performed an extensive investigation about the methane burning with different CO_2 concentrations, in order to learn about the influence of this gas on burning velocity. Their objective was to link it to the potential use of biogas in gas turbine in order to reduce the NO_x formation (specifically the thermal NO), because the presence of CO_2 in the biogas decreases considerably the burning velocity and, hence, the energy conversion efficiency. The [CO_2/CH_4] ratio was fixed at 0.4 for both lean and rich premixed CH_4–air flames stabilized at atmospheric pressure. Premixed flames were stabilized on a flat flame burner at atmospheric pressure and were studied experimentally and numerically, encompassing lean ($\Phi = 0.7$) and rich ($\Phi = 1.4$) flames. Also, Cohé et al. (2009), thinking about renewable fuels such as biogas issuing from anaerobic digestion of biomass or organic waste, and industrial waste gases containing CO_2, studied experimentally both laminar and turbulent Bunsen flame configurations. The objective was to characterize lean methane/carbon dioxide/air premixed laminar and turbulent flames at different pressures with CO_2 molar fraction of up to approximately 50% in relation to CH_4 concentration. They achieved to identify laminar and turbulent flame propagation velocities, the flame surface density and the instantaneous flame front wrinkling parameters.

Referring to filtration combustion, it should be mentioned that it works on very low reaction temperature (between 1300 and 1600 K) and, thereby, the Zeldovich mechanism would be not important in the NOx formation. As filtration combustion is actually advantageous in burning processes under ultra-low equivalence ratio, thus, it is expected that the mechanism should be appropriate to explain NO_x emissions, in this case, it is N_2O-intermediate Mechanism. It should be highlighted that Sanchez et al. (2001) investigated lean premixed methane–air flames in order to facilitate the numerical description of NO emissions in lean premixed combustion systems. Their computational studies about laminar flames, with detailed nitrogen chemistry, indicated that the NO_2 reaction mechanism is extremely slow, resulting negligibly in small concentrations (typically two orders of magnitude smaller than that of NO). Also, it was seen that the consumption of intermediate species, such as: NH_2, HNO, NH, N_2H, and N among others, is fast enough that all those intermediates maintain steady state everywhere, so that the nitrogen chemistry reduces to the two overall steps:

$$N_2 + O_2 \Leftrightarrow 2NO \tag{9}$$

$$N_2 + \frac{1}{2}O_2 \Leftrightarrow N_2O \tag{10}$$

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4. RESULTS AND DISCUSSIONS

For the combustion analysis, the CO_2 dilution rate was characterized through its mole fraction in the fuel (methane) and not in the oxidant (air), considering the biogas as a blend fuel (CH_4 and CO_2 mixture). The reference pressure applied to this study was 0.1 MPa and the CO_2 dilution rate (β) ranged between 0 and 0.6. It should be noted that typical biogas compositions from anaerobic digestion of biomass in landfill or biological reactors range between 35-75% CH_4 and 20-45% CO_2. In the present paper, the results are given for wide low equivalence ratio range ($0.1<\Phi<1$) with reactants supplied at averaged temperature of 300 K. The air-fuel mixture flow velocity taking into the burner, employed in all experiments, ranged from 0.1 to 0.3 m/s and kept constant for all equivalence ratio applied to the tests.

4.1 Temperature Profiles

The experimental results shown in Figures 2, 3 and 4 exhibit the influence of the equivalence ratio on the temperature profiles obtained from the burner operating with gas flow velocity ranging from 0.1 and 0.30 m/s. Heat extraction is performed over increasing equivalence ratios from ultra-lean mixtures to the stoichiometry ($0.1\leq\Phi\leq1.0$). Figure 2 shows that the temperature plateau widens slightly increase as the gas flow velocity is increased. Also, it illustrates that the trapezoidal temperature profile is uniform and that the thermal gradients at the burner ends are large.

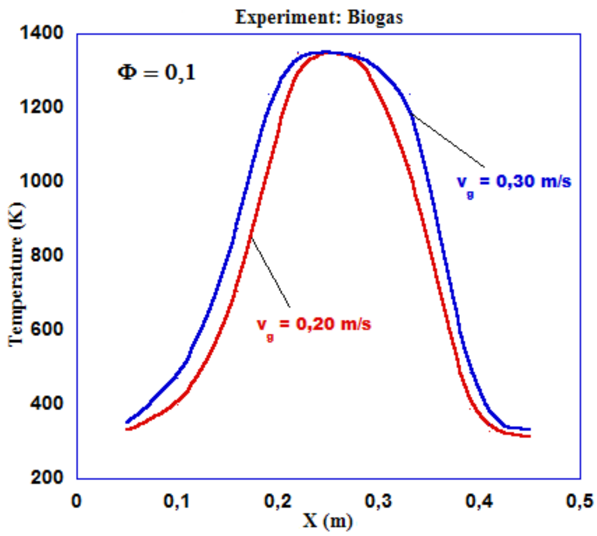

Figure 2 – Temperature distribution profile, varying v_{gf} with constant equivalence ratio (Φ = 0,10.)

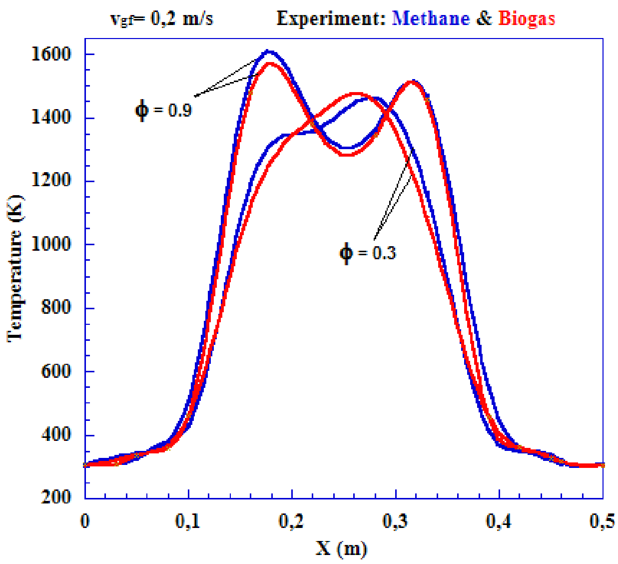

Figure 3 – Temperature distribution profiles: methane & biogas, varying "Φ" from 0.30 to 0.9 with v_{gf}=0.20 m/s

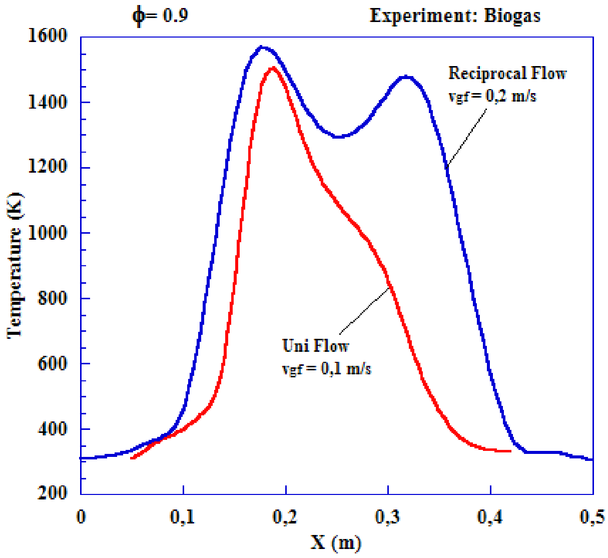

Figure 4 – Temperature distribution profile of biogas: reciprocal & unidirectional flows

The reciprocal flow porous medium burner confines the reaction zone inside its physical limits, or rather between the heat exchanger ends. All the temperature profiles for this equivalence ratio range converge to the same temperature in the regions close to the flanges due to the energy extraction by the heat exchangers. It should be noted that the reciprocating flow changes the temperature profile considerably and store more energy inside the reactor.

4.2 Exhaust Temperatures

Figure 5 shows both the effects of the gas flow velocity and equivalence ratio on the exhaust temperature. Observing the graphs, it is possible to realize that all exhaust temperature profiles can be represented by straight lines with slight difference between the inclination angles. It should be highlighted that the exhaust temperatures are very low (close to the environment temperature) when compared to the conventional burner's exhaust at any operation condition, independently on the equivalence ratio or the gas flow velocity employed in the experiment. This is probably related to the fact of the combustion heat that would be lost by convection through the exhaust is absorbed by the porous medium and transferred to the heat exchangers. These reduced exhaust temperatures signalizes a high energy extraction efficiency in the burner.

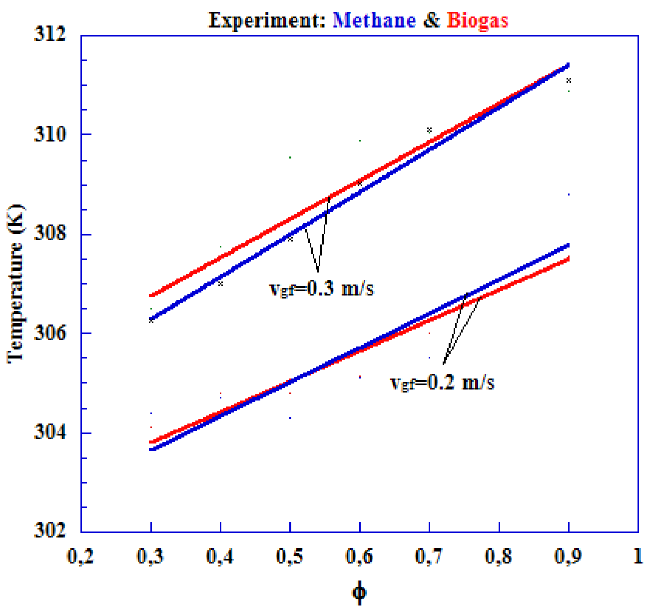

Figure 5 – Exhaust temperature on reciprocal flow for both the reference gases: methane & biogas

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4.3 Energy Extraction Efficiency

The RFPB'S prototype has been developed focusing two goals: ultra-low emissions and high efficiency. Based on that, two heat exchangers pairs were employed in porous burner's ends to improve the energy extraction from the zone reaction and achieve operational stability. The heat exchangers confine the combustion wave propagation between the limits stated by them set at the burner's ends, which act as a kind of thermal barrier for the front. Therefore, an amount of water in the heat exchangers (at both the burner's sections) is proportionally adjusted to the released heat and to the gas flow direction. The experimentally measured energy extraction efficiencies are in the range from 73 to 93%, depending on the equivalence ratio and gas flow velocity employed as well as on the kind of fuel, as shown at Figure 6. The efficiency increases with the equivalence ratio and the gas flow velocity, being able to reach energy extraction efficiency close to 90%. It should be commented that the efficiency results were obtained with a prototype in laboratory-scale, so they could be higher considering that the heat losses effects are especially strong for small experimental setup, due to the high area-volume ratio.

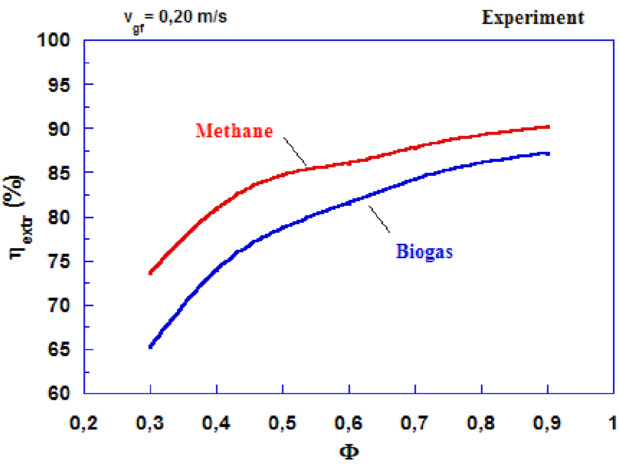

Figure 6 – Energy extraction efficiency for both the study fuels: methane & biogas (v_{gf} = 0,2 m/s)

4.4 NO_x Emissions

The RFPB presents a special capacity of producing such low CO and NO_x emissions, when compared to the conventional burners. The effects of equivalence ratio on emissions for different gas flow velocities are shown at Figures 7 and 8. Especially about the effects of the equivalence ratio on the NO_x production for different gas flow velocities, both the figures indicate that the NO_x emissions increase as the equivalence ratio is increased.

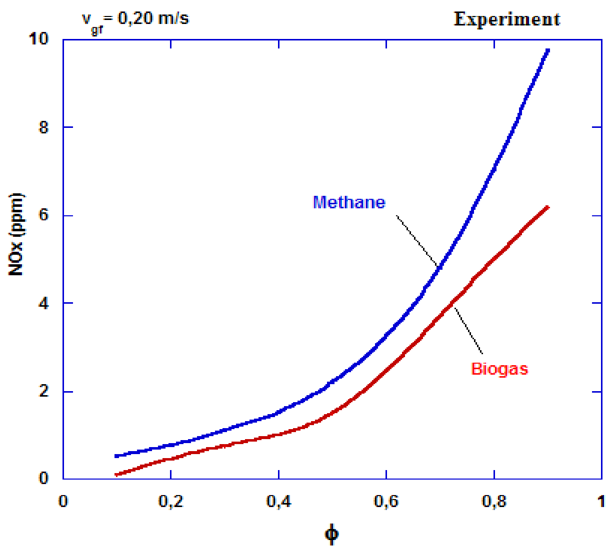

Figure 7 – NO_x emission profiles for both the study fuels: methane and biogas (v_{gf} = 0.2 m/s)

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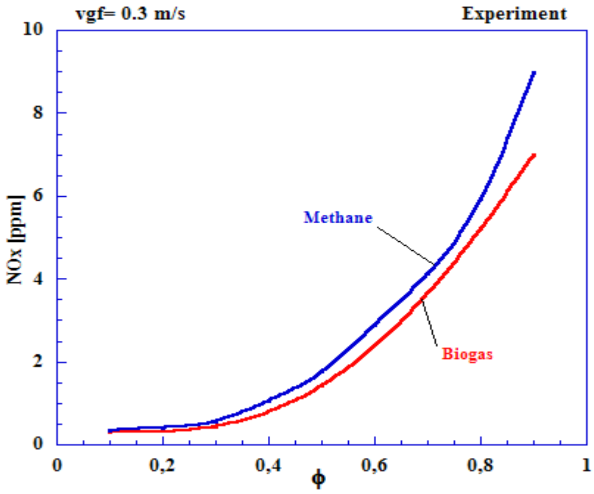

Figure 8 - NO_x emission profiles for both the study fuels: methane and biogas (v_{gf} = 0.3 m/s)

It should be noted that under ultra-low equivalence ratio (Φ<0.3) NO_x emissions are lower than 1.0 ppm for both the studied gases. In general way, for better understanding of the NO_x emission process, some arguments should be invoked: i) The fact that the combustion temperature is low (1300-1600 K) reduces the possibility of NO production through the Zeldovich mechanism; ii) It is also expected the peaks of the intermediate species to be low on a wide reaction zone, however there are possibilities of occurring the N_2O-intermediate mechanism at ultra-lean mixtures and of being produced some intermediate species, such as the radicals O, OH, CH, which are important on the Fenimore mechanism; and iii) The reciprocating combustion temperature distribution affects on the NO production, so that, as the combustion temperature increases during a half cycle, the NO emission trends increases too.

4.5 Flammability Limits

One of the principal goals of this experimental investigation is to demonstrate that the RFPB is an effective technology to deal with low heat content fuels, like biogas, for instance, in which their impurities and inert gases normally result in disturbances on the combustion stability and on emission indices, when conventional burners are applied. All the figures presented, until now, already have reached this goal, in which ultra lean air-fuel mixture could be employed in the porous burner. However, Figure 9 aims to point out how important is the reciprocal flow for extending the flammability limits. Despite the unidirectional flow filtration combustion already makes it possible as shown, until now, the reciprocating flow system can almost eliminate the effects of presence of CO2 in biogas composition, not only about stability but also about emissions and efficiency. Fig. 9 suggests, then, a correlation between the lower equivalence ratio limit with the higher CO2 content in biogas. So, operation points below this characteristic curve, in principle, are not able to put the unidirectional flow porous burner to work satisfactorily.

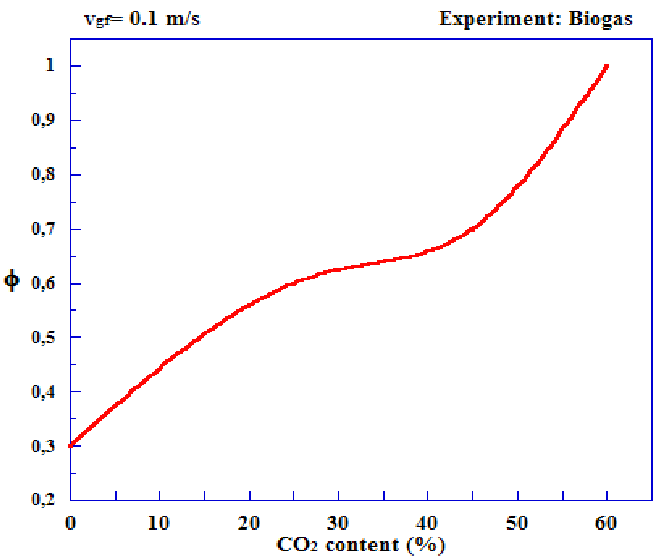

Figure 9 - Flammability limit for unidirectional flow porous burner as a function of CO_2 content (vfg = 0.1 m/s)

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5. CONCLUSIONS

The RFPB has been successfully in burning both the study fuels, biogas and methane, and the conclusions are summarized below:

- The temperature profile has a typical trapezoidal shape with a minimum at the reactor midpoint. The heat exchangers did not allow an expansion of the temperature distribution to the burner ends.
- The presence of heat exchangers confines the reaction zones in the central insulated section, allowing stable combustion for the wide equivalence ratio range.
- A stable combustion at the burner was found running a wide operation condition range, $0.10 < \Phi < 1$ for both the study gases, methane and biogas, when reciprocal filtration combustion is applied, providing not only efficient energy extraction and low emissions.
- Reciprocating combustion has demonstrated to be very important in terms of influence on flammability limits for both the study fuels.
- NO_x and CO molar fractions increase from 0.1 ppm to lesser than 10 ppm for a wide ultra-low equivalence ratio range ($0.1 < \Phi < 0.7$).
- The experimental results have pointed out that RFPB has reached efficiencies of about 90% at any experimented gas flow velocity under a wide equivalence ratio range ($0.10 < \Phi < 0.9$).

6. ACKNOWLEDGEMENTS

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