

COMBUSTION OF LOW CALORIFIC VALUE GASEOUS FUELS IN A POROUS BURNER CONFINED IN A HEATED ENCLOSURE

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Abstract. *The main purpose of this work is to investigate the combustion of gaseous fuels with low calorific value in a porous burner, in particular, to study the effect of the composition of the fuel on flame stability and pollutant emissions, in both, open and confined heated environment. The enclosed operation was realized in a laboratory-scale furnace, with temperature-controlled, isothermal walls. Mixtures of CH₄, H₂ and CO diluted with CO₂ and N₂ were used as low calorific value fuels. The mixtures had compositions that resulted in lower calorific values varying from 4.5 MJ/kg to 50 MJ/kg, while keeping the constant pressure adiabatic flame temperature at the equivalence ratio 0.5 at 1207 K. This work was divided into two parts. In the first part, of the porous burner was evaluated in an open environment and, in the second part, in a confined hot environment. The results obtained in open environment have been published elsewhere. The second part of this work, the operation in a heated enclosure was analyzed. As in the open environment, in confined hot environment it can be observed that the hydrogen concentration in the fuel mixture increases the flame speed and enlarges the burner stability range. The stability range is determined by the flame position as it moves from the injection plate to the lift off condition. Here, the adiabatic flame temperature is approximately constant for all fuel mixtures. Therefore, the flame position is not influenced by the overall energy content of the reactant mixture but by the variation in consumption flame speed as the fuel composition changes. This results in an increase of the upper stability limits.*

Keywords: *Porous burner; low calorific gaseous fuels; flame stability; pollutant emissions.*

1. INTRODUCTION

Porous burners present a large range of flame stability limits due to of the heat transfer between the combustion products and the porous matrix and, subsequently, between the porous matrix and the external environment. Excellent reviews may be found in Wood and Harris (2008), Oliveira and Kaviany (2001) and Howell et al. (1996).

In industry, there is often a need to burn in confined heated environments, such as ovens, furnaces, dryers, etc.. This operation in a warm environment, however, decreases the temperature difference for the external heat transfer during stable and safe operation, thus affecting the stability range. There are few works addressing the operation of porous burners in confined hot environments. Hsu et al. (1993) found variations in CO and NO_x emissions when the porous burner was operated in a confined environment. Additionally, the combustion of low calorific gaseous fuels may present difficulties related with both flame stability and combustion efficiency (Giles et al., 2006; Chomiak et al., 1989 and Adouane et al., 2002). Systems with high heat recirculation rates can, however, increase the stability range and allow for an effective combustion of these fuels (Weinberg, 1971 and Hardesty and Weinberg, 1974). The present work intends to contribute to redress this problem.

The main purpose of this work is to investigate the combustion of gaseous fuels with low calorific value in a porous burner, in particular, to study the effect of the composition of the fuel on flame stability and pollutant emissions, in both, open and confined heated environment.

The enclosed operation was realized in a laboratory-scale furnace, with temperature-controlled, isothermal walls. Mixtures of CH₄, H₂ and CO diluted with CO₂ and N₂ were used as low calorific value fuels. The mixtures had compositions that resulted in lower calorific values varying from 4.5 MJ/kg to 50 MJ/kg, while keeping the constant pressure adiabatic flame temperature at the equivalence ratio 0.5 at 1207 K.

For comparison, this work was divided into two parts. In the first part, of the porous burner was evaluated in an open environment and, in the second part, in a confined hot environment. The results obtained in open environment have been completed and was published (Francisco et al., 2010). Briefly, the results indicated that, for this burner design, the macroscopic flame shape of the fuel mixtures remains approximately the same as compared with pure methane, but the former flames move further upstream from the burner exit. This is caused by the increase of the laminar flame speed as the H₂ content in the mixtures increases. As a result, the stability limits of the fuel mixture increase and the stability range enlarges. It was also observed that for Wobbe Index varying from 5 to 44 MJ/Nm³ it is possible to burn stably at $\approx 260 \text{ kW/m}^2$, which reveals the fuel interchangeability potential of the present burner design.

The second part of this work is given below, where we evaluated the influence of confined hot environment on stability limits, range of power and pollutant emissions, using fuel mixtures of low calorific value. The results obtained in confined environment were compared with the results in open environment (Francisco et al., 2010).

2. EXPERIMENT SETUP

Figures 1 show a photograph of the experimental setup used in the tests in confined environment. The burner is made with four layers of porous foams, with 80% of volumetric porosity, each with a diameter of 70 mm and a thickness of 20 mm. The ceramics used are mostly composed by alumina (above 60%) with smaller proportions of phosphorous, zircon and other oxides.



Figure 1. Photograph of the experimental setup used in the tests in confined environment.

Figures 2 shows a schematic drawing of the porous burner and the furnace used in this work. As shown in Figure 2 (a), the PR comprises two layers with 40 pores per inch (ppi) and the SBR contains two layers with 10 ppi. An injection plate with a single central orifice with 16 mm diameter is placed under the PR. The use of this type of orifice produces a regime of combustion in which a jet flame with a conical shape attached to the orifice rim burns stably over a large stability range for a given equivalence ratio (Catapan et al., 2005). The furnace was built from a vertical stainless steel cylinder with an internal diameter of 200 mm and a length of 1500 mm. The walls are heated by electrical resistances and the internal temperatures are controlled by a control unit.

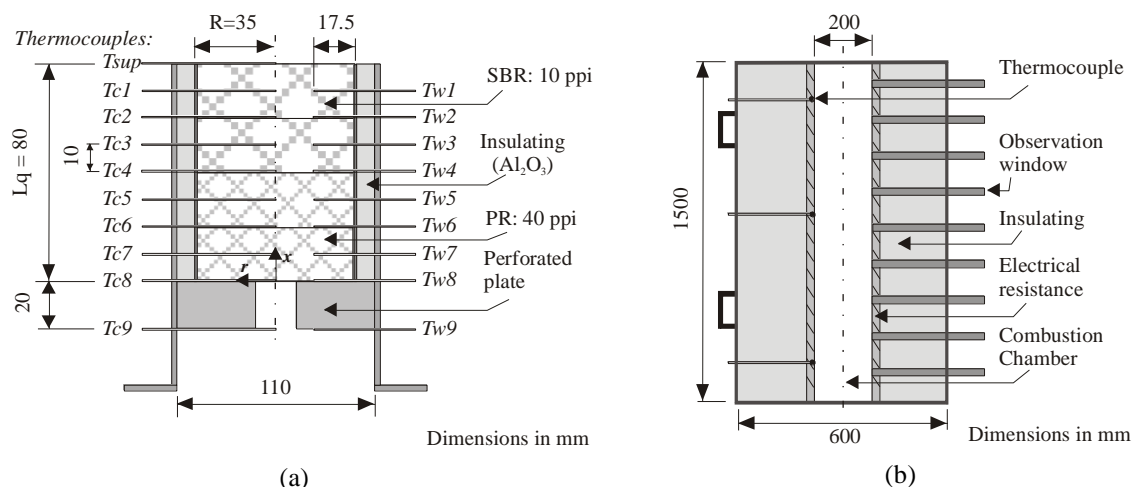


Figure 2. (a) Schematic of the porous burner coupled under the furnace and (b) schematic of the furnace used to simulate a confined hot environment.

Figure 3 shows the schematic of the experimental setup. The fuel supply system is composed of bottles of pressurized gases, a reducing-control valve and a check valve. The gases include 99.8% pure CH₄, 99.997% pure CO,

99.995% pure CO₂, 99.999% pure H₂ and 99.999% pure N₂. Electronic flow meters connected to control valves were used for measuring and controlling the flow rate of the gases. The gaseous fuels and the air were fed to the burner through a stainless steel pipe with 1 m length and 25 mm diameter, which homogenized the reactant mixture before reaching the burner.

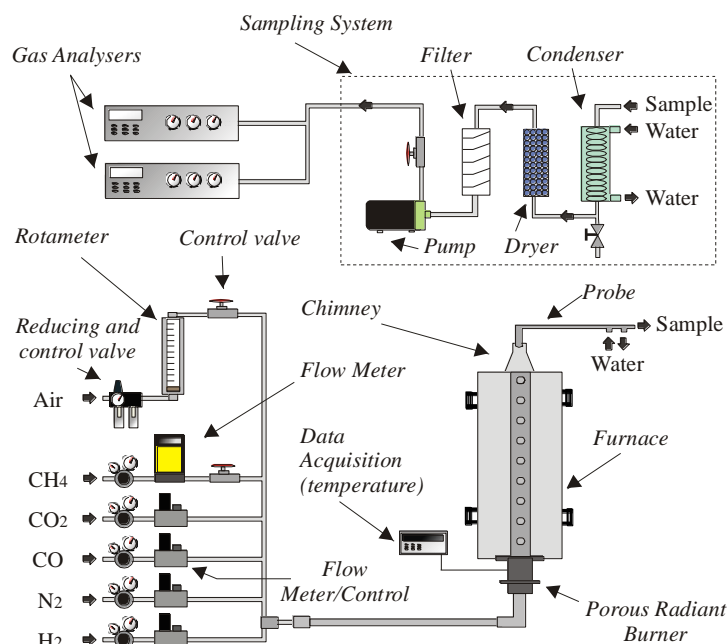


Figure 3. Schematic of the experimental setup.

A chimney was placed at the top of the furnace to homogenize the flue-gas and to facilitate sampling. The combustion products were sampled with the aid of a water-cooled stainless steel probe for the measurement of O₂, CO, CO₂, HC and NO_x concentrations. Before reaching the analyzers, the sample was cleaned and dried. The analytical instrumentation included a magnetic pressure analyzer for O₂ measurements, non-dispersive infrared gas analyzers for CO and CO₂ measurements, a flame ionization detector for HC measurements and a chemiluminescent analyzer for NO_x measurements. Zero and span calibrations with standard mixtures were performed before and after each daily session. The maximum drift in the calibration was within $\pm 2\%$ of the full scale. In the post-flame region, probe effects are negligible and errors arise mainly from quenching of chemical reactions, sample handling and analysis. Our best estimates have indicated uncertainties of less than 8% for the concentrations of the gas species in the post-flame region. Repeatability of the post-flame gas species concentration data was, on average, within 5%.

The temperatures within the porous burner were measured with the aid of 18 R-type thermocouples (Pt/Pt-13% Rd) made with 250 μm diameter wires placed inside alumina double-holed tubes with a diameter of 1.59 mm. The thermocouples were positioned at $r/R = 0$ and $r/R = 0.5$ (see Fig. 2 (a), where R is the ceramic foam radius), and connected to a data acquisition system interfaced with a computer. Because of the thermal equilibrium established between the thermocouple hot junction, the gas and the solid phase the measurements provided by this sensor should be understood as a mean temperature between the gas and the solid phases.

The wall temperatures within the furnace are controlled by a temperature controller (2132 – Eurotherm Controls), that includes thermocouples of type K. The PRB is placed on the bottom of the furnace.

3. EXPERIMENTAL PROCEDURE

Initially, a near stoichiometric mixture is set and the flame ignited at the burner top. The flame front penetrates quickly into the porous medium reaching the PR, as indicated by a temperature rise in thermocouple Tc6 (see Figure 2). This initial heating process takes around 10 min. Subsequently, the desired test condition is set and the flame propagation observed. The flame is considered stable when the temperatures remain constant for at least 20 min.

The flame stability limits were determined by keeping the equivalence ratio constant and varying the total mass flow rate in small increments. The lower stability limit was defined as the mass flow rate at which the flame front reaches the position of thermocouple Tc7 (see Figure 2), located in the PR. Below this limit, the injection plate reaches its degradation temperature. The upper stability limit was defined as the mass flow rate at which flame detachment occurred and it was observed when the measured temperatures in the porous medium were less than 650 °C. The maximum equivalence ratio used was limited by the maximum temperature supported by the porous media. For the ceramic foams used in this work, we observed that temperatures above 1600 °C resulted in a change in structure

evidenced by a color change and the appearance of vitrified points. Thus, the maximum temperature allowed was set in 1550 °C. This temperature occurs near the tip of the conical flame.

4. RESULTS AND DISCUSSION

In the present work, for analyzing the porous burner in confined hot environment, were selected the fuel mixtures with 0%, 40%, 60% and 100% of methane concentration. For each fuel mixture, the stability limits was evaluated experimentally by keeping the furnace temperature constant at 500°C.

Then, for the fuel mixture with 40% of methane concentration, was varied the furnace temperature to evaluated the influence on the stability limits and pollutant emissions. The furnace temperature was varied between 300°C and 850°C.

Table 1 presents the characteristics along with some properties of the fuel mixtures were used. The properties presented include the molar mass, M_f , density, ρ_f , lower heating value (LHV), higher heating value (HHV), Wobbe Index (WI), fuel mass fraction in the reactant mixture, $Y_{f,n}$, mean constant pressure specific heat, c_p and the constant pressure adiabatic flame temperature, T_{ad} . The H/C and C/O ratios were kept between 0.5-4.0 and 0.8-infinity (no oxygen in the fuel), respectively, for the fuel mixtures.

Table 1. Properties of the fuel mixtures used.

Fuel mixture	1	2	3	4
Composition (volume %)				
CH ₄	0	40	60	100
CO	33.3	20	13.3	0
H ₂	11.1	6.7	4.4	0
CO ₂	11.1	6.7	4.4	0
N ₂	44.4	26.7	17.8	0
H/C	0.5	2.6	3.2	4
C/O	0.8	2.0	3.5	-
Properties				
M_f (kg/kmol)	26.9	22.6	20.4	16.0
ρ_f (kg/m ³)	1.1	0.922	0.833	0.656
LHV (kJ/m ³)	4954	16091	21659	32795
HHV (kJ/m ³)	5154	17648	23896	36390
$WI^{(1)}$ (MJ/m ³)	5	18	26	44
$Y_{f,n}^{(2)}$ (kg/kg)	0.306	0.081	0.054	0.028
$c_p^{(3)}$ (kJ/kg K)	1.16	1.19	1.20	1.20
$T_{ad}^{(4)}$ (°C)	1208.8	1206.3	1206.0	1205.7

(1) Wobbe Index calculated with LHV at 298 K, 1 atm, using $\rho_{air} = 1.17 \text{ kg/m}^3$.

(2) Mass of fuel per mass of reactant mixture for combustion with standard simplified dry air at $\phi = 0.5$.

(3) Mean constant pressure specific heat between T_o and T_{ad} .

(4) Constant pressure adiabatic flame temperature considering full species equilibrium in GRIMech 3.0.

The range of LHV (or WI) of the mixtures established and studied includes fuels with lower heating values (LHV from 3 to 7.9 MJ/m³ at 298 K, 1 atm), which are typical of landfill, synthesis, residual and waste gases, and with high heating values (LHV from 23.6 to 63 MJ/m³ at 298 K, 1 atm), which are equivalent to natural gas. Combustion systems can usually burn fuels within a 10% variation in the WI without any adjustment of the control systems or injector orifices. Note that the WI values in Table 2 vary by almost 10 times. The concentration of the inert components (N₂ and CO₂) varies from 11 to 55%. The CO/H₂ mole ratio is kept equal to 3.

4.1. Stability limits in a confined hot environment

In general, the behavior of the porous burner in a confined hot environment is similar to behavior in an open environment. Figure 4 shows the flame stability limits of the porous burner in a confined hot environment for the fuel mixtures listed in Table 1 for $\phi = 0.5$.

Three different regions can be identified, namely, the lift off region (above the upper stability limit), the stable flame region and the thermal damage region (below the lower stability limit). The continuous lines identify the upper and lower burner stability limits. The figure represents the mean flow velocity, u_{ch} , defined as the volumetric flow rate of reactants divided by the transversal sectional area of the burner, as a function of the methane concentration in the fuel mixture. For stationary plane flames, the mean flow velocity is equal to the flame speed. However, for the present burner, the flame has a conical shape and the equilibrium between the reactants flow velocity and the burning velocity is reached only locally.

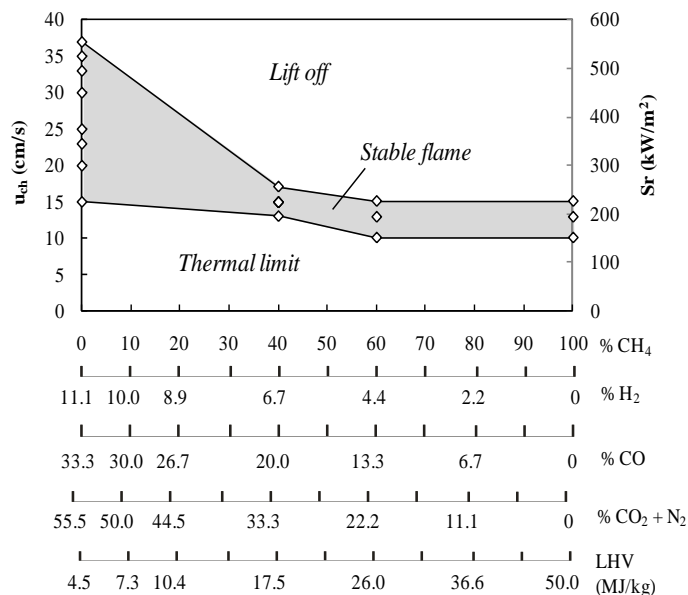


Figure 4. Flame stability limits of the porous burner in a confined hot environment.

The results indicate that there were no significant differences in the form of operation diagram of the porous burner in an open and confined hot environment. Again, one can observe that the hydrogen concentration in the fuel mixture increases the flame speed and enlarges the range of stability of the burner (Francisco et al., 2010 and Halter et al., 2005). The range from lower to upper stability limits is determined by the flame position as it moves from the injection plate to the lift off condition. Here, the adiabatic flame temperature is approximately constant for all fuel mixtures (Table 2). Therefore, the flame position is not influenced by the overall energy content of the reactant mixture but by the variation in consumption flame speed as the fuel composition changes. The laminar flame speed increases with the increase in H₂. The flame then penetrates deeper within the porous medium and stabilizes against higher mean flow velocities which are closer to the distribution plate. This results in an increase of the upper stability limits. We note that the maximum burner power for 100% CH₄ was 0.95 kW (246 kW/m²) while for 0% CH₄ it was 2.27 kW (590 kW/m²), which is about 139% higher. For methane concentrations higher than 40%, the stability limits do not vary appreciably.

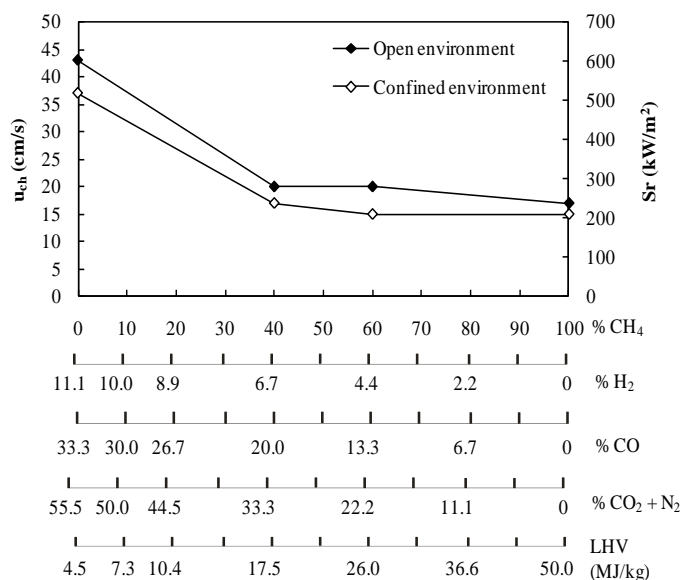


Figure 5. Upper limit of stability obtained for the fuel mixtures tested in open and confined environment.

However, comparing the results in open and confined hot environment, can be observed a reduction of the upper limit of stability for all the fuel mixtures tested in a closed environment. Figure 5 shows the upper limit of stability obtained for the fuel mixtures tested in open and confined environment.

Reducing the upper limit of stability in confined hot environment is caused by the advancing flame front to the surface of the burner. Thus, to the same mean flow velocity and equivalence ratio, in confined hot environment, the flame front moves into the surface of the burner exit.

The largest reduction at the upper limit of stability occurred for the mixture with 60% of CH₄, reducing to 328 kW/m² in open environment to 246 kW/m² in a closed hot environment, accounting for approximately 25% reduction. For mixtures with 0%, 40% and 100% of CH₄, the reduction was in the order of 12 to 15%.

The influence of the furnace temperature (T_f) within the limits of stability of the burner was evaluated for fuel mixture with 40% of CH₄. The furnace temperature was varied between 300 and 850 °C. For this variation, can be observed that the maximum power obtained was reduced by 15% compared to the open environment and then remained constant for all T_f evaluated.

4.2. Influence of confined hot environment on the temperature distribution

Figure 7 shows the temperatures measured at the burner centerline and at R/2 as a function of the length of the burner to fuel mixture with 40% CH₄, the mean flow velocity of 15 cm/s and equivalence ratio of 0.5. It is possible to note that in confined hot environment the temperature distribution remained approximately constant for all furnace temperature tested.

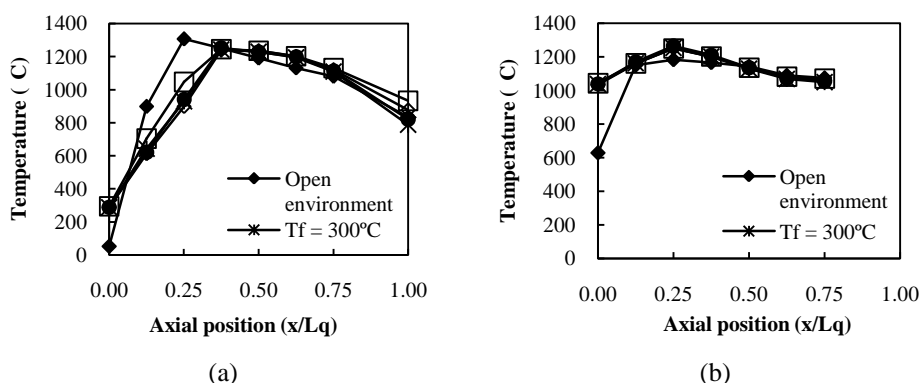


Figure 7. Temperature (a) at the burner centerline and (b) at R/2 as a function of the axial position for different furnace temperature (40% CH₄ / $\phi = 0.5$ / $u_{ch} = 15$ cm/s).

Figure 8 and 9 shows the temperature at the burner centerline as a function of the axial position for the fuel mixture between 0% and 100% CH₄ ($\phi = 0.5$ and $u_{ch} = 15$ cm/s).

In confined hot environment, the flame front moves into the surface of the burner. This effect was observed for all operating points in open and confined environment.

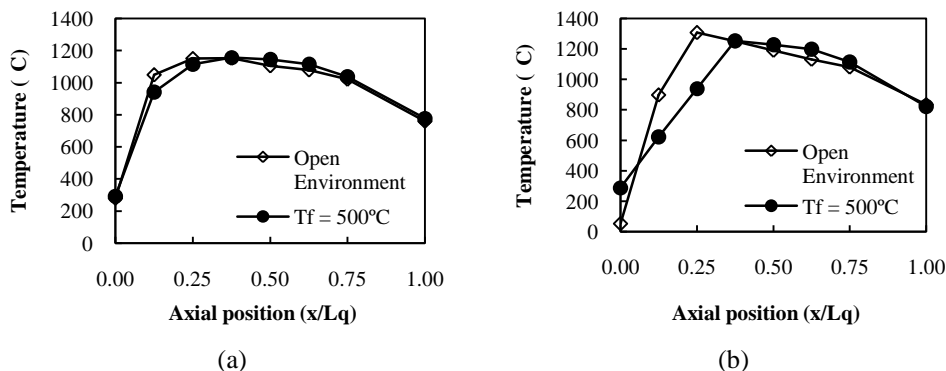


Figure 8. Temperature at the burner centerline as a function of the axial position for the fuel mixture with (a) 0% CH₄, (b) 40% CH₄, for fuel mixtures with $\phi = 0.5$ and $u_{ch} = 15$ cm/s.

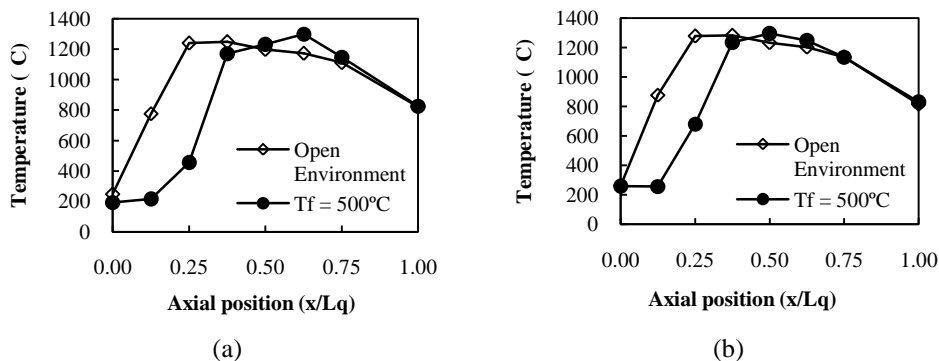


Figure 9. Temperature at the burner centerline as a function of the axial position for the fuel mixture with (a) 60% CH₄ and (b) 100% CH₄, for fuel mixtures with $\phi = 0.5$ and $u_{ch} = 15$ cm/s.

4.3. Influence of confined hot environment on the pollutant emissions

The pollutant emissions in confined hot environment were measured using the same methodology applied in open environment, but the chemical species were collected on the surface of the furnace exit. Thus, over the oven chemical reactions can occur at high furnace temperatures and greater homogeneity in the composition of combustion products.

In confined hot environment, the pollutant emissions indexes of NO_x were not significant for furnace temperatures of 300 °C, 500 °C and 700 °C. However, the temperature of 850 °C, the maximum emission index of NO_x measured was 0.028 g/kg, because the reactions of chemical species along the duct of the furnace. In open environment, the maximum emission index of NO_x for all fuel mixtures tested was 0.09 g/kg.

Figure 9 shows the emission index of CO as a function of mean flow velocity for all fuel mixtures tested in confined hot environment ($T_f = 500$ °C / $\phi = 0.5$). The emissions index of CO in confined and open environment is qualitatively similar.

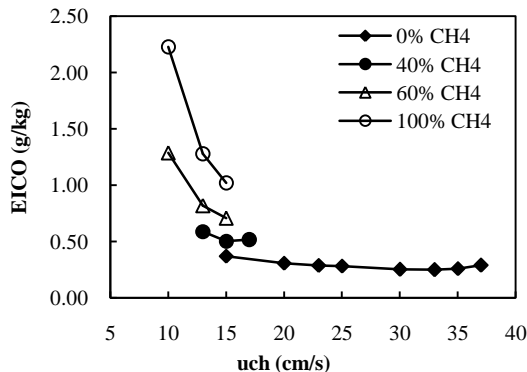


Figure 9. Emission index of CO as a function of the mean flow velocity for the different fuel mixtures ($\phi = 0.5$ / $T_f = 500$ °C).

In open environment, for both lower and higher mean flow velocities the CO emission increases. At lower u_{ch} the flame burns closer to the injection plate. Although there is a longer residence time, the flame temperature is lower. Conversely, at higher u_{ch} the flame burns closer to the outlet surface. In this case, the flame temperature is higher, but the residence time is shorter. Both conditions lead to increased CO emissions. But in confined hot environment, the maximum mean flow velocity is less than in open environment.

Figure 10 shows the effect of increasing the furnace temperature in the emission index of CO, for fuel mixture with 40% CH₄ and equivalence ratio of 0.5. For furnace temperature above of 700 °C, the CO reacts along of the furnace, reducing its rate of emission. For $T_f = 850$ °C, the emission index of CO is approximately zero.

However, the measured values in confined hot environment are higher than in open environment, due to greater homogeneity of chemical species measured. The maximum emission index of CO measured in confined environment was 2.23 g/kg for pure methane (100% CH₄, $u_{ch} = 10$ cm/s and $\phi = 0.5$). In open environment, for the same fuel and operating conditions, the maximum emission index of CO was 0.53 g/kg.

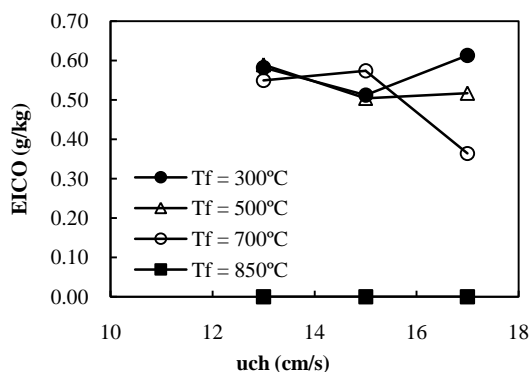


Figure 10. Emission index of CO as a function of the mean flow velocity for the different furnace temperature (40% CH₄ / $\phi = 0.5$).

Figure 11 shows the emission index of HC as a function of mean flow velocity for all fuel mixtures tested in confined hot environment ($T_f = 500^\circ\text{C}$ / $\phi = 0.5$). The emission index of HC decreases with reducing concentration of CH₄. The maximum emission index of HC observed was 0.38 g/kg, obtained for pure methane (100% CH₄, $u_{ch}=10$ cm/s and $\phi = 0.5$). In open environment, the emission index of HC was not significant, and the maximum observed value was 0.02 g/kg.

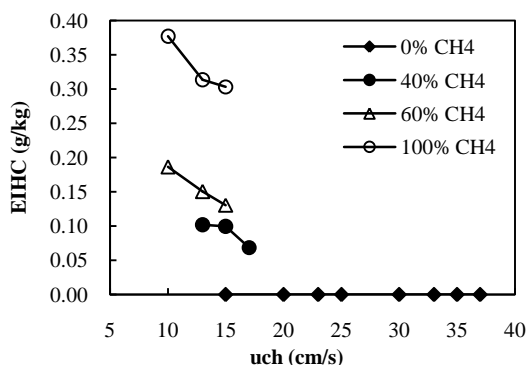


Figure 11. Emission index of HC as a function of the mean flow velocity for the different fuel mixtures ($\phi = 0.5$ / $T_f = 500^\circ\text{C}$).

Figure 12 shows the effect of increasing the furnace temperature in the emission index of HC, for fuel mixture with 40% CH₄ and equivalence ratio of 0.5. The increasing of furnace temperature lowers the emission index of HC. This effect is the result of chemical reactions in the furnace due to high temperature of the walls.

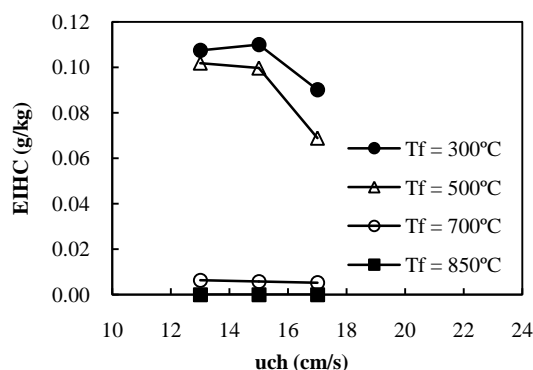


Figure 12. Emission index of HC as a function of the mean flow velocity for the different furnace temperature (40% CH₄ / $\phi = 0.5$).

5. CONCLUSIONS

A range of low calorific value gaseous fuel mixtures containing CH₄, H₂, CO₂, CO and N₂ have been burned in a porous radiant burner confined in a hot environment in order to analyze the effects of the fuel composition on flame

stability and pollutant emissions. This results was comparing with the results in open environment published (Francisco et al., 2010). In the fuel mixtures studied the CH₄ composition varied from 0 to 100% with the concentrations of the other gases varying in such a way that the constant pressure adiabatic flame temperature for all reacting mixtures was kept constant. In this study, the equivalence ratio was also kept constant.

The fuel mixtures selected were with 0%, 40%, 60% and 100% of CH₄. For each fuel mixture the range of stability has been experimentally evaluated keeping the equivalence ratio and furnace temperature constant at 0.5 and 500 °C, respectively.

Then, was evaluated the influence of furnace temperature on the behavior of the porous burner for fuel mixture with 40% of CH₄ and equivalence ratio of 0.5. The range of flame stability and pollutant emissions were evaluated for the furnace temperatures at 300 °C, 500°C, 700 °C and 850 °C.

The results have indicated that the macroscopic flame shape of the fuel mixtures remains approximately the same as compared with open environment, but the former flames move further downstream from the burner exit. Since the flame moves further downstream, the upper stability limits decreases comparing with results in open environment. The maximum reduction of the upper stability limit for all fuel mixtures tested was 25%.

The increase of furnace temperature at 300 °C to 850 °C did not influence the limits of stability or behavior of the flame in the porous burner. The greatest influence of T_f was in the emission index of pollutants. In confined hot environment, the chemical species were collected on the surface of the furnace exit. Thus, over the furnace there was greater homogeneity in the composition of combustion products.

There were no emissions index of NO_x for furnace temperatures between 300 °C and 700 °C. However, due to the reactions of chemical species along the duct of the furnace, for T_f at 850 °C the maximum level of NO_x measured was 0.028 g/kg.

Due to the homogeneity of chemical species, the emission index of CO measured in confined hot environment was greater than in open environment. The maximum emission index of CO measured in confined environment was 2.23 g/kg for pure methane (100% CH₄). For T_f at 850 °C the emission index of CO was reduced to approximately zero.

The emission index of HC decreases with decreasing concentration of CH₄. The maximum emission index of HC observed was 0.38 g/kg, obtained for pure methane (100% CH₄). Further, the increasing the furnace temperature reduced strongly to emission index of HC.

6. REFERENCES

- Adouane, B.; Hoppesteyn, P.; Jong, W.; Wel, M. V. D.; Hein, K. R. G.; Spliethoff, H., 2002, " Gas turbine combustor for biomass derived LCV gas, a first approach towards fuel-NO_x modeling and experimental validation", Appl. Therm. Eng., Vol. 22, pp. 959-970.
- Catapan, R. C.; Pereira, F. M.; Oliveira, A.A.M., 2005, "Development of a porous radiant burner with a combined thermal and fluiddynamic mechanism of flame stabilization", Proceedings of the 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil.
- Chomiak, J.; Longwell, J. P.; Sarofim, A. F., 1989, " Combustion of low calorific value gases; Problems and prospects", Prog. Energy Combust., Vol. 15, pp. 109-129.
- Francisco Jr., R. W.; F. Rua, F.; Costa, M.; Catapan, R. C.; Oliveira, A. A. M., 2010, " On the combustion of hydrogen rich gaseous fuels with low calorific value in a porous burner", Energy Fuels, Vol. 24, pp. 880-887.
- Giles, D. E.; Som, S.; Aggarwal, S. K., 2006, " NOx emission characteristics of counterflow syngas diffusion flames with airstream dilution", Fuel, Vol. 85, pp. 1729-1742.
- Halter, F.; Chauveau, C.; Djebaili-Chaumeix, N.; Gökalp, I., 2005, " Characterization of the effects of pressure and hydrogen concentration on laminar burning velocities of methane–hydrogen–air mixtures", Proc. Combustion Institute, Vol. 30, pp. 201-208.
- Hardesty, D. R.; Weinberg, F. J., 1974, " Burners producing large excess enthalpies", Combust. Sci. Technology, Vol. 8, pp. 201-214.
- Howell, J. R.; Hall, M. J.; Ellzey, J. L., 1996, " Combustion of hydrocarbon fuels within porous inert media", Prog. Energy Combustion, Vol. 22, pp. 121-145.
- Hsu, P.; Evans, W. D.; Howell, J. R., 1993, " Experimental and Numerical Study of Premixed Combustion Within Nonhomogeneous Porous Ceramics", Combust. Sci. Technology, Vol. 90, pp. 149-172.
- Oliveira, A. A. M.; Kaviany, M., 2001, " Nonequilibrium in the transport of heat and reactants in combustion in porous media", Prog. Energy Combustion Science, Vol. 27, pp. 523-545.
- Weinberg, F. J., 1971, " "Combustion Temperatures: The Future&quest ", Nature, Vol. 233, pp. 239-241.
- Wood, S.; Harris, A. T., 2008, " Porous burner for lean-burn applications", Prog. Energy Combustion Science, Vol. 34, pp. 667-684.