LEAN AND RICH ETHANOL COMBUSTION INSIDE POROUS MEDIA

Rafael Hafemann Moser, moser@labcet.ufsc.br

Rafael de Camargo Catapan, catapan@labcet.ufsc.br

Amir Antonio Martins Oliveira, amir@emc.ufsc.br

Laboratory of Combustion and Thermal Systems Engineering
Department of Mechanical Engineering
Federal University of Santa Catarina
Florianópolis - SC

Abstract. *This work presents the development of an experimental apparatus to study lean and rich ethanol combustion inside porous media. Stable operating points for various equivalence ratios and flame speeds are presented in a stability diagram. Temperature distributions along the center of the porous media are shown for stable operating points at equivalence ratios of 0,55 and 1,9. A gas analyzer was used to measure the composition of the products and evaluate the performance of the burner. Negligible amounts of CO were detected for lean combustion.*

Keywords*: Ethanol, porous burner, lean combustion, rich combustion.*

1. INTRODUCTION

Considerable efforts have been made in the development of combustion of liquid fuels in porous media in the past 20 years. The porous burner is more advantageous than the conventional open spray flame burner for several reasons: enhanced evaporation of droplet spray owing to regenerative combustion characteristics, enhanced mixing of reactants inside porous media, low emissions of CO and NOx, high combustion intensity with moderate turndown ratio and compactness (Jugjai *et al*., 2002).

Liquid fuels have the advantage of easy handling and well-developed extraction, refining and distribution facilities. However, premixed combustion of liquid fuels is more difficult since liquid fuels must first be atomized and vaporized, before being homogenously mixed with air. The possibility of stable and complete combustion inside porous media requires some special conditions. Kaplan and Hall (1995) found that the ceramic material, the configuration of the porous burner, pore size, droplet size and distance between the spray nozzle and the porous media are critical parameters to maintain stable operation.

Several authors suggest that utilization of porous media burner for liquid fuels is a promising approach for future applications, which includes incineration of liquid hazardous waste and total combustion for heating process (Kaplan and Hall, 1995). Recently, special attention has been direct to study the rich combustion of a variety of liquid fuels for synthesis gas production. Compared with the other reforming processes, i.e. steam reforming and autothermal reforming, the rich combustion has a better dynamic response, no external heat source is required and the system is more compact.

Pedersen-Mjaanes *et al*. (2005) studied the rich combustion of methanol, methane, octane and automotive-grade petrol inside porous media. Species concentrations were measured and operating limits were tested of steady rich flames stabilized inside inert two-layer alumina foam burner and two-layer alumina bead burner. Conversion efficiency of methanol to syngas of 66% and hydrogen mole fraction of 42% were achieved. The authors concluded that rich combustion inside a porous medium can be used to reform liquid and gaseous fuels into syngas. More recently, rich n-heptane and diesel combustion inside porous media were experimentally investigated by Pastore and Mastorakos (2010) over a range of various mixture inlet velocities for an equivalence ratio of 2,0. The reformer demonstrated several steady operating points. Diesel reforming tests were performed at a higher preheat temperature and the reformate analysis showed a reforming efficiency up to 77.6% at P = 9 kW and equivalence ratio 2,0 with a concentration of about 15.2% and 19.1% of H_2 and CO respectively.

In this context, the objective of this work is to develop an experimental setup to study lean and rich ethanol combustion in porous media. The specific objectives of this article are: to evaluate the performance of the experimental setup and to study the stability of ethanol flames inside porous media reactor.

2. EXPERIMENTAL SETUP

2.1. Apparatus

The experimental apparatus was built to test lean and rich combustion of liquid fuel in porous burners as illustrated in Figure 1. The set-up can be divided in three subsystems: the ethanol supply system, the air supply system and the porous burner.

The ethanol supply system is composed of a pressurized tank, an automotive glow plug, a PWM (Pulse Width Modulation) controller, a thermostat and an automotive fuel injector. The tank is pressurized at 400 kPa by bottled nitrogen (95 % pure). A glow plug is used to heat the ethanol and the thermostat maintains its temperature at 80 ºC. The ethanol is sprayed in the mixture chamber by an automotive fuel injector. A PWM controller interfaced with Labview regulates the opening time of the injector (Duty Cycle), allowing the control of the ethanol mass flow rate between 4 and 100 cm^3/min. The flow rate was calibrated with a "bucket and stopwatch" method giving an uncertainty of ±2%.

The air supply system is composed of an air compressor and a tank, a reducing valve, a shut-off valve and a flow meter and controller Omega FMA 775A with measurement range between 0 and 200 lpm and an uncertainty of ±2% of full scale. The air is heated by an electric resistance controlled by a temperature controller, which includes a type K thermocouple. The air is injected downward in the mixture chamber, creating a countercurrent flow of ethanol droplets and air, increasing the ethanol vaporization rate. At the end of the mixture chamber, a ceramic foam 10 ppi and 20 mm length is used as a laminarization section.

The porous burner is composed by two layers of ceramic foams 50 mm diameter and 40 mm length, and 80% of volumetric porosity, totalizing a reactor length of 80 mm. The ceramic foams (manufactured by Foseco) are made mainly by alumina (Al_2O_3) and zirconia (ZrO_2). An injection plate with a single central orifice with 11 mm in diameter is placed upstream from the ceramic foams. The purpose of this injection plate is to stabilize the flame inside the ceramic foams, preventing flashback (Catapan *et al*., 2011). Figure 2 shows a schematic of the porous burner.

Type R (platinum and platinum + 13 % rhodium, from Omega Engineering) thermocouples placed inside the alumina double-holed tubes are used to measure the temperature within the porous matrix. The temperature measurements indicate the position of the flame and if the operation point is stable. The thermocouple measurements are processed by a data acquisition system (34970A - Agilent) interfaced with a computer. The by-products were sampled by a water cooled stainless steel probe and analyzed by a gas analyzer (Testo – Model 327) with measurement range from 0 to 4000 ppm of CO and 0 to 21% of O_2.

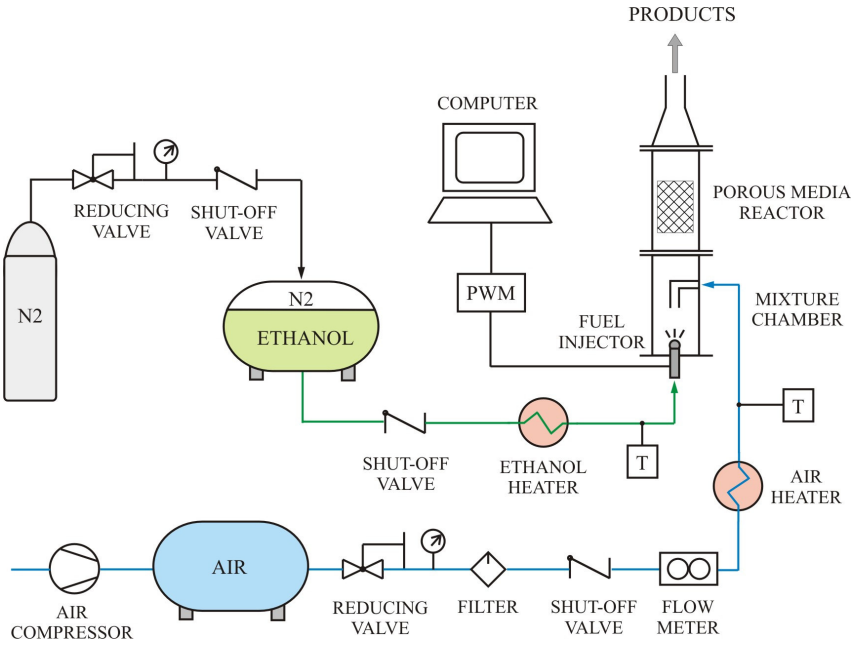

Figure 1. Schematic of experimental setup.

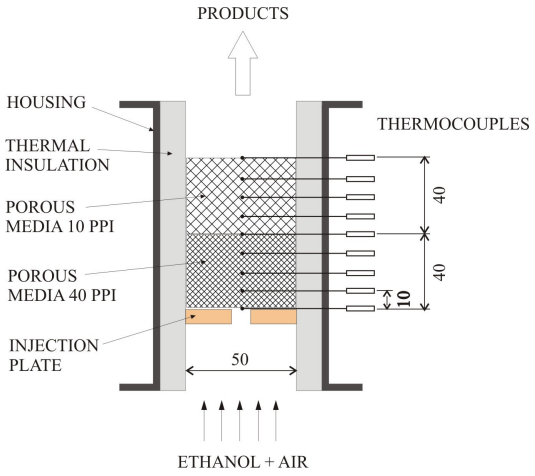

Figure 2. Schematic of porous burner.

2.2. Experimental Setup Performance

Preliminary tests performed with the experimental setup demonstrated that the ethanol droplets were not being completely vaporized. Insufficient vaporization could be detected by measuring temperatures lower than the boiling point of ethanol (78 ºC) at the entrance of the burner. Then, parameters such as: air preheat temperature, ethanol preheat temperature, ethanol pressure at the spray nozzle and different mixture chamber configurations were changed and separately evaluated in order to enhance the ethanol vaporization and create an adequate mixture of reactants. The actual conditions of the experimental setup as described in section 2.1. showed a satisfactory performance.

No procedure was used to characterize the homogeneity of the mixture ethanol/air. It was assumed that features such as: countercurrent flow of ethanol and air, laminarization section at the end of the mixing chamber and injection plate are sufficient to create a homogeneous mixture of reactants.

The porous burner was tested for approximately 50 hours and no failure was observed, except for the ceramic foam. Alumina did not melt, even for peak temperatures of 1600 ºC, but became fragile and got fractured. Similar behavior was observed by Pedersen-Mjaanes *et al*. (2005) and the authors explained this fact as a weakening or fracturing within the material caused by sudden thermal gradients during ignition, cooling down periods and changes in equivalence ratio. Although the ceramic foam got fragile and broke, the fractures did not seem to affect the burner performance since the alumina was wrapped in thermal insulation and tightly conditioned inside the burner housing.

The repeatability of the experiment is considered to be satisfactory. Each operating point was tested two times in order to build the stability diagram and a maximal difference of 2 cm/s was detected for the blow off and flashback limits and the peak temperature differed less than 50ºC.

3. RESULTS AND DISCUSSIONS

Experimental tests for ethanol lean and rich combustion were carried out in order to find stable operating points and detect the operating limits of the porous burner. Here, flames are considered stabilized inside the porous media as the temperature measurements indicates a variation lower than 5ºC in a period longer than 10 minutes. The blow-off limit is verified as the flame front moves downstream and the combustion reaction takes place outside the porous burner. The opposite behavior determines the flashback limit, when the flame moves upstream and reaches the first half of the 40 ppi porous media.

3.1. Lean Combustion

A stability diagram with the operating points tested is presented in Figure 3. Since the flame is stabilized, the flame speed is equivalent to the flow velocity in the burner, calculated from the burner area, the flow rate and the measured temperature of the reactants before entering the burner.

The lean combustion stability diagram shows stable operating points for equivalence ratios between 0,50 and 0,55 in a narrow range of flame speed, from 74 to 76 cm/s. One reason for this narrow stability zone could be that $\Phi = 0{,}50$ is close to the lower flammability limit of ethanol inside porous media. Howell *et al*. (1996) showed that the stability zone for methane flames is wide for equivalence ratios close to the stoichiometric conditions and becomes narrower as the equivalence ratio decreases. Operating points at equivalence ratios lower than 0,49 were not tested since the ethanol

flow rate control was limited by the minimum scale of the equipment. For equivalence ratios higher than 0,55 the maximal temperature supported by the ceramic foam (1550ºC) was exceeded and the operation was aborted.

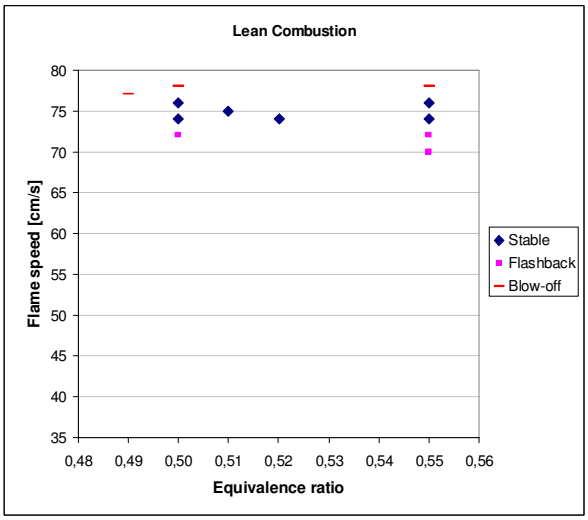

Figure 3. Operating envelope for ethanol lean combustion.

Figure 4 presents the axial temperature distribution along the center of the porous media for steady flames at equivalence ratio of 0,55. When the flame speed is raised from 74 cm/s to 76 cm/s the flame front is shifted further downstream to a position closer to the end of porous matrix. The peak temperatures for u_f = 74 cm/s and u_f = 76 cm/s were 1418 ºC and 1402 ºC, respectively.

The burner performance was evaluated by measuring the carbon monoxide emissions with a gas analyzer. Complete combustion creates a negligible amount of CO. If the emissions are high, the fuel is not being completely burned possibly due to insufficient mixing of reactants or deficient fuel vaporization. The measurements indicated 9,9% O2 and 0 ppm CO for the operating point Φ = 0,55 and u_f = 74 cm/s and 10,4% O2 and 0 ppm CO for the operating point Φ = 0,55 and u_f = 76 cm/s.

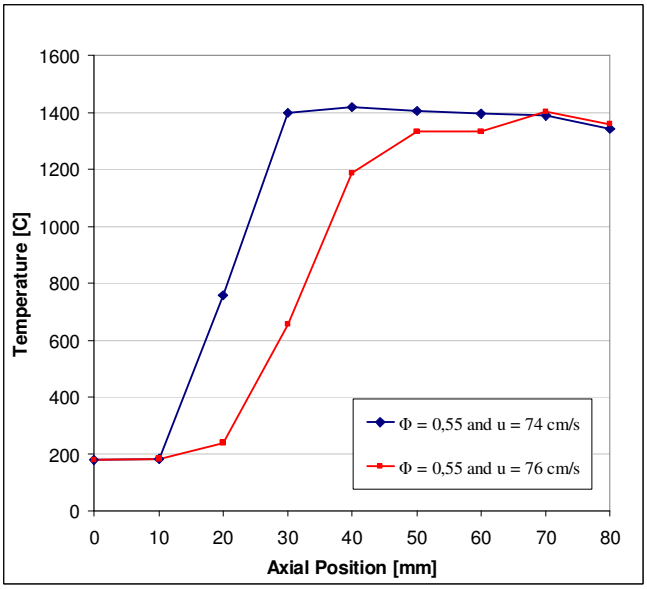

Figure 4. Temperature distribution inside porous burner for equivalence ratio 0,55 and flame speeds 74 cm/s and 76 cm/s.

3.2. Rich Combustion

The rich combustion stability diagram showed a broader range of flame speed as illustrated in Figure 5. Stable operating points were found at Φ =1,9 and flame speeds from 56 cm/s to 68 cm/s. Figure 6 presents axial temperature distribution along the center of the porous media for steady flames at equivalence ratio of 1,9. Peak temperatures of 1459 ºC and 1473 ºC were registered for u_f = 56 cm/s and u_f = 64 cm/s, respectively. Both temperature profiles indicate the flame front almost at the same position, differing from the temperature profiles of lean combustion showed before. Measurements of the products composition were not performed for rich combustion since the CO level is too high and the measurement range of the gas analyzer is not compatible.

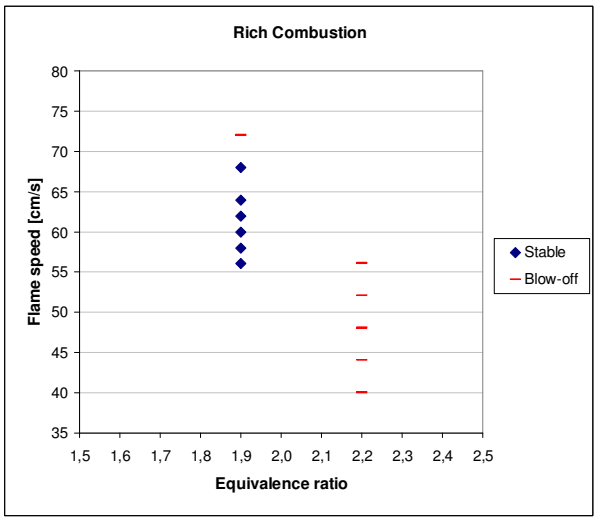

Figure 5. Operating envelope for ethanol rich combustion.

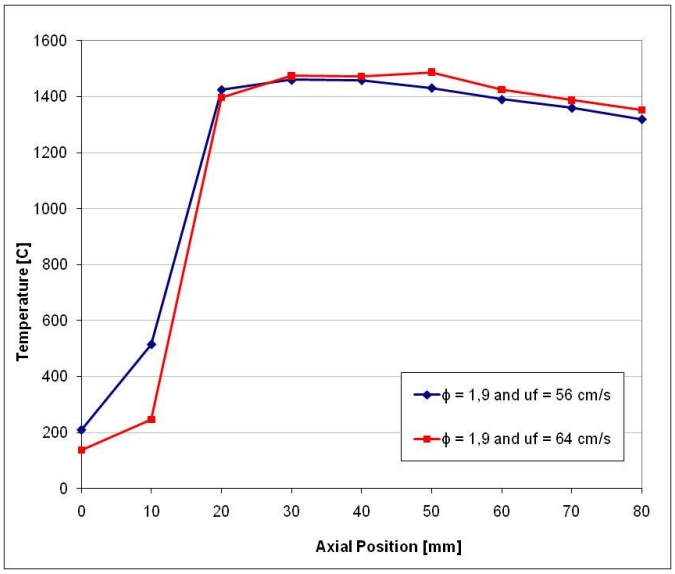

Figure 6. Temperature distribution inside porous media for equivalence ratio 1,9 and flame speeds 56 cm/s and 64 cm/s.

4. CONCLUSIONS

An experimental setup was built to test lean and rich combustion inside porous media. Satisfactory ethanol vaporization and an adequate mixture of reactants were achieved with the setup proposed in this work. Stability diagrams showing stable operating points were presented and a broader zone of flame speed (from 56 cm/s to 68 cm/s) for a constant equivalence ratio was found for rich combustion.

Temperatures along the center of the porous media were measured with the purpose of identifying the flame position and if the combustion is stable. Temperature distributions were presented for lean combustion at equivalence ratio of 0,55 and flame speeds 74 cm/s and 76 cm/s. Temperature profiles inside porous media for equivalence ratio of 1,9 and flame speeds 56 cm/s and 64 cm/s were also presented.

The combustion products were sampled by a water cooled probe and analyzed by a gas analyzer. Negligible amounts of CO were detected for lean combustion, indicating that the fuel is being completely burned.

5. REFERENCES

Catapan, R., Oliveira, A. A. and Costa, M., 2011, "Non-uniform velocity profile mechanism for flame stabilization in a porous radiant burner", Experimental Thermal and Fluid Science, vol. 35, pp. 172-179.

Howell, J. R., Hall M. J., Ellzey J. L., 1996, "Combustion of Hydrocarbon Fuels Within Porous Inert Media", Prog. Energy Combustion Science, vol. 22, pp. 121-145.

Jugjai, S., Wongpanit, N., Laoketkan, T. and Nokkaew, S., 2002, "The Combustion of Liquid Fuels Using a Porous Medium", Experimental Thermal and Fluid Science, vol. 26, pp. 15-23.

Kaplan, M. and Hall, M. J., 1995, "The Combustion of Liquid Fuels Within a Porous Media Radiant Burner", Experimental Thermal and Fluid Science, vol. 11, pp. 13-20.

Pastore, A., and Mastorakos, E., 2010, "Rich N-Heptane and Diesel Combustion in Porous Media", Experimental Thermal and Fluid Science, vol. 34, pp. 359-365.

Pedersen-Mjaanes, H., Chan, L. and Mastorakos, E., 2005, "Hydrogen Production from Rich Combustion in Porous Media", International Journal of Hydrogen Energy, vol. 30, pp. 579-592.

6. RESPONSIBILITY NOTICE

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