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STUDY OF THE COMBUSTION OF BIOETHANOL WITH EXCESS OF WATER USING A POROUS BURNER WITH COUPLED EVAPORATOR

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Abstract. *Currently, there is much interest in the production of bioethanol from renewable raw materials, mainly sugarcane and corn, to minimize carbon dioxide emissions, a greenhouse gas that contributes to global warming. During the ethanol production process, a distillation step is necessary to reduce the concentration of water present in the mixture, thus increasing the degree of purity of the fuel. The reason for this is that the use of raw bioethanol, with excess water, results in operating instability problems and requires higher energy rates in the fuel evaporation stage. However, for higher concentrations of ethanol, the cost of the distillation process ends up increasing the final value of the product. Thus, the objective of this project is to evaluate the burning of raw bioethanol, with excess water, using a porous burner and an evaporator coupled to the system. The parameters evaluated experimentally were the heat transfer rate from the flame to the evaporator, the burner stability range and the radiation efficiency. The analysis of the evaporator coupled to the burner was initially performed using pre-mixed methane and air, equivalence ratio of 0.5 and power range between 0.4 and 3.1 kW. In this condition, the rate of heat transfer to the evaporator measured experimentally represented about 10% of the energy generated by the combustion reaction. Radiation efficiency was around 18 to 22%. For a power of 1,1 kW using anhydrous ethanol, the energy required to evaporate the mixture is 76 W. The increase in the fraction of water in bioethanol results in an increase in the amount of energy required in the fuel evaporation step.*

Keywords: *bioethanol combustion, porous media burner, evaporation heat transfer, flame stability, biofuels (ethanol)*

1. INTRODUCTION

Environmental pollutants and global warming issue are the main concerns of the huge growth rate of industrial and domestic energy demands during the last few decades. Furthermore, fossil fuel resources are limited and running out quickly (Gharehghani et al., 2021). Currently, there is much interest in the production of bioethanol from renewable raw materials, mainly sugarcane and corn to minimize carbon dioxide emissions, a greenhouse gas. The United States remained the world leader in ethanol production in 2022, despite the pandemic-induced reduction in output. The U.S. saw its share of total global output decline slightly to 53 percent, but we remained responsible for more than half of worldwide production. Meanwhile, Brazil's share of total world production rose slightly to 31 percent (RFA, 2022). In 2022, the national sugar production was 36.3 million tons, 3.4% higher than the previous year, while the production of ethanol decreased by 6.1%, yielding the amount of 28.1 million m^3 (EPE, 2023).

However, with the emergence of new sources of biofuels, it becomes necessary to encourage the development of technologies capable of using these fuels in a stable and safe way. In this context, PM (porous media) reactors, referred to heat recirculating reactors characterizes as self-organized heat recirculating from reaction zone to fresh mixture without any addition of external heat source. Heat recirculating accomplishes by radiation and conduction of solid matrix in the flow direction or/and heat exchange between the fresh and exhaust mixture in the transverse direction through burner walls (Devi et al., 2023), see Figure 1. Various fluid modes and heat transfer processes enhances heat recirculating (Shi et al., 2023). Combustion in inert porous media was experimentally investigated on a porous burner test bench. This bench allows independent control of air and fuel flows, measurement of the burner temperature profile and monitoring of the flame front displacement. through the porous medium. In this way, it is possible to observe the effects of thermal and flow parameters on the flame stabilization capacity for a given burner configuration. Sugarcane is the main feedstock used to produce ethanol fuel in tropical areas such as India, Brazil and Colombia, while corn dominates in other areas such as the US, EU and China (Mendiburu et al., 2022).

The porous medium provides several benefits for combustion. Firstly, it enhances the contact between the fuel and air, ensuring efficient mixing and reducing the likelihood of incomplete combustion or the formation of harmful by products such as carbon monoxide (CO). Additionally, the porous structure promotes heat transfer, allowing for uniform and controlled combustion. The design of the porous burner media can be optimized to achieve specific combustion characteristics, such as flame stability, low emissions, and high thermal efficiency. Factors such as the pore size, porosity, and material composition of the burner medium can influence the combustion performance. By carefully tailoring these parameters, it is possible to achieve efficient and clean combustion of methane in porous burners.

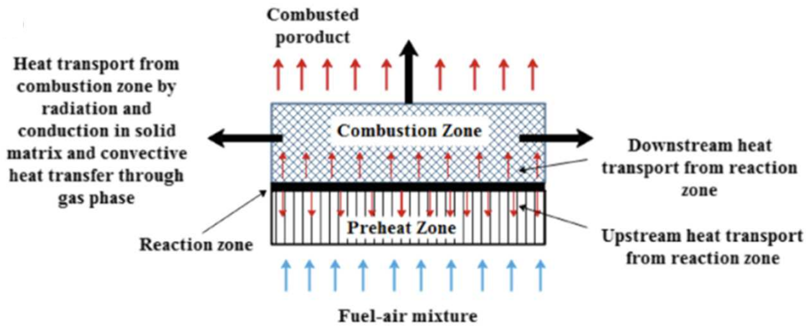

Figure 1. Heat transfer in porous media (Devi et al., 2023).

Burner surface temperature is significant in radiation and porous inner temperature causes intrinsic preheat of the mixture. Therefore, in order to enhance thermal efficiency of the burner, the burner surface temperature and the preheat of the porous mixture should be increased. However, side temperature of porous media does not directly affect the heating load. (Soltanian et al., 2023). Porous medium combustion technology has been commercialized since the early 20th century. Currently, PMC finds extensive applications in industries like wood and paint drying, food processing, chemical industries, etc. (Banerjee, Paul, 2021).

The idea of utilizing the energy of the premixed flame to preheat the air-fuel mixture within the porous solid medium was long time ago (Weinberg et al., 1988). After Weinberg's idea, in recent years, many researchers have explored the different applications of porous radiant burners, which work based on the combustion of porous media for gaseous and liquid fuels. Combustion of the air-fuel mixture within a PM helps to stabilize the flame within the pore structure of the inert matrix. After burning products heat the PM (porous media) downstream of the flame zone. Some of this heat is then conducted and radiated back to the upstream section, which heats the incoming fuel-air mixture. Unlike a conventional free flame, which has a single flame speed corresponding to each equivalence ratio (Wu et al., 2015), porous burners have a range of speeds where it is possible to obtain a stable flame. In this way, for each equivalence ratio there is a lower and upper limit of flame stability. The main advantage of PM burner is that low calorific value fuels can be burned efficiently in the porous matrix with low emissions. Heat recirculation in the upstream section promotes preheating of the incoming air-fuel mixture, thus increasing combustion efficiency (Shaik et al., 2022). In general, porous burners present a large range of flame stability limits because of the heat transfer between the combustion products and the porous matrix and, subsequently,between the porous matrix and environment (Francisco Jr. et al., 2013).

Several studies have utilized various burner designs to recover the heat loss of the exhaust gas to preheat the incoming fuel/air mixture, the preheating effect on super adiabatic combustion of propane/air mixture was studied (Huang et al., 2002). Porous burners are designed to provide efficient and stable combustion by promoting better mixing of fuel and air and enhancing the flame stability, Figure 2. When methane is introduced into the porous burner, it flows through the interconnected network of pores within the burner medium.

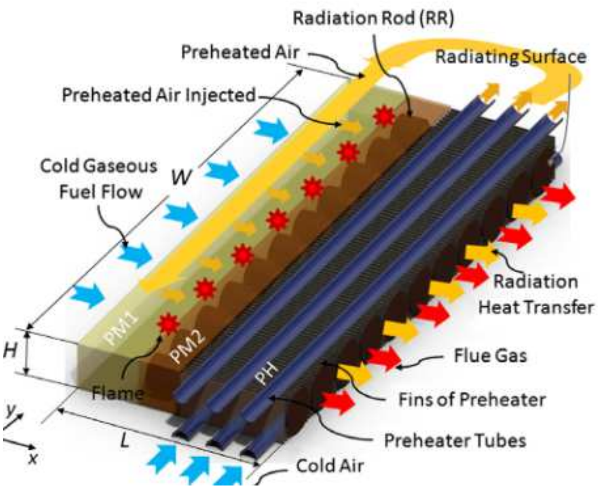

Figure 2. Two-layer porous burner with heat exchanger (Vandadi et al., 2013).

Different practical and industrial applications were proposed and developed (Bakry et al., 2023). The porous material can be a ceramic or metallic foam, sintered metal, or any other material with a high surface area and interconnected porosity. The purpose of this medium is to facilitate better mixing of fuel and air and to enhance the surface area available for the combustion reactions. A reaction system represents reacting molecules at temperatures lower than their products, chemical formulas are used to symbolize this kinetics. The physical-chemical phenomenon combustion is the release of energy, heat in joules, and the exothermic process is the reaction of the fuel and oxidant providing heat and products. As the methane flows through the pores, it comes into contact with the oxygen from the surrounding air. The oxygen molecules dissociate and combine with the methane molecules to produce carbon dioxide (CO_2) and water vapor (H_2O) through the following chemical reaction:

$$CH_4 + 2O_2 \text{->} CO_2 + 2H_2O + \text{Heat} \quad (1)$$

This reaction (1) releases a significant amount of heat, which is utilized for various applications, such as heating, cooking, or power generation. The combustion process in the porous medium is characterized by a distributed reaction zone, where the reaction occurs over a large surface area rather than at a distinct flame front as in traditional burners. The porous structure promotes heat transfer, allowing for uniform and controlled combustion. The design of the porous burner media can be optimized to achieve specific combustion characteristics, such as flame stability, low emissions, and high thermal efficiency. Factors such as the pore size, porosity, and material composition of the burner medium can influence the combustion performance. By carefully tailoring these parameters, it is possible to achieve efficient and clean combustion of methane in porous burners. Overall, combustion in porous burner media with methane involves the controlled mixing of methane and oxygen within a porous material, resulting in the release of heat and the production of carbon dioxide and water vapor. This approach offers advantages in terms of enhanced mixing, improved flame stability, and efficient heat transfer, making it a promising technology for various combustion applications. Thus, porous media burners (PMBs) have proven to be ideal for dealing with these problems due to their reduced pollution and technical and energy efficiencies (Janvekar et al., 2017). Despite many studies on evaporation, the process of energy transfer across the evaporation interface is far from completely clear due to the complex and changing flow pattern in the liquid and vapor domains and the non-equilibrium phenomenon during evaporation. For example, thermocapillary convection can strongly affect the rate of evaporation and the magnitude of the temperature discontinuity (Guo et al., 2022). Sustainable development goals are to reduce greenhouse gas emissions and seek renewable energy to replace traditional energy (Zhang et al., 2023).

During the bioethanol production process, a distillation step is necessary to reduce the concentration of water present in the mixture, thus increasing the purity of the fuel. However, for higher concentrations of ethanol, the cost of this distillation process ends up increasing the final value of the fuel. Also, hydrogen energy was considered as a prospective clean energy source because of its high calorific value, net-zero emissions and abundant sources. (Dai, Wu, 2023) .

Thus, the objective of this project will be to evaluate the effect of water concentration in bioethanol in relation to the burner stability range and radiation efficiency. The results obtained may be used for the development of combustion equipment for industrial or residential applications, operating with bioethanol with higher concentrations of water and, therefore, lower operating costs. However, ethanol is increasingly attracting study attention due to its availability and less harmful effect than methanol or methane. In considerations of methanol and ethanol pro-duction, methanol is mostly produced by the chemical conversion of various syngas, whereas ethanol is primarily produced through the fermentation of biomass, which is readily available in most countries (Chen et al., 2023).

2. METHODOLOGY

The experimental bench was based on the proposal by (Kotani, Takeno, 1982), which states that the introduction of heat recirculation inside the porous plug makes it possible to sustain combustion with flow rates much larger than the normal burning velocity, so the combustion in a two-layer ceramic porous medium burner coupled to a spiral-shaped heat exchanger is experimentally investigated on a test bench as shown in Figure 3. This bench allows independent control of air and fuel flows, measurement of the burner temperature profile and monitoring of the displacement of the flame front through of the porous medium. In this way, it is possible to observe the effects of thermal and flow parameters on the flame stabilization capacity for a given burner configuration.

(a) (b) (c)

Figure 3. Two-layer porous burner with heat exchanger. (a) SiC porous media in two different porosities. (b) Heat exchanger coupled. (c) Radiant burner in operation.

Thermocouples R-type (green color) are arranged in a vertical battery of four thermocouples, with 20 mm between each thermocouple, Figure 4. This assembly allows monitoring the axial displacement of the flame front and the homogeneity of the temperature profile. Each thermocouple is introduced through one of the holes in the test section. The tip of the thermocouple comes into thermal equilibrium with the gases and the solid through convection, radiation, and conduction. Thus, the measurement provided by these sensors must be understood as an average between the gas and solid temperatures at that position, Figure 4.

Figure 4. Test bench photography.

The fuel flow control system involves the use of an electronic mass balance and a steel tank containing liquid ethanol that is pressurized by compressed air, Figure 5. The electronic balance is coupled to the computer and is used to instantly measure the mass of injected liquid ethanol on the burner. The air pressure inside the tank is controlled by a precision pressure regulating valve, which operates between 0.5 and 2 bar.

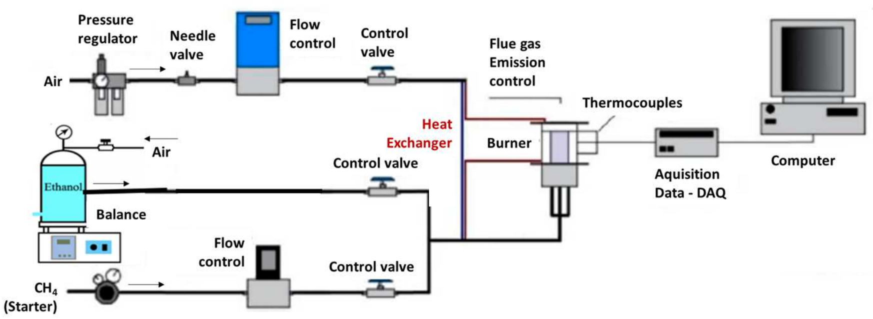

Figure 5. Schematic diagram of the test bench.

The air comes from a 6.9 bar pressure compressed air line, connected to the line is a pressure regulating filter (20 µm filter element) plus coalescing filter (0.3 µm filter element), where oil and moisture are extracted, and the pressure is reduced to 4.5 bar.

The burner is ignited using pure methane pre-mixed with air.The methane used in the tests is 99.5% pure (White Martins – methane 2.5). Table 1 lists the bench control instruments with their measurement uncertainties.

Table 1. Uncertainty of measurement of the components of the experimental apparatus.

Measuring instrument	Uncertainty
Air – Mass flow controller OMEGA FMA-A2323	± 1.0% Full scale
CH4 – Mass flow controller OMEGA FMA-2408A	± (0.8% Read + 0.2% Scale)
Ethanol – mass measuring scale SHIMADZU UX4-200H	d = 0.01g / e = 0.1g
Thermocouple K-Type (NiCr–NiAl)	±2.2 ºC or 0.75%
Thermocouple R-Type (Pt-Pt/Rh 13%)	± 1.5ºC or 0.25%
Data acquisition system Keysight DAQ970A	± 1.0ºC

First, the burner is started with methane fuel in an operating condition where the flame easily propagates into the porous medium. The initial condition chosen was the equivalence ratio of 0.45 and 42.4 slpm of air (equivalent to a flame velocity of 19 cm/s). Ignition is done manually at the top of the burner. The flame starts as a free blue flame and, as the burner surface is heated, the flame front starts to propagate into the porous medium. The position of the flame front is defined, in each of the three thermocouple batteries, as being coincident with the highest temperature thermocouple.

The flame then propagates to the interface between the flame stabilization region (FSR) and the preheating region (PR), remaining stationary in this position for some time, due to its difficulty in entering the small pores of the region. preheating. After about two minutes with the flame front at the interface, the temperatures in this region already reach values around 1300 ºC and, thus, the entire FSR is preheated before the burner is taken to the point of operation. Next, the air and methane flow rates are adjusted to the equivalence ratio and gas flow to be tested, and then the flame is expected to stabilize. This burner preheating procedure is necessary because, in this way, the tests are carried out in a situation closer to that of its normal operation. For a flame to be considered stable, it is necessary that the temperatures of the 13 thermocouples installed in the test section remain without significant changes (less than 5ºC) for at least twenty minutes.

For a flame to reach this steady-state condition, it is necessary to wait more than 15 minutes. Then, the total gas flow rate is varied in small increments, seeking to discover the maximum and minimum values between which the flame stabilizes within the FSR for the test equivalence ratio. The upper limit of stability is defined as the last stable flame obtained before flame detachment occurs. It is considered flame detachment when any part of the flame front leaves the FSR becoming visible in the form of a free blue colored flame. Likewise, the lower stability limit is defined as the last stable flame obtained before any part of the flame front has propagated into the PR, which characterizes the flashback.

The propagation of the flame front into the PR is controlled by the set of two thermocouples located 10 mm below the interface between FSR and PR. When a temperature Spike is being registered by one of these two thermocouples, there is a flashback.

3. RESULTS

Five different experiments were performed as described in Table 2. The compilation of more than 40,000 points collected on the test bench is statistically robust, as the standard deviation was always less than three kelvins for each temperature stabilized for around 30 minutes in each combination of parameters. The data presented symmetry in its sampling distribution, always with a 95% confidence interval for the mean.

Table 2. Combustion parameters of experiments

Run	Fuel	Ø	$\dot{Q}_{air}$ (SLPM)	$\dot{m}_{fuel}$ (g/s)	Remark
1	Pure ethanol	0.45	33.24	0.033	Stable flame for more than 20 min
2	Pure ethanol	0.45	37.27	0.037	Stable flame for more than 20 min
3	Pure ethanol	0.45	41.32	0.041	Stable flame for more than 20 min
4	20% water	0.53	35.12	0.045	Stable flame for more than 20 min
5	20% water	0.53	39.30	0.050	Stable flame for more than 20 min

All tests were carried out with an equivalence ratio of 0.45 or 0.53 and reactant temperature at 300 K. It can be seen that the pure ethanol injected into the evaporator heated up to a temperature of 105 ºC, for the three initial tests, with different thermal powers. An analysis is performed using temperature profiles for each of the five experiments previously presented, Figure 6.

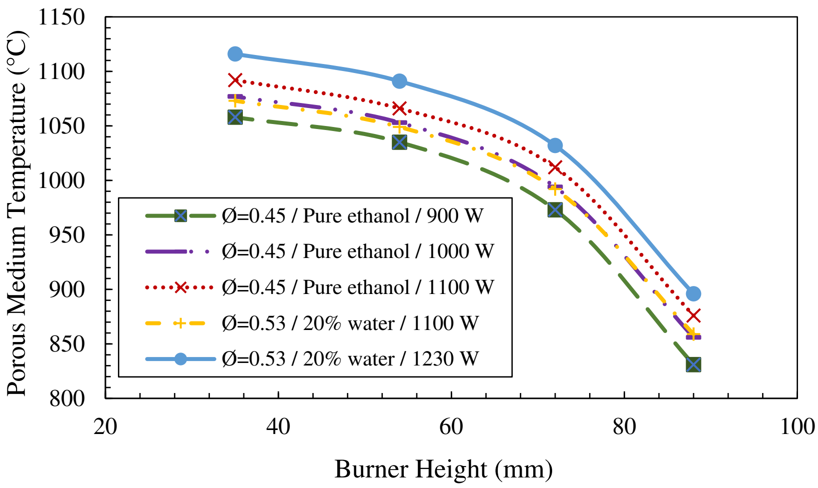

Figure 6. Temperatures observed inside porous medium, almost 40,000 points.

The position of each type R thermocouple along the vertical axis (height in mm) has its origin on the lower face of the first porous medium (zero point), thus verifying the position of the flame is always a little below the downstream and upstream interface (40 mm) in a stable state.

The higher temperatures are related to the greater power used (1230 W) and the higher equivalence ratio (Ø = 0.53). The lowest temperature profile is also observed with pure ethanol, for Ø = 0.45 and with a power of 900 W. Furthermore, it can be observed that for a thermal power of 1100 W, the mixture with 20% water presented lower temperatures in the porous medium.

Figure 7 shows the thermal power supplied to the burner as a function of the equivalence ratio.

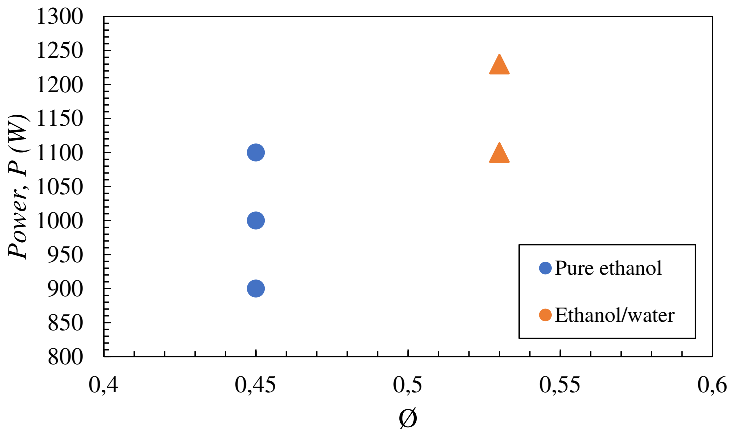

Figure 7. Ethanol combustion at two equivalence ratio and power levels.

For pure ethanol it was possible to obtain a stable flame for an equivalence ratio of 0.45. However, for the mixture with 20% water, the lowest equivalence ratio obtained was 0.53. For lower equivalence ratios, the temperature in the porous medium was below 1000 ºC and the temperature of the reactant mixture at the evaporator outlet (before entering the porous medium) was below 100 ºC, which could result in condensation of water in the piping and on the plate. injection.

Figure 8 shows the temperatures of the burner's porous surface after flame stabilization, using pure ethanol and 20% excess water inside the evaporator.

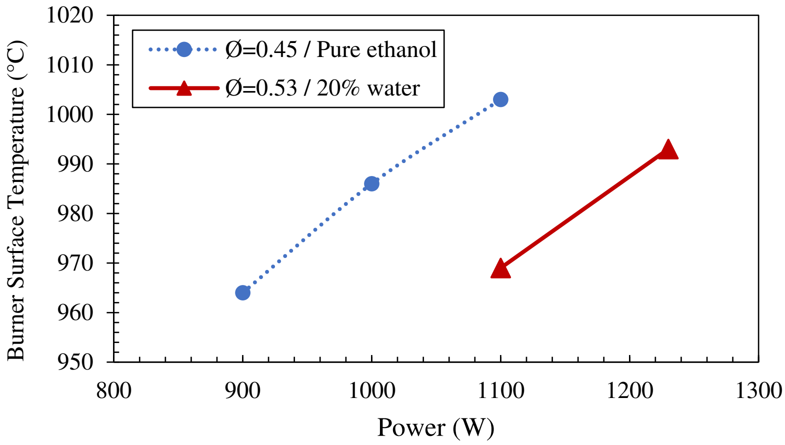

Figure 8. Temperatures on radiant surface versus applied power to porous burner.

Lower power values applied to the radiant porous burner resulted in lower surface temperatures. For pure ethanol, increasing the thermal power from 900 to 1100 W resulted in an increase in the surface temperature from 964 to 1003 ºC.

Furthermore, for the power of 1100 W, pure ethanol showed a surface temperature 3.5% higher. This effect is the result of the lower reaction temperature due to the addition of water to the fuel mixture.

Figure 9 shows the radiation efficiency as a function of the thermal power applied to the burner. This efficiency is the ratio between the heat transfer rate by radiation at the burner exit surface and the thermal power. The emissivity was approximated to 1.0.

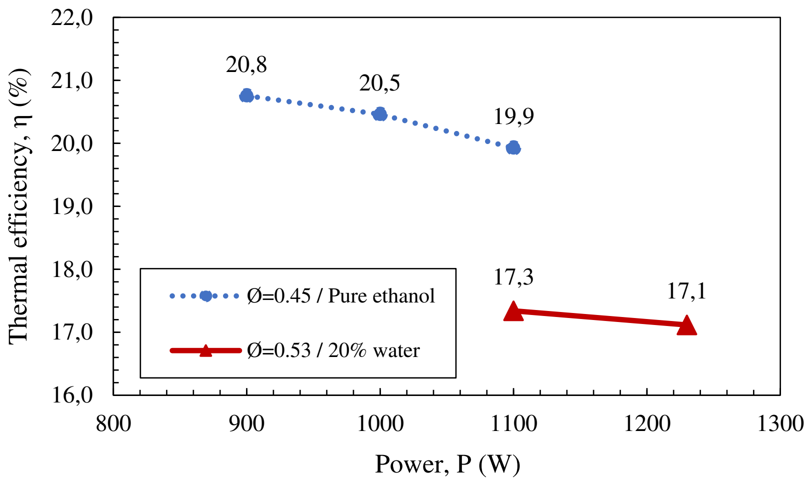

Figure 9. Thermal efficiency and Powers of the PMB.

It can be seen that the highest thermal efficiency was obtained for pure ethanol at a power of 900 W (20.8%). The increase in power resulted in a reduction in efficiency for both fuels. This effect is the result of the simultaneous increase in energy loss from the burner walls to the environment and the energy transported by the exhaust gases at the burner exit, thus reducing thermal efficiency.

For a power of 1100 W, the addition of water to the mixture resulted in a 13.1% reduction in thermal efficiency, due to the lower surface temperature, thus reducing the heat transfer rate by radiation.

4. CONCLUSIONS

The objective of the present work was to evaluate the evaporation and combustion of ethanol with excess water in a porous radiant burner with a coupled heat exchanger, always considering a flame stability regime.

In general, it can be observed that the water addition to the fuel mixture did not influence the burner's flame stability, only in the operating conditions. For the mixture with 20% excess water, it was possible to obtain a stable flame by increasing the equivalence ratio from 0.45 to 0.53. Thus, resulting in an increase in the reaction temperature and allowing the transfer of energy necessary for the complete evaporation of the fuel in the coupled heat exchanger.

Furthermore, the addition of water resulted in a 13 % reduction in thermal efficiency for a power of 1100 W. The maximum thermal efficiency obtained was 20.8 % for pure ethanol, with an equivalence ratio of 0.45 and a power of 900 W.

The power ranges and equivalence ratio obtained are a result of the burner design and the temperature limitations of the porous medium. The project continues with the complete mapping of the burner operating conditions, with different equivalence ratios and water concentrations.

5. ACKNOWLEDGEMENTS

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