ANALYSIS OF A POROUS BURNER WITH AN INTEGRATED HEAT EXCHANGER AND RADIAL INJECTION OF THE REACTANTS

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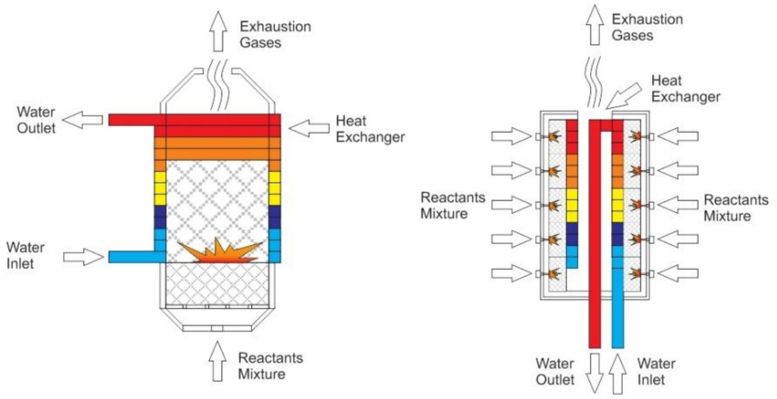
Abstract. *Here, we present an experimental study of combustion in an inert porous medium in a liquid heating device application. The experiment consists in a cylindrical porous burner with an integrated annular water heat exchanger. The reactants were injected radially into the burner and the flame stabilizes within the porous matrix. The water circulates in a coiled pipe positioned at the center of the burner. This configuration allows for heat transfer by conduction and radiation from the solid matrix to the heat exchanger. The objective of this work is to evaluate the influence of the radial heat loss to the circulating fluid on the flame stability within the porous burner. This configuration allows for the operation of the burner at high power rates without exceeding the temperature limit of the porous medium. The device showed thermal efficiencies between 65 and 90%, depending on the operational point. Thermal energies (hot water) up to 4 kW were generated. The maximum power reached for a steady flame was 5 kW. The fuel used was natural gas.*

Keywords*: Combustion, porous medium, water heating.*

1. INTRODUCTION

The combustion in porous media has been widely studied in the last years and excellent reviews can be found in the literature (Hardesty and Weinberg, 1974; Kotani and Takeno, 1982; Oliveira and Kaviany, 2001). The enhanced combustion control allowed by this technology results in more flexible firing systems that are more appropriate to the specific needs of each application (Möβauer et al., 1999). Among the various applications of porous burner (Trimis and Durst, 1996) one can cite, for example, water heating, environment heating and drying. In this work, a new configuration for a water heating device for household applications based on a porous burner is studied.

In previous work related to the use of a porous burner for water heating (Delalic et al., 2004; Francisco and Oliveira, 2006) the injection of reactants was performed at the base of the burner in the axial direction as shown in Figure 1a. Here, a new configuration is proposed based on the radial injection of reactants. Figure 1b shows the porous burner with radial injection. The injection rings are positioned equally spaced along of the length of the burner.



(a) (b)

Figure 1. Porous burner with axial injection and radial injection.

A household water heater must be capable of supplying hot water for two showers simultaneously, but it must be also economical when only one shower is used. Then, the device needs to achieve a high turn down ratio while maintaining the thermal efficiency. The proposed configurations can achieve both goals with low emissions and reduced size compared to currently available household water heaters.

In the following, the basic concept of the device and the experimental setup used in the experiments will be present in detail. Then, preliminary results are presented and the potential of the new water heater concept is discussed.

2. WATER HEATER CONCEPT

The water heater concept consists of an annular porous matrix with radial injection of reactants at its external surface and a pipe coil heat exchanger mounted at the internal cavity of the porous medium. A schematic representation of the preliminary prototype is shown in Figure 2. It was built with 3 distribution rings with 6 injectors in each ring. This system distributes the reactants radially at the external surface of the burner. The outer surfaces of the burner are insulated with alumina blanket and the assembly is encapsulated in a stainless steel housing

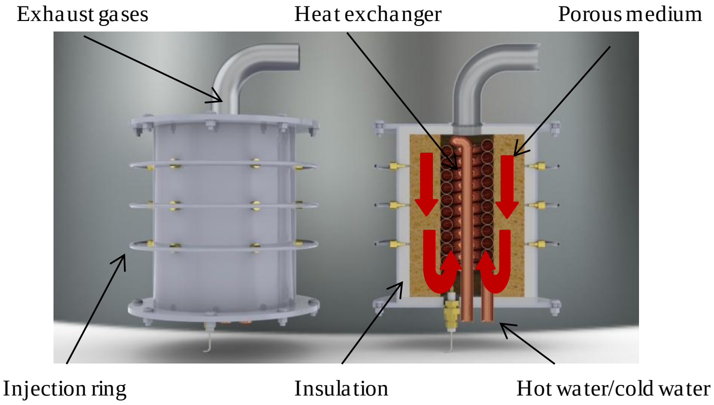


Figure 2. Basic conception of the compact water heater.

In this model the reactants (natural gas/air) are injected radially in porous medium by the injectors and at each injection point, a flame is stabilized within the porous medium. The combustion products flow downward through the porous matrix as shown in Figure 2. At the bottom of the device the gas products pass to the internal cavity of the annular porous medium and flow upward in contact with the pipe coil towards the chimney. The outer area of the pipe coil is in direct contact with the porous medium absorbing heat by radiation, conduction and convection. The inner area of the pipe coil is in contact with the combustion products only and absorbs heat by convection.

Ceramic foams with 65% zirconia and 35% alumina are used. The volumetric porosity of these foams is 85%. This material can operate at temperatures up to 1600 °C. Figure 3 shows a photograph of the device assembly.

Figure 3. Photo of the burner open surface and the coil positioned in the center of the porous medium.

3. EXPERIMENTAL SETUP

The experimental setup consists basically of a water supply line, a natural gas supply line, an air supply line, the compact heater prototype and a data acquisition system for measuring the temperatures. Figure 4 shows the schematic representation of the experimental setup built in this work.

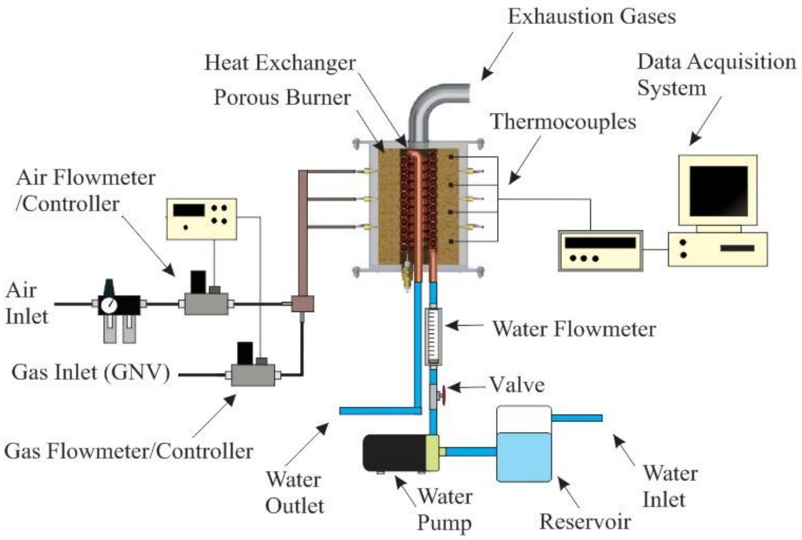


Figure 4. Rendering of the experimental setup for experimental prototype evaluation.

The air and natural gas flow were measured individually and then mixed in a 1 meter long tube to ensure an homogeneous mixture of reactants in the burner inlet. In the water line, a reservoir is used to maintain a constant flow and pressure throughout the test. A needle valve was added at the water pump outlet to control the water flow. The water flow measurement was performed with a rotameter flow meter (Omel / model 4T), preceeded by a 1 meter length section pipe, without bends or constrictions.

Temperatures inside of the porous medium and the surface of the burner were measured using R type thermocouples (platinum-platinum / 13% rhodium.) The water temperature was measured with K type thermocouples (Cromel / Alumel), with Teflon insulation and installed at 3 cm distance from the inlet and outlet water heater. A data acquisition system was used to convert the analog signal generated by the thermocouples into a digital signal. Table 1 presents a description of the main components of the experimental setup.

Table 1. Equipments used in the experimental setup.

Equipment	Manufacturer	Model
Natural gas flow meter	Omega	FM1770
Air flow meter	Omega	FL-400A
Water flow meter	Omel	4T
Data acquisition system	AGILENT	34970A (40 channel)
Thermocouples	Omega	Type K
Thermocouples	Omega	Type R
Water pump	Schneider	BCR-2000 (1/3 cv)

Table 2 presents the maximum experimental uncertainties for equivalence ratio, Ø, thermal power, S_r and energy given to cooling water Q_w based on error propagation analysis.

Table 2. Estimated experimental uncertainties.

$IM_{Ø}$	0.070
IM_{Sr}	0.071 kW
IM_{Qw}	0.525 kW

4. EXPERIMENTAL PROCEDURE

The methodology employed to study the water heater is based on previous works from literature (Hsu et al., 1993, Francisco, 2008 and Catapan, 2007) with adaptations for the present device.

First, the flame is sparked inside the porous medium, using a flame igniter. Then, several operating points (equivalence ratio / thermal power) are applied to determine the flame stability limits and the operation limits of the burner.

The flame is considered stable when the temperatures measured by the thermocouples are stable for 20 minutes with oscillations under ± 20ºC. The flame stability limits were determined by keeping the equivalence ratio (Ø) constant and varying the thermal power supplied to the burner in small increments. The lower stability limit was defined as the lowest power at which it was possible to obtain a stable flame. The upper stability limit was defined as the point at which the flame front is extinguished due to contact with the cold wall of the heat exchanger. The maximum equivalence ratio used was defined as a function of operating temperature inside the porous medium. For a burner made of zirconia-alumina, temperatures above 1600 °C resulted in degradation of the ceramic structure - change in color and vitrified points (Pereira, 2002). Thus, the maximum temperature was set to 1550 ° C.

5. PRELIMINARY RESULTS

The preliminary tests reported in this article were obtaining using only the distribution ring at the middle. Figure 5 shows the operation diagram obtained for this configuration of the burner for a water flow of 5 lpm. The upper (fill circles) and lower (open squares) lines represent the maximum and minimum thermal power obtained respectively. The region between the upper and lower lines represent the region where stable flames were obtained.

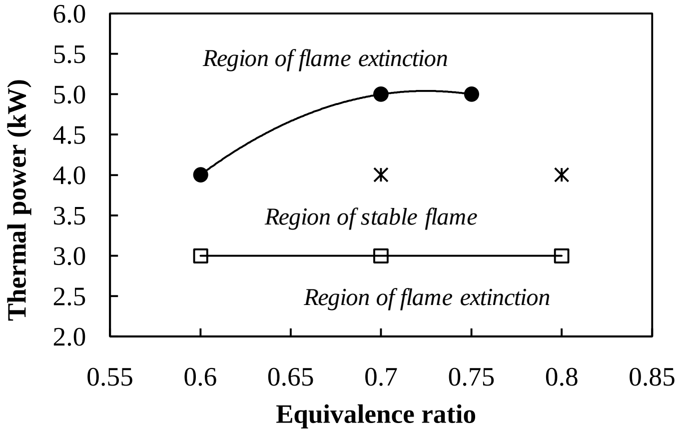


Figure 5. Operation diagram of the burner.

The range of equivalence ratios used varied from 0.6 to 0.8, resulting in thermal powers from 3 to 5 kW. For an equivalence ratio of 0.8 the maximum thermal power applied was 4 kW, due to the high temperature at the interface between the porous medium and the insulation.

Figure 6 shows the increase of the water temperature (ΔT_w) as it flows through the coil pipe heat exchanger as a function of equivalence ratio. The parameter ΔT_w is determined by the thermocouples placed at the water inlet and outlet of the system. The thermal power applied to the burner varied between 3 and 5 kW.

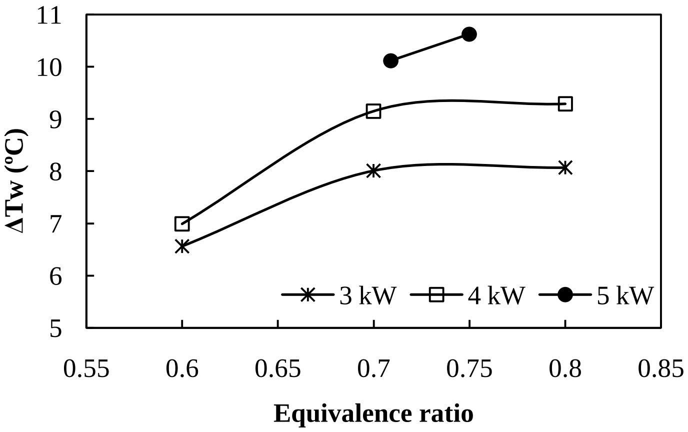


Figure 6. Increase of the water temperature (ΔT_w) as a function of equivalence ratio.

The ΔT_w increases with increasing the thermal power for the same equivalence ratio. It can be observed that the maximum ΔT_w obtained was 11 °C for 5 kW and equivalence ratio equal to 0.75. The ΔT_w obtained for this flow rate of water (5 lpm) is still lower than that necessary for household applications (20 °C). Increase of the input power using the other distribution rings and optimization of the coil pipe are the next steps aiming at reaching intense heating with high thermal efficiency.

Figure 7 shows the burned gases temperature where they leave the porous medium and start to flow upward at the center of the water heater. The temperature of the exhaust gases, at the chimney varied from 50 to 70 °C for all conditions tested. As expected, the burned gases temperature increases with increasing power.

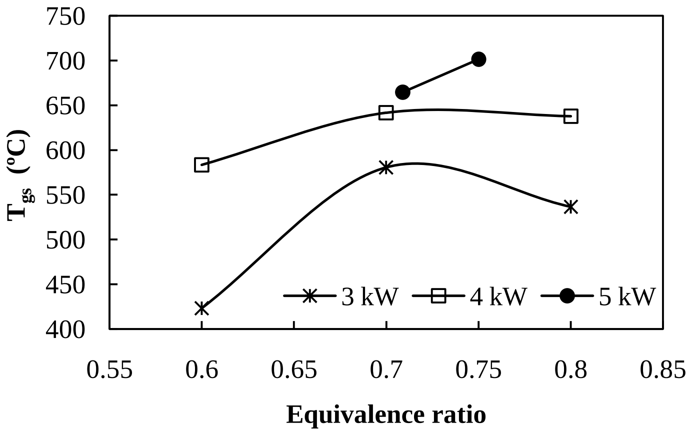
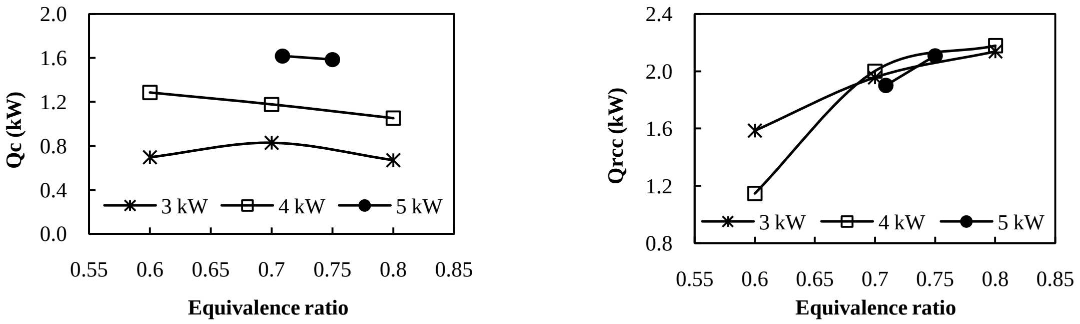


Figure 7. Burned gases temperature where they leave the porous medium and start to flow upward at the center of the water heater as a function of equivalence ratio.

The temperature of exhaust gas at the entrance of the coil ranged between 536 and 700 º C.

For the measurement of the temperature variation of gas products as they flow upward passing by the coil pipe heat exchanger, it is possible to estimate the heat transfer by convection from the gas to the coil. From the total heat absorbed by the water it is possible to determine the amount of heat transfer at the other side of the coil, where it is in direct contact with the porous medium. Figure 8 shows the amount of energy transferred to the coil by convection at the inner wall of the coil and the amount of energy transferred by radiation, convection and conduction at the outer wall of the coil.



(a) (b)

Figure 8. Energy transferred to the water by convection at the inner wall of the coil pipe (a) and by radiation, convection and conduction at the outer wall of the coil (b).

The heat transfer at the inner side of the coil varies from 0.65 to 1.66 kW. The heat transfer at the outer side of the coil varies from 1.2 to 2.2 kW, showing that the porous medium has a significant role in heating the water. The energy loss at the outer walls of the burner was estimated from 0.2, for total power of 3 kW, to 1.2 kW, for total power of 5 kW. These are significative values with a large uncertainty. New measurements with a thermographic camera may improve the estimate. Thermal insulation will also be applied.

Figure 9 shows the thermal efficiency of the water heater as a function of the equivalence ratio. The thermal efficiency is defined as the ratio of the energy absorbed by the water to the power input imposed to the burner.

As expected, increasing the equivalence ratio or decreasing the thermal power result in an increased thermal efficiency. For 3 kW, the range of efficiencies varied from 90 to 93% for all equivalence ratios tested, while for 4 kW the efficiency varied from 61 to 81%. This result indicates that the proposed configuration needs to be optimized in order to achieve high efficiencies at higher power inputs.

The thermal power increase above 5 kW results in flame extinction due to the flame front tendency to move to regions closer to the coil (cold wall). It may be noted also that for equivalence ratios above 0.7 the efficiency increase is low, being more significant for ratios between 0.6 and 0.7.

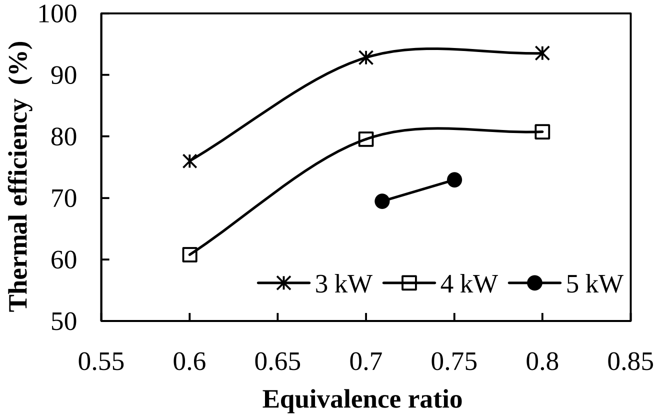


Figure 9. Thermal efficiency as a function of the equivalence ratio for thermal power between 3 and 5 kW.

6. CONCLUSION

This article presents preliminary experimental results of a new water heater based on an annular porous burner. The range of equivalence ratios tested varied from 0.65 to 0.8. The power range was varied from 3 to 5 kW. Increasing the equivalence ratio or decreasing the total power input of the burner resulted in increased thermal efficiencies of the water heater. Thermal efficiencies varying from 60 to 92% were obtained.

The maximum increase of the water temperature obtained was 11 ºC for 5 lpm, which is lower than that necessary for a comfortable bath (20 °C for 8-12 lpm). This preliminary prototype will be optimized in order to achieve intense heating with high thermal efficiency.

7. ACKNOWLEDGEMENTS

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