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Experimental analysis of natural gas combustion in a porous burner

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ABSTRACT

The study aims to evaluate a novel porous medium burner (PMB) with a heat exchanger for household heating systems. In this regard, a PMB together with a heat exchanger is designed and built in the laboratory. The changes of temperature in the porous medium combustion chamber have been recorded, and the pressure losses in the burner, thermal efficiency of the burner, and the concentration of NO polluting gasses have been measured. The obtained results indicate that the maximum temperature is at the beginning of the combustion zone and the end of the preheating zone; but, with the increase of power and the excess air ratio, the flame front moves forward. At a constant power, with the increase of the excess air ratio, the total flow rate increases, followed by the increase of pressure loss. The thermal efficiency results indicate that the highest efficiency is achieved at the excess air ratio of 1/2. This is due to the fact that at this ratio, the combustion products have their highest temperature. The volume of excess air has a significant influence on the amount of NO produced. With the increase of excess air, the volume of NO gasses diminishes.

1. Introduction

Combustion within porous media is a continuous topic of many studies in the recent decades. Burners with a porous combustion chamber are advanced types of burners that burn the air and fuel mixture inside a porous body. The act of combustion in these burners, contrary to the ordinary premixing burners, does not occur through free flames, but takes place in 3D form, without flame, and inside the openings of a porous body. Implementing the technology of burners with porous combustion chambers is one way of reducing the energy consumption and the amount of generated pollution. Low NO_x and CO emission, high efficiency, high power densities, and large dynamic range are the advantages that distinguish porous media combustion from conventional free flames.

De Soete [1] is one of the first researchers who investigated the subject of combustion in porous media. He experimentally explored flame stability and propagation in sandy media of different sizes, and presented a semi-empirical model for computing the flame speed and determining the effect of preheating via heat conduction in solids.

Weinberg [2] and Hardesty et al. [3,4] investigated the effect of preheating the mixture entering a porous medium on the increase of flame speed. Korzhavin et al. [5] performed some experiments to determine the speed of flame propagation in porous medium and observed that the flame speed can be 1–30 times the speed of a free flame. They attributed this increase of flame speed in porous medium to flow turbulence but the heat return mechanism was not discussed.

Takeno and Sato [6] proposed inserting a porous solid of high conductivity into the flame zone to transfer the post flame enthalpy to enhance the fresh mixture preheating. Afterwards, many analytical and experimental studies have been made to analyze the combustion characteristics of porous medium burner for premixed gaseous fuel-air mixture system.

In a number of experimental works (Hashimoto et al. [7], Kotani et al. [8], Kotani and Takeno [9]]), the researchers used a series of ceramic tubes as a porous medium. Their experiments showed that, firstly, a flame can become stable in three zones: (1) between the tubes, (2) at the downstream of flow and at the exit, and (3) at the upstream of flow and at the entrance to the tubes; and, secondly, the emission of NOx and CO gasses diminishes considerably when the flame becomes stable in the porous region. Babkin et al. [10] found out that when the pore sizes become small, the flame speed diminishes. This agreed with the results of Desoete's experiments [1].

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Nomenclature

C_p	specific heat capacity, J/kg K
HV	heating value, J/kg
HHV	higher heating value, J/kg
LHV	lower heating value, J/kg
$\dot{m}_g$	fuel mass flow rate, kg/s
$\dot{m}_w$	water mass flow rate, kg/s
$\dot{Q}_g$	energy given to water, J
$\dot{Q}_w$	heating energy content of injected fuel, J
T	temperature, K

Greek symbol

η	thermal efficiency, dimensionless

Chafin et al. [11] are the first researchers who performed some experiments to determine the amount of discharged pollutants. They examined the stability range, temperature distributions, and emissions over a range of the equivalence ratios and flow rates. They demonstrated that very low concentrations of NO_x occur for fuel/air equivalence ratios from 0.6 to 0.9.

Hsu et al. [12] investigated the premixed methane combustion within two section porous burner. Four series of experiments were carried out to determine the lean limit using three different pore sizes in the downstream ceramic cylinder. The results showed that the maximum flame speed inside the porous medium was higher than free flame speed and the lean limits in the porous burner were lower than that of the free flames. Flame stability at the interface and exit plane was shown both numerically and experimentally.

Khanna et al. [13] experimentally studied a two-section cylindrical porous burner with 25.6 pores per centimeter (ppc) partially stabilized zirconia (PSZ) ceramic in upstream section and 3.9 ppc PSZ in the downstream section. Their investigation demonstrated that by increasing the flame speed for all equivalence ratios, both NO_x and CO emissions increase at the exit of burner. Also, radiant burner output was measured and found to increase with inlet flow velocity but the radiant thermal efficiency of the burner decreases with increasing flame speed.

Howell [14] used ceramic foam with a dodecahedral structure in order to increase the combustion efficiency. These types of porous materials have many advantages. They enjoy a very low pressure loss, and they also have a larger specific surface area than ceramic blocks with straight holes. Therefore, in these materials, the convection heat transfer between gas and solid is increased.

Trimis and Durst [15] conducted a study on a porous burner including preheating, combustion heat exchanger zones. The heat exchanger is embedded in the reaction region of the combustor. They found that their combined burner-heat exchanger system in 10–15 times smaller in volume than existing burner and heat exchanger units. Low level of emission, and high power dynamic rang are the other exceptional advantages of this system compared to conventional burner heat exchangers.

Matthew et al. [16] evaluated the experimental and numerical results for a two-part burner using an air/propane mixture. They also used the air/methane mixture for comparison. The examined burner contained two cylindrical sections made of yttria-stabilized alumina (YZA) ceramic foam (diameter and height of each section were 101.6 and 50.8 mm, respectively) with different porosity factors. These upstream and downstream sections had a ppc of 6.23 and 9.3, respectively. These parts were placed in the lower half of a casing insulated by aluminum oxide, and the upper half of the casing was empty.

Delalic et al. [17] analyzed and tested a two-part porous burner connected to a heat exchanger. Barra and Ellzey [18] investigated a two-section porous burner through experiment and computations experimentally. In that study, the stable operating range was identified for propane/air and methane/air mixtures. The burner consisted of an upstream section of upstream section of reticulated yttria- stabilized zirconia with 23.6 ppc and downstream section of 3.9 ppc.

Avdic [19] modified a combined heating system, by coupling the combination of the particular PMB with solar collectors, to satisfy the requirements of environments. His experimental results showed that the porous medium burner could operate as a “submerged” burner.

Farzaneh et al. [20] analyzed numerically a porous burner with integrated heat exchanger, where a two-dimensional axisymmetric problem raised in premixed combustion. Their numerical results showed a good agreement with experimental data, and consequently proofed that the numerical scheme has a good accuracy to show the details of the flow and heat transfer in different regions of the porous burner. Based on their results, it was concluded that the developed numerical program could be considered as an excellent tool for investigation the combustion in porous burner.

The overall picture of the global scenario of research and developments in porous medium combustion (PMC) and its applications was provided by Abdul Mujeebu et al. [21]. In another study, Mujeebu et al. [22] comprehensively reviewed the applications of Porous Media Combustion Technology, while a part of his study focused on an exclusive outline of the applications of PMC such as household heating systems and burners, air-heating systems, gas turbines and propulsion, combustion of liquid fuels and etc.

Wang et al. [23] experimentally investigated the axial temperature variations of the porous media burner during startup and switch-off processes. They studied the effect of the burner inlet gas flow rate, equivalence ratio, and diameter of alumina pellets on the combustion temperature distribution along the burner axis and the combustion wave velocity.

Al-attab et al. [24] studied the performance of PMB fueled by producer gas from biomass gasification. They developed a downdraft gasifier system along with a PMB burner and heat recovery unit. In order to have complete combustion, the combustion region was isolated from cooling through a ceramic ring.

The main goal of this research is to acquire the knowledge for the development of the technology of making a compact porous medium burner and heat exchanger for household applications. So, a porous burner with integrated heat exchanger is manufactured and tested for variety of operating conditions. Centerline temperature and NO emission are measured and the effects of the thermal load and excess air ratio are discussed on the pressure drop and thermal efficiency of the burner.

2. Design of the porous burner

The most important criterion which determines whether or not a combustion process takes place inside a porous structure is its critical pore size. If the size of the pores is smaller than this critical dimension, flame propagation is prohibited; the flame is always