Effect of Porosity on Combustion Performance in Packed Bed Porous Media

Abdullah Alrashidi
Department of Mechanical Engineering, College of Engineering, Northern Border University, Arar, Saudi Arabia
abdullah.alrashidi@nbu.edu.sa

Ismail M. M. Elsemary
Department of Mechanical Engineering, College of Engineering, Northern Border University, Arar, Saudi Arabia | Combustion and Energy Technology Lab, Mechanical Engineering Department, Shoubra Faculty of Engineering, Benha University, Cairo, Egypt
i.semary@feng.bu.edu.eg | ismail.elsemry@nbu.edu.sa (corresponding author)

Ahmed A. Abdel-Rehim
Combustion and Energy Technology Lab, Mechanical Engineering Department, Shoubra Faculty of Engineering, Benha University, Cairo, Egypt
ahmed.azim@bue.edu.eg

Osama E. Abdellatif
Combustion and Energy Technology Lab, Mechanical Engineering Department, Shoubra Faculty of Engineering, Benha University, Cairo, Egypt
osama.abdellatif@feng.bu.edu.eg

Mohamed Fayek Abd Rabbo
Combustion and Energy Technology Lab, Mechanical Engineering Department, Shoubra Faculty of Engineering, Benha University, Cairo, Egypt
fayek44@yahoo.com

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ABSTRACT

This study investigates the effect of packed bed material porosity and air-to-fuel ratio on the combustion stabilization of a premixed gaseous mixture. An experimental work was carried out in a single-layer concept of a packed bed on a constant cross-sectional area tubular burner. Two types of materials, Alumina (Al_2O_3) and Zirconia (ZrO_2), with different porosities, namely 0.36, 0.4, 0.44, and 0.46, were tested. The results showed that porosity has a significant effect on the position of the reaction zones. As porosity decreases, the reaction zone moves downstream of the packed bed. The excess air ratio does not affect the position of the reaction zone but has an impact on the temperature distribution inside the porous medium. The packed bed material affects the volume of the reaction zone and the temperature distribution inside the porous media, where Zirconia has a reaction zone volume higher than Alumina. The concentration of NO_x was reduced with increasing porosity. Zirconia media exhibits a lower level of NO_x emission compared to Alumina. For an excess air ratio of 1.6, the maximum NO_x values were 22.5 and 17.5 ppm for Alumina and Zirconia, respectively.

Keywords-porosity; porous media; flame stability

I. INTRODUCTION

Fuel limitations, combustion inefficiencies, and high pollutant emissions have motivated researchers to improve combustion efficiency and introduce more mature technologies [1-4]. An attractive design in combustion technologies is the use of a porous medium, as introduced in [5]. Combustion in porous media has been widely investigated and proven to be well-suited for lean combustion on a wide range of different fuels. In [6-7], the effect of a porous media arrangement was studied on a CH_4/air combuster, and the experimental and simulation results indicated that the inner and outer layers had a positive impact on the combustion process. Many studies focused on the usage of liquid fuels, such as kerosene and ethanol [8-12]. In [13-14], a comprehensive review of research and development in the combustion of liquid fuels within a porous medium was carried out. The utilization of porous media can enhance liquid fuel evaporation and combustion with a significant reduction in pollutant emissions [10, 13, 15]. Other studies have demonstrated that employing a porous medium allows the use of lean or even ultra-lean combustion with low heating value gases, such as methane, ethane, propane, hydrogen, and mixtures of different gases [14-20]. Porous media can be deployed in different applications of the combustion system, namely cooking stoves and boilers [21-24]. Similarly, there are several studies on the performance of porous media implemented in combustion systems using simulation and numerical modeling techniques [25-30]. The stability limit of premixed flames in porous media has always been an attractive parameter to be examined when changing the fuel type and porous material. Many studies have explored the flame stabilization of premixed gaseous fuels using single or double layers of porous media. In [31], the effect of preheating conditions on the initiation and extinction of super-adiabatic combustion was studied in a steady flow of propane/air mixture. It was found that there were critical conditions in the steady flow through the inert porous column. In [32], flame stabilization was investigated in a two-layer porous media combustor with different sizes of alumina balls for the premixed combustion of lean methane-air mixtures. In [33], the characteristics of the combustion of a premixed methane-air mixture in a porous inert medium under high pressure and temperature revealed that there was excellent flame stability with respect to both flashback and blow-out limits in all operating conditions under investigation. Furthermore, it was discovered that the blow-out stability was not affected by pressure but depended on the inlet temperature of the mixture. In [34], the combustion characteristics of a two-layer porous burner for methane and LPG revealed that there was a homogeneous temperature distribution, low NO_x and CO emissions, and wide flexibility with respect to fuels and thermal loads. There are two main types of porous media: single-layer and two-layer. The single layer is capable of producing higher temperatures even with lean combustion, due to its ability to recirculate the excess enthalpy during combustion by sustaining the flame within the cavity of the porous media. However, limited studies are available on the single-layer concept because it is susceptible to flashback [35]. One potential technological advancement for burning extremely lean fuels, which are normally unignitable, is the use of porous burners. Commercial porous burners are currently implemented in a variety of industries, including food processing, paper/wood drying, metal heat treatment, coating/paint drying, glass/chemical processing, and space/water heating [18].

The literature highlights the importance of creating porous media burner systems that are easy to use, affordable, and require little maintenance. Due to the qualities of these materials and their resilience to temperature cycles, ceramic materials such as silicon carbide, alumina, and zirconia have been previously investigated. When building a porous media burner, there are still factors to consider, involving porosity, air-to-fuel ratio, and the effect of the porous media material on flame stabilization. Therefore, the search for straightforward, affordable, and easily implementable burner designs that have a unique heat transfer efficiency justifies more research and analysis. This study aims to investigate how the air-to-fuel ratio, porosity, and porous media material affect the flame. Two types of ceramic materials, Zirconia and Alumina, with varying porosities (0.48, 0.44, 0.40, and 0.36) were experimentally examined to discover which of them is the most appropriate.

II. EXPERIMENTAL SETUP

The experimental work was carried out on a constant cross-sectional area tubular burner supplied with controlled air and fuel supply systems, using suitable measuring devices, as shown in Figure 1. The burner was made of a transparent material tube with an outer diameter of 44 mm and an inner diameter of 40 mm opened to the atmosphere. The porous media was backed and supported by a mesh which was mounted on the top of a steel rod of 4 mm diameter at the center of the tube, as illustrated in Figure 2.

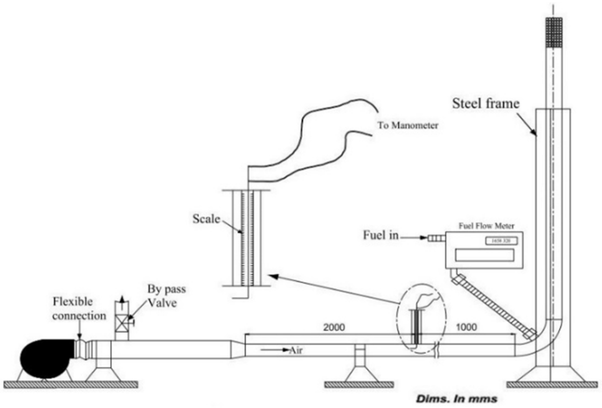

Fig. 1. Schematic layout of the experimental test rig.

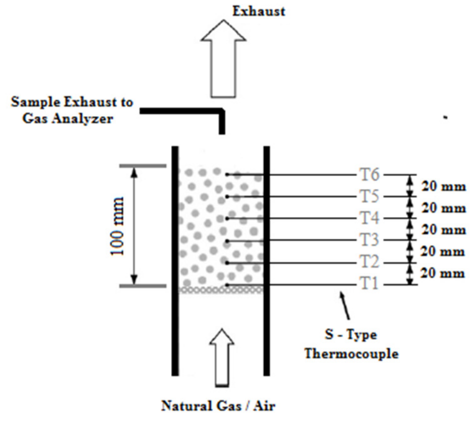

Fig. 2. Test section.

A controlled amount of air was supplied to the test section by a centrifugal blower through a pipeline that branched into two sections: one was directed to the test section and the other was connected to a bypass valve, as portrayed in Figure 1. The air mass flow rate was determined by measuring the air velocity through a Pitot tube with a digital sensor. The uncertainty of the air mass flow rate was estimated to be ±0.8%.

Natural gas was injected into the air stream at a sufficient distance from the bed to provide a uniform and homogeneous gas mixture flowing into the burner. The amount of fuel was controlled and measured using a fuel flow meter that was provided with a control valve to adjust its flow rate. The uncertainty of the fuel flow rate was estimated to be ±1.7%. The properties of the natural gas utilized in the experimental test, provided by the local gas company (PETROGAS), were density = 0.754 kg/m^3, calorific value = 42852 kJ/kg, and molecular weight = 18.87.

The temperature profile was obtained by deploying six thermocouples connected to a data acquisition system. The thermocouples were S-type (platinum - platinum radium 10%) with 0.5 mm diameter and 100 mm length. The thermocouples were distributed along the burner test section as presented in Figure 2, with a distance of 20 mm between them. This arrangement was suitable to indicate the flame location inside the burner medium. The flame temperature distributions were acquired upstream and downstream of the flame zone. The uncertainty of the temperature measurement was estimated to be ±0.6%. The exhaust gas components were measured by a gas analyzer. Two types of baked bed materials, Alumina and Zirconia, with porosities of 0.36, 0.4, 0.44, and 0.46 were tested. Table I displays the properties of the two materials.

TABLE I. PROPERTIES OF ALUMINA AND ZIRCONIA

	Alumina (Al_2O_3)	Zirconia (ZrO_2)
Density (gm/cm^3)	3.61	6
Thermal conductivity (W/m.K)	18	3
Specific heat (J/kg.K)	800	460

III. RESULTS AND DISCUSSION

Four different porosities were compared for the two materials. Figure 3 exhibits the temperature profiles along the axial line for different porosities of 0.36, 0.4, 0.44, and 0.48 in a 10 cm height of backed Alumina and Zirconia balls. The inlet air velocity and the amount of fuel injected were kept constant. It is observed that by decreasing the porosity of the packed bed, the peak temperature moves downstream of the bed. As porosity increases, the cavities between the balls increase, helping the flame to diffuse inside the bed at low levels before crossing the whole bed height. For this reason, many studies recommend including another layer of low-porosity material before the bed [36]. Also, there is a slight increase in the peak temperature for the Zirconia-packed bed compared to that of the Alumina one because of the difference in thermal properties between the two materials. Figure 3 also reveals that there is no significant difference between porosities of 0.36 and 0.4 for both materials.

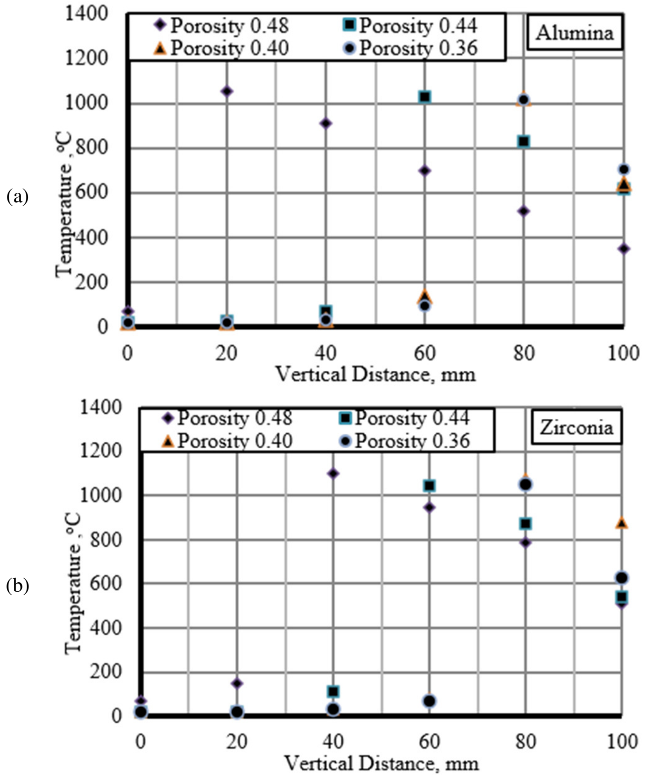

Fig. 3. Effect of porosity on maximum flame position for Alumina and Zirconia porous media for the same air inlet velocity of 0.3 m/s.

Figures 4 and 5 provide the temperature profiles for Alumina and Zirconia for different porosities and different air/fuel ratios. At the same inlet velocity and by changing the air-to-fuel ratio, the flame can be stabilized at the same axial location, which could be indicated by the location of the peak temperature in the bed. The peak temperature through the porous media is slightly decreased when increasing the excess air. This occurs due to the reductions in the combustion efficiency caused by the cooling effect when increasing the amount of air.

Figure 6 shows the exhaust gas pollutants represented by NO_x and CO for the two materials in different excess air ratios for the same porosity of the packed bed. It is obvious that the concentrations of both NO_x and CO in the exhaust decrease as the amount of air increases. This can be explained by the extra amount of air that reduces the temperature, as described above. Figure 6 also indicates that CO and NO_x concentrations decrease as the ball diameter decreases (porosity decreases). Although the temperature of Zirconia is slightly higher than that of Alumina, the NO_x emissions are lower for Zirconia. This can be explained by the fact that Zirconia acts as a catalyst to reduce the NO_x emissions [37, 38].

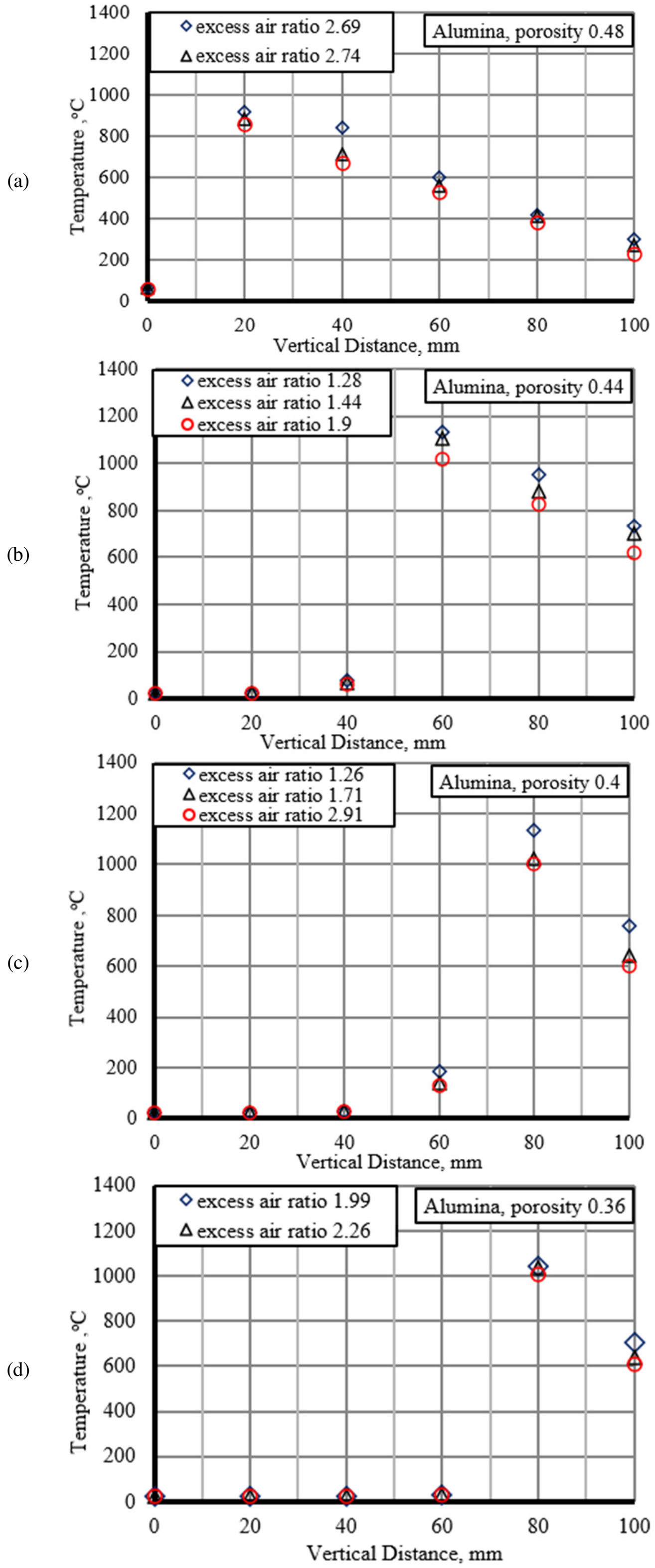

Fig. 4. Effect of excess air on flame temperature for Alumina porous media with different porosities of (a) 0.48, (b) 0.44, (c) 0.40, and (d) 0.36 at an inlet air velocity of 0.3m/s.

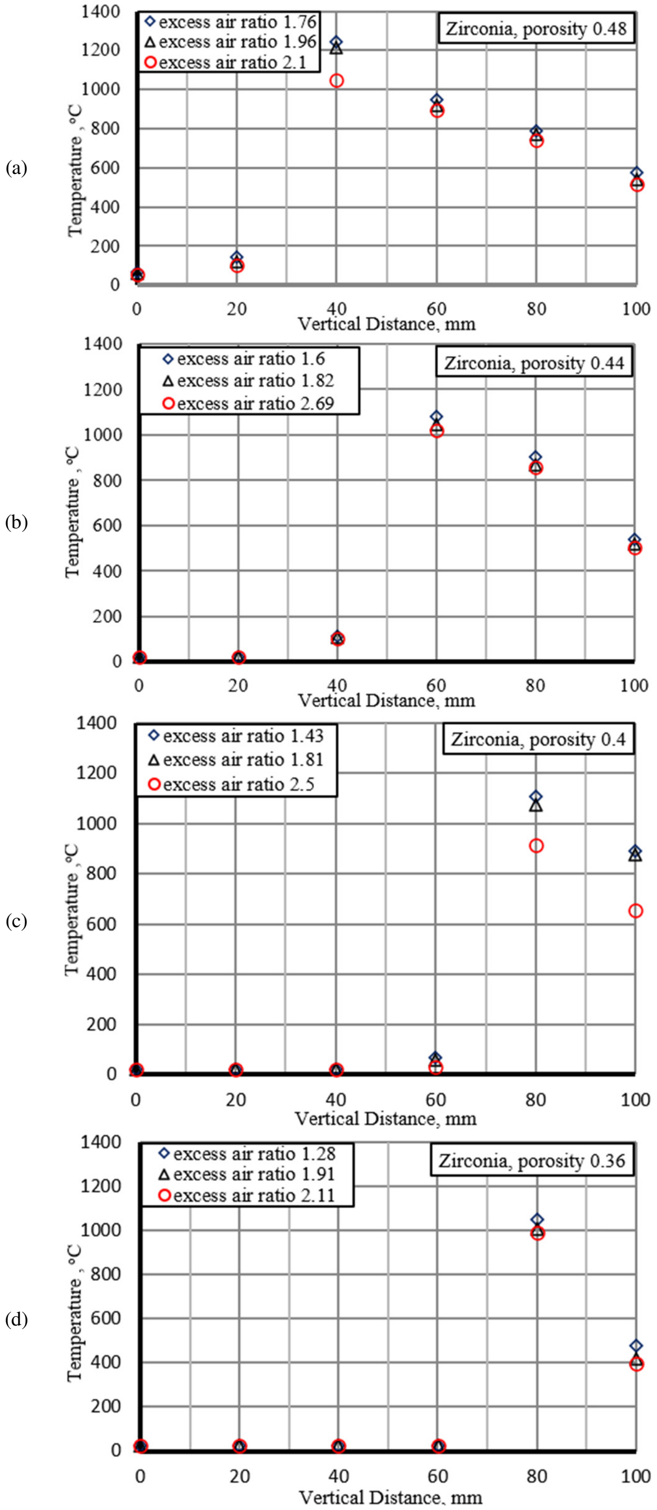

Fig. 5. Effect of excess air on flame temperature for Zirconia porous media with different porosities of (a) 0.48, (b) 0.44, (c) 0.40, and (d) 0.36 at an inlet air velocity of 0.3m/s.

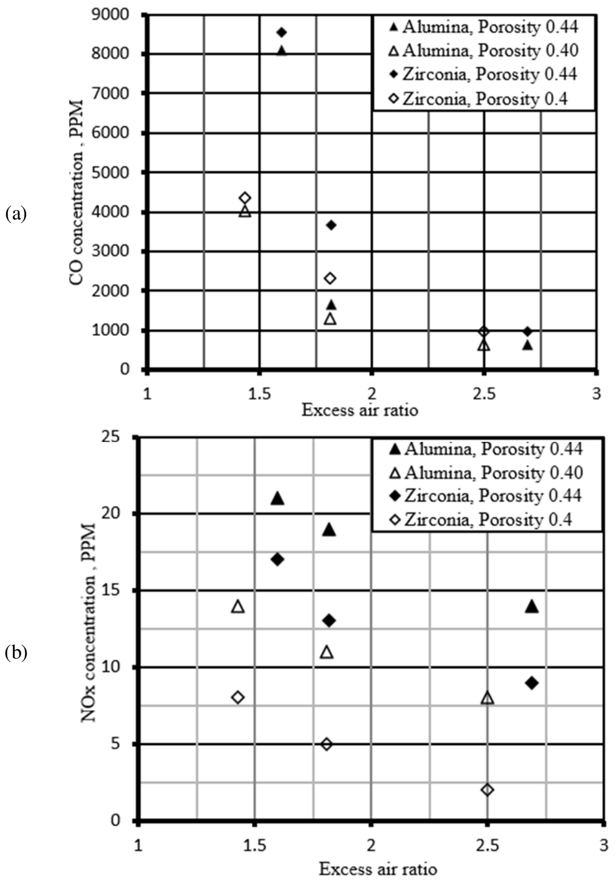

Fig. 6. Effect of excess air ratio on (a) CO and (b) NO_x concentrations for Alumina and Zirconia porous media at the same air inlet velocity of 0.3 m/s.

IV. CONCLUSION

This study presented an experimental work to examine the combustion of a premixed flame using natural gas in a packed bed of porous media. A burner consisting of a vertical tube fitted with porous media was utilized for the experimental tests. The results exhibited that the porosity of porous media has a significant effect on the position of reaction zones. As the porosity decreases, the reaction zone moves downstream of the packed bed.

The position of the reaction zone was at 40, 60, and 80 mm for porosities, 0.46, 0.44, and 0.40 and 0.36, respectively. For the same inlet air velocity, the excess air ratio did not affect the position of the reaction zone but influenced the temperature distribution inside the porous media so that the peak temperature inside the porous media decreased when increasing the excess air ratio. The peak temperatures for the Zirconia burner at 0.48 porosity were 1250, 1200, and 1050°C for excess air ratios of 1.76, 1.96, and 2.1, respectively. The porous medium material has an effect on the reaction zone volume and the temperature distribution inside the porous media, as Zirconia had a higher reaction zone volume than Alumina owing to its lower thermal conductivity. The concentration of NO_x reduced as the porosity increased. Zirconia porous medium displays a lower level of NO_x emission compared to Alumina. For an excess air ratio of 1.6, the maximum value of NO_x was 22.5 ppm for Alumina and 17.5 ppm for Zirconia.

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