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Impact of preheat zone properties on the flammability limits of crude biogas combustion in a two-layer porous radiant burner

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Abstract. The present work is aimed at comprehending the combustion phenomena of crude biogas in a Porous Radiant Burner (PRB), with varying properties of the porous inserts. In this regard, experimentation has been done on an in-house developed two layered PRB, incorporated with porous combustion zone (CZ) and preheat zone (PZ). Combustion in PRB is based on the concept of excess enthalpy where heat from the burnt products preheat the fresh fuel air mixture to give enhanced combustion. Hence, the porous inserts used in the PRB have a significant role to play in its performance characterization. This investigation is thus aimed at studying the effect of PZ porosity and thickness on the lean stable flame limits and the position of stable flame inside the PRB. The CZ was composed of SiC foam (porosity 90%), while straight hole Al_2O_3 ceramic with varying porosity and thickness were used as the PZ for the test cases. The investigation was done for the varying input powers of 5 to 10 kW. Results indicate that PZ porosity and thickness has a significant influence on flame stability. One particular case, where the PZ porosity was 7% and thickness of 15 mm offered the best lean stable combustion, within the equivalence ration of 0.75-0.97.

1. Introduction

The Porous Media Combustion (PMC) technology, has gained immense recognition because of its distinct advantages over Free Flame Combustion (FFC). The Conventional Burner (CB) systems are featured by a free flame, and occurs in a gaseous ambience where transfer of heat takes place chiefly by convection. Gases have poor thermal conductivity and low opacity which does not facilitate heat transfer from post flame to pre flame. Because of improper heat transport, the CBs are less productive and arises some undesirable features such as low flammability limits, low power density, weak power modulation, high level of pollutant emission etc. [1]. On the other hand, Porous Radiant Burners (PRBs), based on the PMC technology can provide better performance than CB, due to its capability for excess enthalpy combustion. This phenomenon utilizes the concept of using a solid porous matrix in the combustion zone for enhanced heat transfer from the burnt to the unburnt portion of the air-fuel mixture [2]. Due to the material properties of the matrix, it offers improved heat transfer by conduction, convection and radiation. The flames in PMC remains trapped within the porous matrix itself [3]. PMC technology is advantageous due to effective utilization of heat transfer, higher burning rate, increased power dynamic range, expansion of lean flammability limit, enhanced combustion with lower calorific value fuels and low emission of pollutants [4].

The performance of PRBs have been mostly analyzed in terms of its thermal efficiency, heat recirculation rate, stability limits and temperature profiles [5]. Bubnovich et al. [6] worked on the development of a PRB, and investigated its thermal performance by varying the porous material and its sizes. In another study, for the case of a variety of ceramic structures, the foam was reported to offer better stability over balls or honeycomb structures [7]. Bakry et al. [8] analyzed the condition of stable flame at elevated pressure and temperatures and found that the lean blow-out limit was almost independent of the pressure but highly affected by the preheating temperature of the mixture. Both experimental and numerical investigation on effect of varying porosity on temperature distribution and flame stability was done by Kanga et al. [9].

Two layer PRB has gained more popularity because of its better heat transport facility which in turn provides extended flame stability limits [10]. The conductive and radiative heat recirculation in PRB aids in enhanced combustion, where it is possible to the easily stabilized the flame at the interface of the two porous ceramics. The properties of the porous material influence the combustion performance of a burner to a huge extent. Ceramics are the mostly preferred material in two layer PRBs and alumina (Al_2O_3), zirconia (ZrO_2), and silicon carbide (SiC) based materials are the commonly used ones, because of their high thermal resistance, large surface area, and chemical stability [11]. In comparison to Al_2O_3, ZrO_2 and SiC are ceramics are high temperature resistant but offer low thermal shock resistance. Study on material selection and porosity of the porous media has been of great interest for the PMC research community. A PRB with PSZ-reticulated foam having porosity of 65 pores per inch (ppi) in the upstream region and 10, 30, or 45 ppi in the downstream region was investigated by Hsu et al. [12,13]. Another research group worked on the performance study of PRB using yttria-stabilized ZrO_2/Al_2O_3 and ZrO_2-toughened mullite foam [14]. Results from their study indicated that for better combustion performance, the upstream region should possess low thermal conductivity, low volumetric heat transfer coefficient, and high radiative extinction coefficient, whereas the downstream region should be of high thermal conductivity, high volumetric heat transfer coefficient, and a moderate radiative extinction coefficient. Study on SiC based PRB has also been extensively carried out [10,15-16]. Malico et al. [15] and Farzaneh et al. [16] used different materials to study a PRB. They used 3 and 5 mm Al_2O_3 spheres in the preheating and heat-exchanger zones, while 10 ppi SiC porous foam in the combustion zone. Mishra et al. [10] studied the heat transfer in a two-dimensional rectangular PRB, composed of a preheat zone made of Al_2O_3 and a combustion zone made of SiC. They established that pores with small diameters must be used to avoid flashback. Moreover, they also concluded that flame front should move upstream when the burner radiates to a high-temperature environment or when solid conductivity and convective heat transfer coefficient increases. The results from the previous studies highlight that SiC and ZrO_2 are usually favored for the combustion zone and Al_2O_3 for the preheat zone, in a two layer PRB.

The PRBs are a suitable tool for utilization of LCV fuels, as they offer enhanced combustion on account of their heat recirculation phenomenon. The survey of literature reveals that the process of flame propagation and stabilization in a PRBs is implicitly related to properties of the porous inserts, flame locations, etc. Another important consideration was found as fuel composition. Although study has been carried out in the field of Low Calorific Value fuels in PMC, yet only few research is available for biogas combustion (simulated biogas) [17-18], and there is lack of study for crude biogas combustion in PRB. For practical applications, simulated biogas is not an agreeable option as it is expensive. Also, in developing countries like India, where biogas as alternative source of energy is succeeding with smaller anaerobic digestion plants mainly in rural areas. Proper selection of porous inserts is vital to achieve learn burn condition and superior performance of a PRB. In view of this, rigorous research is required to comprehend the combustion characteristics of crude biogas during combustion in porous media based burners. Above mentioned previous works shows that porosity and thickness of the porous inserts strongly impacts stable burner operation in a tested input power (P_i) range. This piece of research is thus an effort to understand the crude biogas combustion characteristics with varying preheat layer thickness and porosity. This will help in the development of crude biogas operated practical PRBs for lean-burn applications.

2. Experimental methodology

In this section, the experimental procedure followed during performance assessment are discussed. Details of the experimental setup and PRBs are also included in this section.

2.1. Experimental setup

Figure 1 gives the setup used for the experimental tests. Mass flow rate measurements of air and crude biogas was done with a Coriolis mass flow meter. The arrangement of fuel-air distribution system along with the double layer Porous Radiant Burner (PRB), composed of a mixing chamber, Preheating Zone (PZ) and Combustion Zone (CZ) is shown in Fig 2.

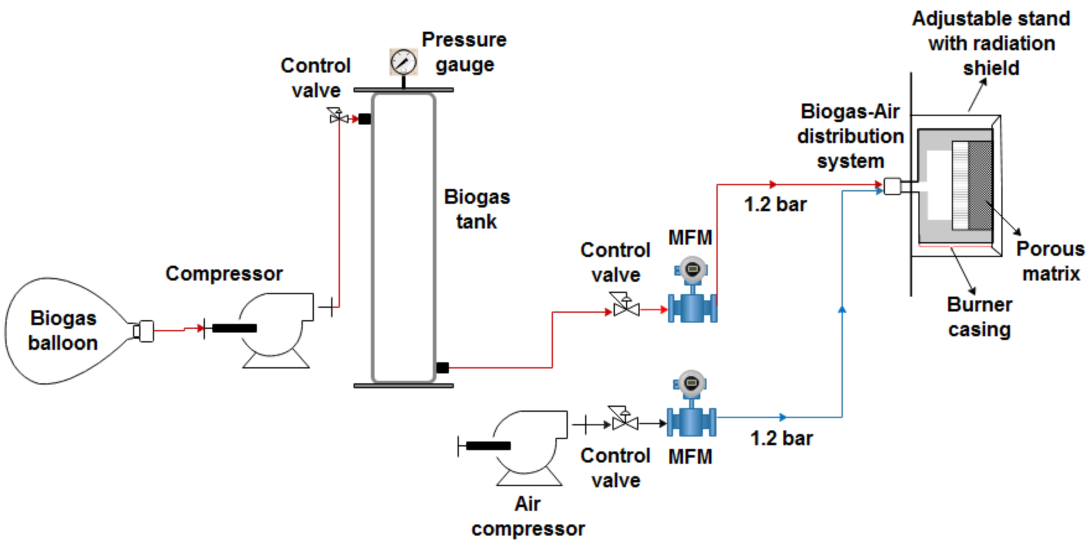

Figure 1: Schematic of the experimental setup

The CZ comprised of SiC porous foam and for PZ two different Al_2O_3 straight hole ceramic was used for experimentation. The details of the porous materials are given in Table 1. The crude biogas used in the study was derived from anaerobic digestion of cow dung. It was composed mainly of 43-56% CH_4 and 34-38% CO_2, as measured in a gas chromatograph.

Table 1. Details of porous inserts

Case	Preheat zone (PZ) Al_2O_3 straight hole ceramic	Combustion zone (CZ) SiC foam
A	Porosity: 32% Thickness: 20 mm Diameter: 120 mm	Porosity: 90% Thickness: 20 mm Diameter: 120 mm
B	Porosity: 32% Thickness: 15 mm Diameter: 120 mm	Porosity: 90% Thickness: 20 mm Diameter: 120 mm
C	Porosity: 7% Thickness: 15 mm Diameter: 120 mm	Porosity: 90% Thickness: 20 mm Diameter: 120 mm

Various instruments were used during the experimental investigation. Proper calibrated thermocouples (K type) were used to achieve maximum possible accurate results, with a maximum fluctuation of ± 1°C. The Coriolis mass flow meter indicating the mass flow rates of fuel and air had an accuracy of ± 0.35% of full scale.

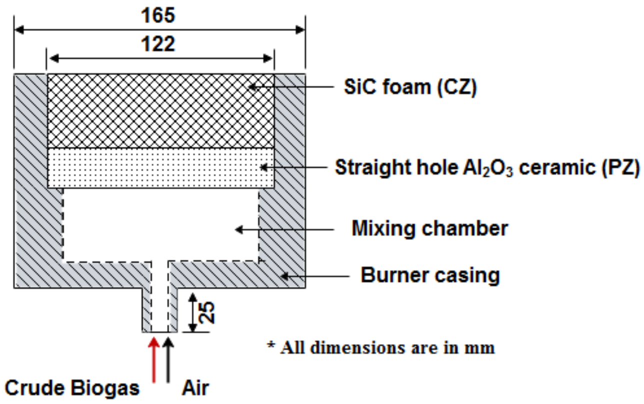

Figure 2. Schematic of the PRB

2.2. Flame stability limits

Determination of the stable combustion range is the primary factor for investigation while developing a new burner system. The stable limits of a burner can be categorized into three classes: blow-off, stable, and flashback. The condition of "blow off" occurs when the inlet velocity of incoming air fuel mixture is higher than the flame speed of the burnt mixture in porous media and in this case, the flame travels downstream and moves out of the burner surface. The situation opposite to this is "flashback," where flame travels upstream due to lower velocity of fuel-air mixture than the flame speed. The stable zone of combustion is usually designated by the range of equivalence ratio (ϕ) in which the burner was stable at a particular input power (P_i). The ratio of air-fuel ratio ($\frac{A}{F}$) at stoichiometric condition to actual A/F is the ϕ (Eq 1).

$$\phi = \frac{\left(\frac{A}{F}\right)_{stoichiometric}}{\left(\frac{A}{F}\right)_{actual}} \tag{1}$$

To find the stable combustion limits, initially, the burner was ignited at a high ϕ, in a particular P_i, and then the flow rate of air was steadily increased to obtained a specified ϕ. After the burner stabilized, the flow rate of air was altered to find the stable operating range. When the fluctuation of temperature remained within 10°C for 30 min, the flame was considered stable. The ϕ at which the flame front reached the base of the preheater in a two layer PRB was classified as the "lower stability limit," below which "flashback" occurred. On the other hand, the ϕ at which the flame floated on the surface of the PRB was defined as the upper stability limit, which marked the initiation of "blow off" (Fig. 3).

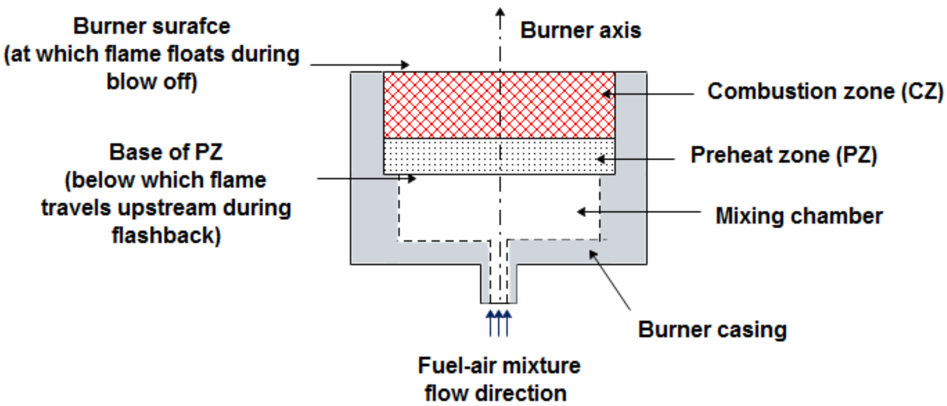

Figure 3. Positions of flashback and blow off in a two layer PRB

2.3. Axial temperature distribution

To comprehend the combustion characteristics of the burner, temperatures inside the burner in axial direction were recorded. Figure 4 shows the locations at which temperatures were measured. The positions 0, 1, 2, 3 and 4 indicate the temperature values in the base of the preheater, the PZ, the interface, the CZ and surface, respectively. The thermocouples at positions 0 to 4 were located at a radial distance of 20 mm from the periphery.

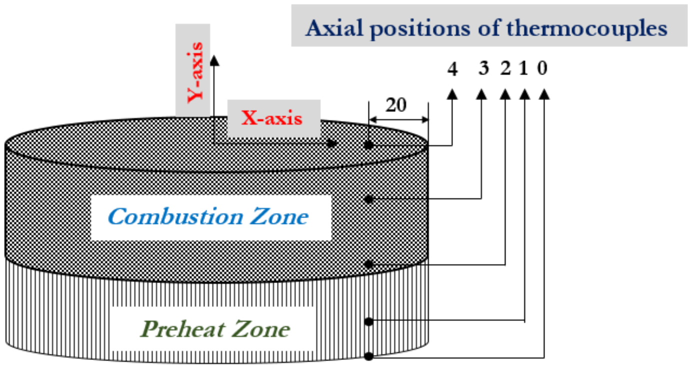

Figure 4. Positions of thermocouples in PRB for axial temperature measurement

3. Results and Discussion

The phenomenon of heat recirculation through a porous insert is a fundamental feature of porous burner operation. Selection of a porous insert with heat transfer properties that allow this recirculation to proceed effectively is, therefore, of primary importance. Thus, it is important to assess the significance of porous inserts properties viz., thickness and porosity. The impact of thickness reduction of PZ insert from 20 mm to 15 mm and then decrement of porosity from 32% to 7% on stability limits have been investigated. The experiments have been performed for the P_i range of 5 to 10 kW. Matrix stabilized combustion was obtained in the whole operating P_i range of 5-10 kW for the selected cases. Within P_i range, selected porous inserts can combust lean fuel-air mixture, but, resulted in different stable ϕ range.

3.1. Stability limits and temperature profiles for Case A

Table 2 shows the PRB's stable limit for Case A. In this table, the limits of ϕ between which flame establishes inside the porous matrix, are shown. Stable flames were obtained for ϕ range between 0.89-0.95 and 0.97-1.15 for P_i range of 5-7 kW and 8-10 kW, respectively. With selected porous inserts during lower P_i of 5 to 7 kW, PRB was found to provide leaner combustion, but the further increment in P_i shifts both lower and upper stability limits towards higher ϕ. Such behavior can be associated with higher heat loss at higher P_i. Higher heat loss is due to increased flame temperatures of the burner at higher P_i (Fig. 5).

Table 2. Stability limits in Case A.

Case A	Input power (P_i) range	5-7 kW	8-10 kW
	Stable ϕ range	0.89-0.95	0.97-1.15

Temperature mapping results for ϕ of 0.95 and 0.97 are shown in Figure. 5. For these cases of ϕ, the maximum temperature was attained in the region "2", which is the interface of the CZ and PZ (Fig. 4 T_2). The position of maximum temperature brings to the conclusion that the interface of CZ and PZ is the reaction region or RZ where the combustion is stabilized. Within the P_i range of 5-7 kW, the interface temperature (Fig. 4, T_2) ranges between 1132-1176°C for ϕ of 0.95. At ϕ of 0.97 and P_i

range 8-10 kW same is found as 1206-1240ºC. Similarly, the CZ temperature (Fig. 4, T_3) varies between 1018-1070ºC and 1086-1103ºC, respectively. With an increase in P_i, the measured temperature is always increasing. A similar variation of axial temperature with P_i and ϕ was also reported in earlier investigations [10]. Temperature on the base of PZ (Fig. 4, T_0) varied 86-95°C and 103-113°C for ϕ of 0.95 and 0.97, respectively (Fig. 5). These values are significantly lower than the ignition temperature of biogas (~650°C) and therefore, there is absolutely no probability of "flashback."

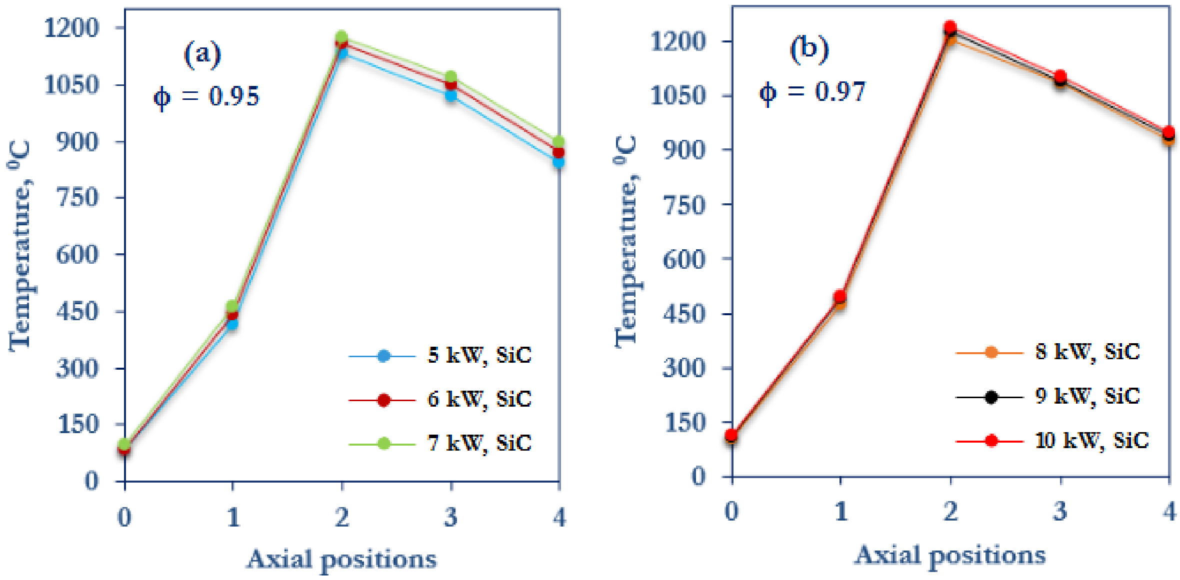

Figure 5. Axial temperature distribution of PRB in Case A for (a) ϕ = 0.95 and P_i = 5-7 kW and (b) ϕ = 0.97 and P_i = 8-10 kW.

3.2. Stability limits and temperature profiles for Case B

The preheating of the air-fuel mixture is highly desirable to improve the performance of the PRB. The upstream section (PZ) acts primarily as a flame arrestor and for the wider burner operation range as compared to Case A, it should possess a low volumetric heat transfer coefficient. Table 3 shows the the flame stability limit when the PZ thickness is decreased from 20 mm (Case A) to 15 mm (Case B). In lower P_i (5-7 kW), the lower stability limit shifts towards leaner mixture in Case B as compared to Case A (Table 2 & 3). However, decrement in PZ thickness has a meagre effect on stability range of higher P_i (8-10 kW).

Table 3. Stability limits in Case B.

Case B	Input power (P_i) range	5-7 kW	8-10 kW
	Stable ϕ range	0.84-0.97	0.97-1.2

From the axial temperature distribution of Case A (Fig. 5) and Case B (Fig. 6), it can be seen that the reduction of PZ thickness improves the burner combustion characteristics. In Case B, the flame stabilization also occurred in the interface of the CZ and PZ (Fig. 6). At ϕ of 0.95, within the P_i of 5-7 kW, the interface temperature (Fig. 4, T_2) ranged between 1182-1225ºC in Case B (Fig. 6a), whereas the same was 1132-1176ºC in Case A (Fig. 5a). Similarly, the surface temperature (Fig. 4, T_4) varied between 867-916ºC (Case B, Fig. 6a) and 843-899ºC (Case A, Fig. 5a), respectively. Thus, higher surface temperatures were achieved with the combination of PM used in Case B. Similar temperature distribution was also observed for ϕ of 0.97.

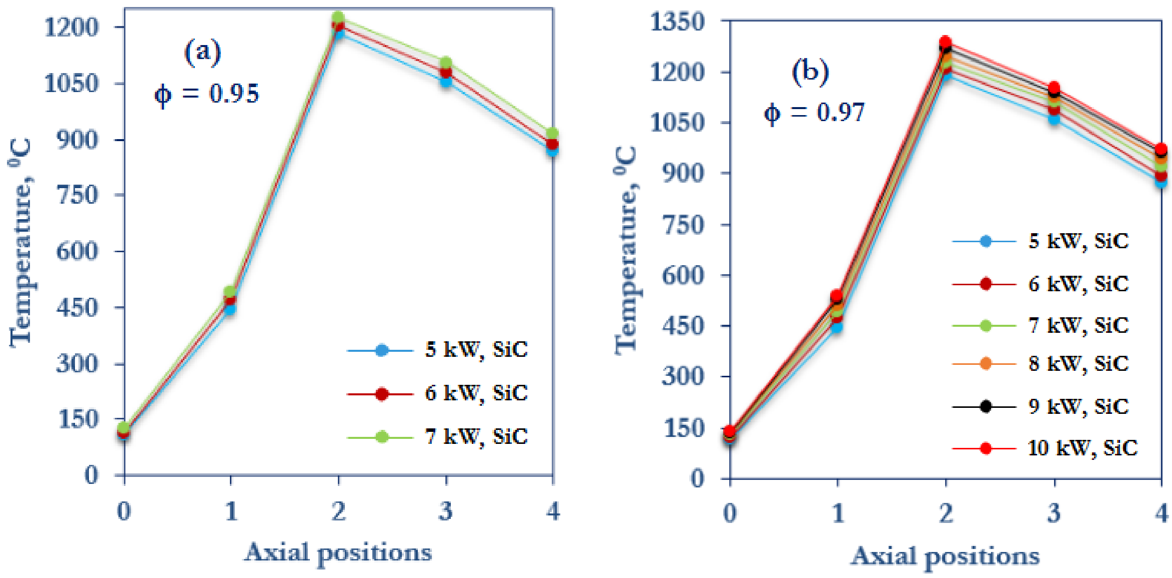

Figure 6. Axial temperature distribution of PRB in Case B for (a) ϕ = 0.95 at P_i = 5-7 kW and (c) ϕ = 0.97 at P_i = 5-10 kW.

3.3. Stability limits and temperature profiles for Case C

The results in Table 4 indicate that variation in upstream (PZ) porosity has a significant influence on the heat transfer characteristics of the burner. It is to be noted that Case C has a stronger influence on lean stability limit than Case B. Decrease in porosity promotes preheating and produces higher flame speeds. Lower porosity enhances diffusion within the material, transports heat toward the inlet and increases heat recirculation. Leaner flame stability limits at Case C are an effect of higher convective heat recirculation between the gas and solid phases through the PZ. As compared to Case B, relatively high heat recirculation occurred in Case C, causing higher stable inlet velocities. The stability analysis establishes that the combination of PZ and CZ used in Case C offers an extended range of lean flammability limit for the whole P_i range of 5-10 kW.

Table 4. Stability limits in Case C.

Case A	Input power (P_i) range	5-10 kW
	Stable ϕ range	0.75-0.97

Figure 7 shows the axial temperature profiles highlighting the impact of the porosity of the PZ. As more solid material per volume conducts more heat, as the porosity of PZ is lower for Case C (Fig. 7) than that of Case B, higher temperature for all tested combination of P_i and ϕ was observed in Case C (Fig. 7).

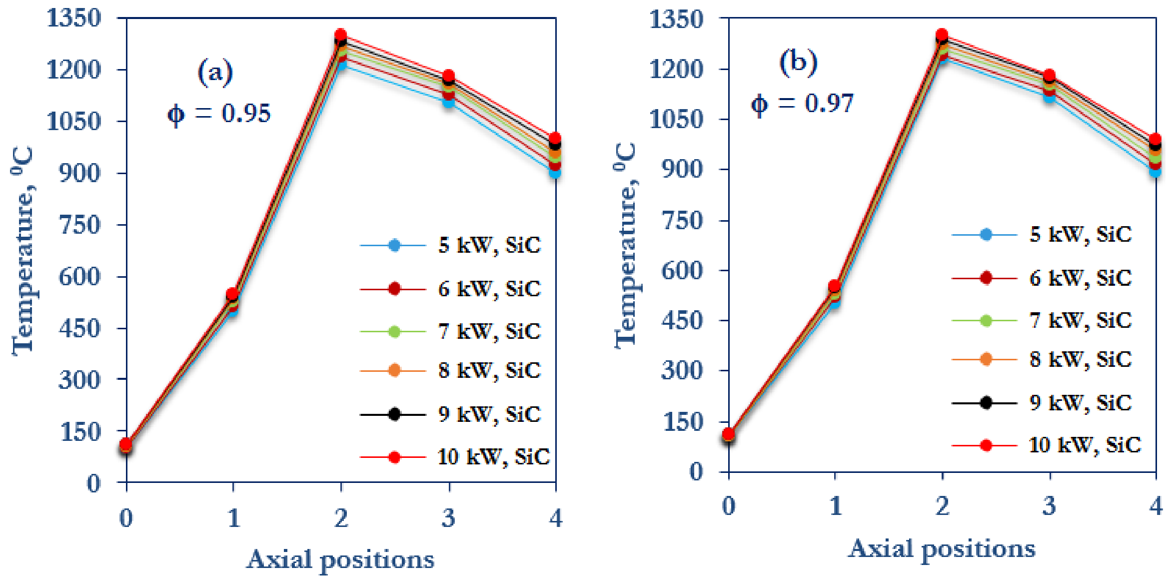

Figure 7. Axial temperature distribution of PRB in Case C (a) ϕ = 0.95 and (b) ϕ = 0.97.

4. Conclusion

In the present study, the combustion of a mixture of crude biogas and air was investigated experimentally in a two-layer porous radiant burner. Al_2O_3 straight hole ceramic and SiC foam structures were used as a porous insert in the preheat zone and combustion zone, respectively. The effects of thickness and porosity of the preheat zone on the stable combustion were evaluated. The axial temperature profiles were measured to characterize the stable range of operating equivalence ratio. For the entire range of the studied input power (5-10 kW), a favourable operating equivalence ratio range of 0.75-0.97 was found with Case C. From the investigation on the preheat zone thickness and porosity, impact of porosity on the burner stability was found to be more dominating. For all the studied cases, the peak temperature of the burner occurred in the interface of the preheat zone and combustion zone, and it increased with an increase in input power. In all the cases, the temperature of the base of the preheater was found to vary between 86-113 ºC, which is significantly lower than the ignition temperature of the biogas (~650ºC). This eliminates the possibility of flashback. However, further improvement is anticipated with modifications in the porous inserts.

Acknowledgments

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