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Self-aspirating Annular Porous Medium Burner (SAPMB) with Adjustable Flame Stabilizer

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Abstract

The aim of this research is to develop a self-aspirating annular porous medium burner (SAPMB) with an adjustable flame stabilizer (FS). The SAPMB is formed by an annular packed bed of 15 mm in diameter alumina spheres. FS is a double perforated plate installed to SAPMB in order to control stabilized location of combustion in the annular packed bed by varying an opening area (*OA*) allowing for incoming of fuel/air mixture. This design is proposed to be used in Small and Medium-sized Enterprises (SMEs), and it has been developed from the KB-10 conventional burner (CB), which has relatively low thermal efficiency of about 35%. A concept of heat recirculation combustion and radiation heat transfer enhancement by using porous medium technology is introduced. Effect of *OA* and firing rate (*FR*) on temperature and flame location in the SAPMB are investigated. It was found that varying *OA* affects stabilized location and flame temperature. Increasing *OA* flame moves upstream and the temperature increases, conversely, decreasing *OA* flame moves downstream and the temperature decreases. Primary equivalence ratio (Φ) is a dominant parameter which is estimated by using empirical equations. An increase in *OA* results in an increase in primary air entrainment, thus Φ decreases. Φ decreases from 11 to 3.7 when increasing *OA* from 5% to 100%. *FR* decreases Φ increase at the given *OA*. It is shown that flame blow off can be avoided by increasing *OA*, and vice versa. Thus, a broad range of stable flame can be achieved by FS installation to SAPMB.

Keywords: Self-aspirating burner; annular porous medium burner; porous medium; flame location; flame stabilizer.

1. Introduction

Nowadays, a concept of heat recirculation combustion by using porous medium is widely applied to improve performances, such as to increase thermal efficiency and minimize pollutants emission of the combustion devices, e.g., furnace, burner, and heat exchanger. Combustion in a porous medium is characterized by increased flame speeds, extended flammability limits and stability across a wide range of conditions. Both combustion and radiation intensities are significantly increased [1, 2]. A self-preheating recirculating recovers from exhaust gas to fresh reactant resulting in a higher combustion temperature than an adiabatic one [3].By the reasons, porous medium burner has been developed to combust low calorific value fuels, e.g. lean premixed combustion of H_2/CO mixtures has been investigated [4]. Moreover, porous media reformer has also been developed for reformation of methane [5, 6]. The results showed that a large turndown ratio of the reformer and burning rate ratios greater than unity [6].

Recently, combustion in porous medium has been applied to cooking gas-burners, e.g. [7, 8], which were proposed to be used in Small and Medium-sized Enterprises (SMEs), and it has been developed from the KB-10 conventional burner (CB), which has relatively low thermal efficiency of about 35%. Yoksenakul W. and Jugjai S. [7] designed and constructed a self-aspirating porous medium burner for gaseous fuel. A conventional burner of KB-10 type was used as a reference where additional installation of an air-compressor is not required. The operating principle is the natural entrainment of a high velocity jet of fuel issued in the ambient still air. A single cylindrical packed bed of Al_2O_3 spheres was used as a porous medium for submerged flame combustion. The stability of combustion could be achieved and stabilized inside the porous medium. However, a relatively high flame length extended into the post flame region, outside the burner, due to the lack of an efficient secondary air entrainment. Consequently, in order to improve secondary air entrainment, A. Petchsangkoon and S. Jugjai [8], modified the single cylindrical burner into the central annular packed bed burner. The experimental results indicated that a shorter post flame length at the burner exit as well as a stabilized flame inside the porous medium with relatively low emission of CO and NO_X can be achieved.

Even though porous medium burner has many advantages over the conventional gas burner, however, to further improve burner performance in terms of interchangeability of fuel gases, an adjustable flame stabilizer (FS) was introduced in this work. FS is used as an adjustable flow area by varying opening area (*OA*) at the entrance of porous packed bed, which permits flame stabilization (i.e. once the flow velocity and burning velocity are well matched) inside the annular packed bed. It is integrated with a Self-aspirating annular porous medium burner (SAPMB) to get the flame easily stabilized within the porous medium (PM) irrespective of the type of gaseous fuel (burning velocity). It is imperative that flame has to be stabilized in the PM in order to get the maximum radiation efficiency for practical efficiency. It is due to a fast-rise in energy consumption especially the derived from fossil fuel which cause high emission of the greenhouse gases, development of flexible combustion devices or appliances is desirable to burn alternative fuels which have difference in flame ability limits. Flame stability within an annular porous medium has been focused. The effects of *OA* and gas input pressure on the flame stabilization and temperature profiles are investigated.

2. Methodology

2.1 Experimental apparatus

An aim of this research is to develop a self-aspirating annular porous medium burner (SAPMB) with an adjustable flame stabilizer (FS) that can replace a low performance, conventional LPG cooking burner.

2.1.1 Self-aspirating annular porous medium burner (SAPMB)

Fig. 1 shows a self-aspirating porous medium burner with an annular shape, which was first proposed by Petchsangkoon and Jugjai [8] in 2014, in order to enhance combustion and thermal performances of the burner by improving secondary air entrainment at the center of the burner. It was formed by an annular packed bed of alumina spheres with diameter of 15 mm and the combustion chamber was made by cylindrical steel of 3 mm in thickness wall and surrounded by high temperature cement. Moreover, to improve flame stabilization and to prevent flame flashback, the annular, conical packed bed shape was arranged to achieve the purpose. The mixing tube is the same as that of the one as using for the conventional burner KB-10 type, where a primary air adjustor (PA) is installed at the entrance. The fuel injector is a 1.5-mm-diameter nozzle.

Even though this self-aspirating porous medium burner can operate with a stable flame and with a preferable pollutants emission, however, getting the flame stabilized within the porous medium burner for maximizing radiation output is a difficult task because the flow velocity of the fuel-air mixture is not well matched with the corresponding burning velocity of the mixture. Unlike the forced draft porous medium burner, the self-aspirating porous medium burner operates based on a natural draft or entrainment of air which is uncontrollable, and thus flame stabilization within it is much more difficult than that occurs in a forced draft porous medium burner. Moreover, changing in type of the fuel and type of the porous medium burner means changing in burning velocity and efficiency of heat recirculation from product to reactants, making flame stabilization within the self-aspirating porous medium burner even more difficult. Therefore, making the flame easily stabilized within the porous medium burner is an important task.

2.1.2 Adjustable flame stabilizer (FS)

Fig. 2 shows the proposed adjustable flame stabilizer to be used with the self-aspirating porous medium burner. FS is designed to get the flame easily stabilized within the packed bed of a self-aspirating porous medium burner, wherein the flow velocity and the burning velocity can be easily matched. FS comprises a pair of circular plates with array of opening slots on their surfaces. The upper plate is fixed and used to support the packed bed of the porous medium burner, whereas the lower one is a moving plate used for adjusting an overlapping area of the opening slots, thus allowing for the inlet velocity of fuel/air mixture to be varied. The maximum flow area of FS is 1,357 mm^2 at 100% *OA*. FS is installed at an interface between the entrance of the packed bed and the exit of mixing chamber. Irrespective of fuel type and porous medium burner used, flame can be easily stabilized within the self-aspirating porous medium burner with the help from FS.

2.2 Experimental methods

Fig. 3 shows schematic diagram of the experimental set up to study the stabilization of flame in the packed bed. Effect of *OA* and firing rate (*FR*) on flame locations are investigated by measuring temperature distribution along the packed bed length. *FR* was varied at 25.3 kW, 40.6 kW, and 55.2 kW for investigation of the effect of *OA* on flame movements at low, medium, and high firing rates, respectively. While, PA is fully open for all cases, therefore, variation of primary entrainment is depended on *OA* and *FR* only for this study. LPG was used as fuel in the experiment. It contains 40% (by volume) of propane (C_3H_8) and 60% (by volume) of butane (C_4H_{10}) with a low heating value of about 108 MJ/m^3.

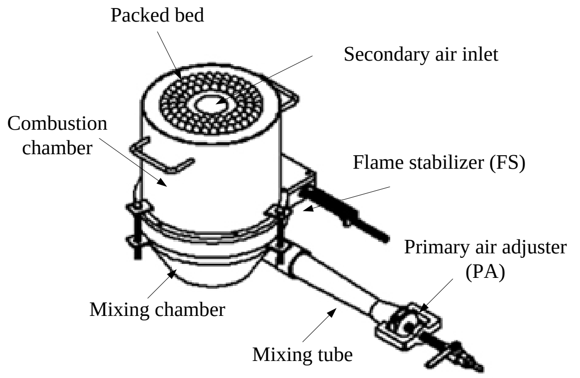


Fig.1. SAPMB integrated with FS.

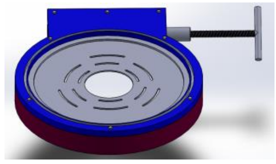
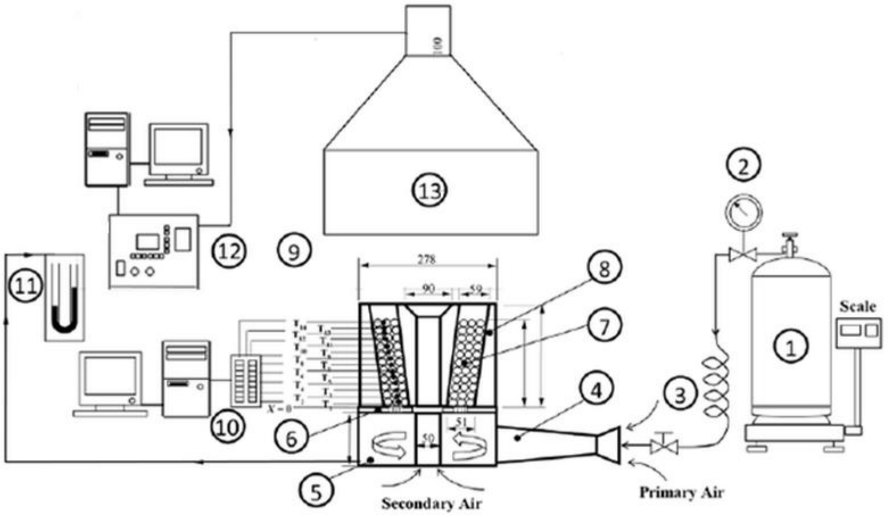


Fig. 2. Flame stabilizer (FS).



1. Fuel storage tank
2. Pressure regulator
3. Ball valve & fuel nozzle
4. Mixing tube
5. Mixing chamber
6. FS
7. Packed bed
8. Cement wall
9. Thermocouples
10. Data logger
11.Manometer
12. Exhaust gas analyzer
13.Hood

Fig. 3. Schematic diagram of the experimental set up.

LPG flow rates were controlled by a pressure regulator with calibrated pressure gauge, and volume flow rates were measured by flow meter the packed bed burner temperatures were measured by setting 14 locations of different thermocouples depending on location as denoted by T_1 - T_{14}. The tip of these thermocouples are located in the middle of the packed bed between inner combustion chamber wall and secondary air inlet wall. To measure the temperatures at T_1-T_4, N-type thermocouples with a measuring range of 0 °C -1200 °C were used. While, for measuring the temperatures where the combustion taking place at T_5-T_{14}, B-type bare thermocouple with a measuring range of 300 °C-1600°C was used. The signals received from thermocouples are digitized by a general-purpose data logger(Delta model DT-600), and then transmitted to a personal computer. The pressure drop across the packed bed (ΔP) is measured by water manometerat the side wall of mixing chamber. A hood for collecting a flue gas was designed and constructed. Emission of the combustion products was measured at the exit of the hood by using a portable exhaust analyzer (MesstechnikEheim model Visit01L), however, it will not be reported in this paper.

3. Determination of primary air equivalence ratio

Primary equivalence ratio (Φ) was determined by using empirical equations adapted from Addamane et al., 2016 [6]. For self-aspirating annular porous burner with integrated flame stabilizer and using LPG (40:60 mixture of Propane and Butane) as fuel, Φ can be estimated by

$$X\Phi^2-(28.08Y)\Phi-28.08^2Z=0 \qquad (1)$$

where, X , Y ,and $Z$are

$$X=\left\{\rho_g\left[\frac{1}{A_tA_i}-\frac{1}{2A_p^2}\left(\frac{T_h}{T_l}\right)^2-\frac{\left(1+K_{eff}\right)}{2A_t^2}-\frac{K_l}{2A_{fs}^2}-N\right]-\frac{M}{Q_g}\right\} \qquad (2)$$

$$Y=\left\{\left(\rho_a+\rho_g\right)\left[\frac{\left(1+K_{eff}\right)}{2A_t^2}+\frac{1}{2A_p^2}\left(\frac{T_h}{T_l}\right)^2+\frac{K_l}{2A_{fs}^2}+N\right]+\frac{M}{Q_g}\right\} \qquad (3)$$

$$Z=\left\{\rho_a\left[\frac{1}{2A_p^2}\left(\frac{T_h}{T_l}\right)^2+\frac{\left(1+K_{eff}\right)}{2A_t^2}+\frac{K_l}{2A_{fs}^2}+N\right]\right\} \qquad (4)$$

and M and N are determined by

$$M = \frac{150\mu LC}{d_p^2}\left[\frac{(1-\bar{\epsilon})^2}{\bar{\epsilon}^3}\right]\left(\frac{T_m}{T_l}\right)^2\frac{1}{A_p} \quad (5)$$

$$N = \frac{1.75LC^2}{d_p A_p^2}\left[\frac{(1-\bar{\epsilon})}{\bar{\epsilon}^3}\right]\left(\frac{T_m}{T_l}\right)^2 \quad (6)$$

A is the area, subscripts i, t, p, and fs refer to at the gas injector, throat, packed bed, and the flame stabilizer, respectively. T_l is inlet temperature, T_h is the exit temperature, and T_m is the mean temperature of packed bed. ρ_a and ρ_g are densities of air and gas, respectively. K_l and K_{eff} are the loss coefficient of the FS and throat area. Q_g is volume flow rate of gas. While $\bar{\epsilon}$ is average porosity, C is correction factor (see. [9, 10] for evaluation), and L is packed bed length.

4. Results and discussion

4.1 Primary air equivalence ratio (*Φ*)

Fig. 4 shows estimated primary air equivalence ratios (*Φ*) of the SAPMB with FS as a function of *OA* at firing rate (*FR*) of 25.3 kW, 40.6 kW, and 55.3 kW, respectively, for low *FR*, medium *FR* and high *FR*. The SAPMB with FS operates with a relatively fuel-rich mixture with *Φ* of larger than 1, which is a nature of a self-aspirating burner [11].

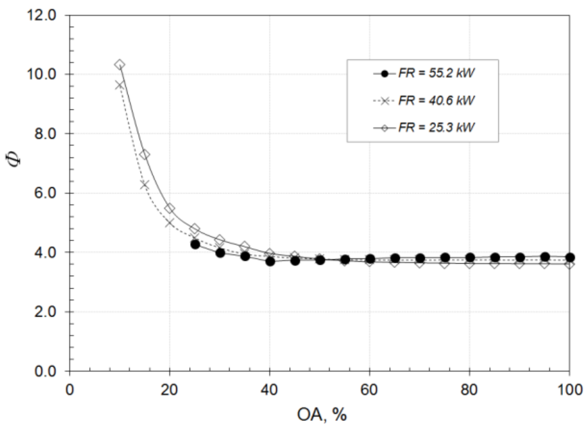


Fig. 4. *Φ* as a function of *OA* and *FR*.

As *OA* increases from 10% to 100% at every *FR*, *Φ* sharply decreases in an initial stage from about 10 to 3.7 until a specific value of *OA* = 50% is reached above which *Φ* becomes constant irrespective of *OA*. It is important to note that different relationships between *Φ*, *OA* and *FR* were observed depending on the range of *OA* being considered.

At *OA* ≤ 50%, *Φ* is strongly controlled by *OA* but with a minor effect by *FR*. *Φ* is inversely proportional to *OA* and *FR*. This is true for the present self-aspirating porous medium burner with a flame stabilizer (FS) since the pressure drop across the packed bed of the porous medium burner and thus the primary air entrainment is strongly controlled by the *OA* for a specific mixing tube used and with a fully opened primary air adjuster. Moreover, at a given *OA*, a trend of relatively low *Φ* was yielded at a relatively high *FR* because of a high momentum rate of the high speed gaseous fuel being injected into the mixing tube for entraining a high amount of the surrounding air.

As *OA* becomes large enough with *OA* > 50%, however, *Φ* is almost constant irrespective of *OA* at a given *FR*. This may be attributed to a pore size of the porous medium burner becomes a major parameter that controls the pressure drop and thus the primary air entrainment. Thus, at *OA* > 50%, *OA* is no longer a controlling parameter for *Φ* and thus for the corresponding burning velocity of the fuel-air mixture. In contrast to *OA* ≤ 50%, *Φ* at *OA* > 50% shows a slight increasing trend as *FR* increases. This may be attributed to the fact that a maximum, possible primary air entrainment for a specific mixing tube used and with a fully opened primary air adjuster has already been reached. In another word, choking of the mixing tube is occurred. Beyond this point, the more the gaseous fuel being supplied into the mixing tube by a fuel injector, the fuel-richer mixture becomes. Despite a higher momentum rate of fuel gas being introduced into the mixing tube, the amount of the entrained primary air form surrounding is almost constant because it is limited by the dimensions of the mixing tube and the fuel injector.

At *OA* > 50%, however, *OA* is expected to play an important role in controlling a local inlet velocity of the fuel-air mixture that is entering the porous medium burner. This provides an opportunity for flame stabilization within the self-aspirating porous medium burner wherein the local flow velocity within the porous medium burner is matched with the corresponding burning velocity of the fuel-air mixture. Irrespective of the type of the fuel-air mixture and the corresponding burning velocity, flame stabilization within the packed bed of the self-aspirating porous medium burner can be achieved by varying *OA* of the proposed flame stabilizer (FS).

4.2 Effect of opening area ratio (*OA*)

Figs. 5, Figs. 6, and Figs. 7, respectively, show the corresponding effect of *OA* on measured temperature profiles inside the SAPMB at high *FR*, medium *FR*, and low *FR* for investigation of flames stabilization. It was found that varying *OA* strongly affects temperature profiles and location of flame inside the packed bed of the porous medium burner.

At high *FR* of 55.2 kW (Fig. 5), decreasing *OA* from 100% to 30% clearly shows location of flame (defined as the location of the maximum temperature) moving downstream with reduction in its temperature.

At *OA* > 50%, such as *OA* reduced from 100% to 50%, the maximum temperature (T_{max}) inside the packed bed slightly decreases, while location of flame is still located at the *X* = 11.25 cm (T_9). This implies that burning velocity and the local flow velocity of the mixture are well matched at *OA* > 50%, thus, the flame is well stabilized.

However, at *OA* ≤ 50%, such as *OA* = 30% flame starts moving downstream with reduction in its temperature. T_{max} location moves from *X*=11.25 cm (T_9) to *X* =15.0 cm (T_{11}) as *OA* is changed from 100% to 30% and T_{max} decreases from 1,470°C to 1,260°C. The decrease in T_{max} with *OA* is due to an increase in the primary equivalence ratio Φ as shown in Fig. 4. In addition, it is clear that at this high *FR* the flame cannot stabilize within the packed bed if *OA* reduce to 30% because of high primary equivalence ratio Φ with low burning velocity. The flame is ready to blow off, as shown in the graph at 30%OA_{t1}, 30%OA_{t2}, and 30%OA_{t3}, flame temperatures also decrease with time (the subscript t1, t2, and t3 refer to the elapsed time of 5, 10, and 15 minutes, respectively after tuning *FS* to 30%*OA*).

Fig. 6 shows effect of *OA* on the measured temperature profiles inside the SAPMB at medium *FR* = 40.63 kW. A similar trend as that of high *FR* = 55.20 kW (Fig. 5) is found for the medium *FR* = 40.63 kW but with a further extension in flame stabilization as low as *OA* =10% before the flame blow-off occurs at *OA* = 5%.

Fig. 7 shows results at relatively low *FR* = 25.3 kW. The flame can be stabilized inside the packed bed even at *OA* as low as 5%. A decrease in Φ together with an increase in inlet flow velocity is not strong enough to blow out the flame. Thus, the flame can stabilize inside the packed bed.

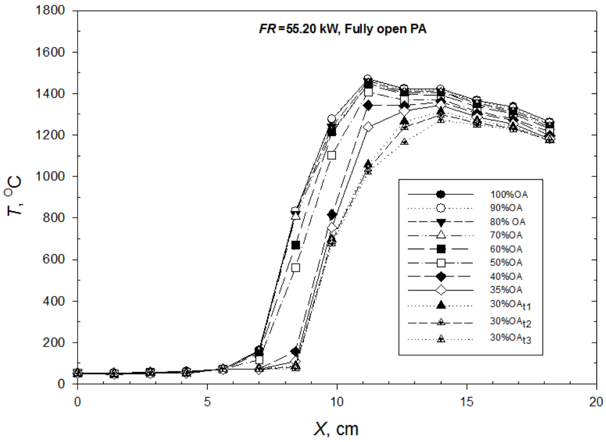


Fig.5. Effect of OA on temperature profiles at high *FR* = 55.2 kW.

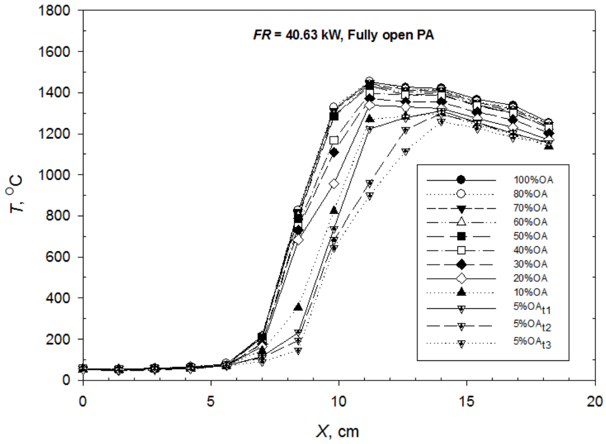


Fig. 6. Effect of *OA* on temperature profiles at medium *FR* = 40.6 kW.

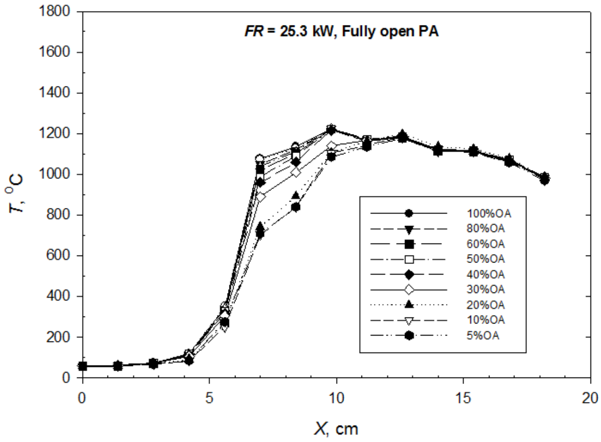


Fig. 7. Effect of *OA* on temperature profiles at low *FR* = 25.3 kW.

However, as comparing to the higher firing rate, flame location move to the upstream side, i.e. the maximum temperature is located at *X*=10 cm (T_8), while those of *FR* = 55.2 kW and 40.5 KW are located at *X* =11.25 cm for constant 100%*OA*. This means that flame is prone to flash back because of a reduction in *FR*.

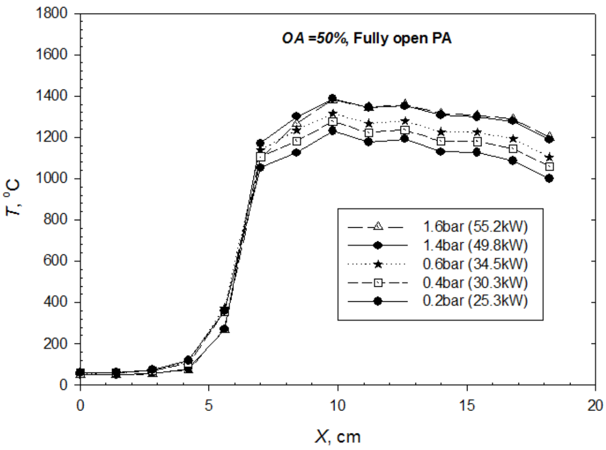


Fig.8 Effect of LPG inlet pressure on temperature profiles in the packed bed.

FS can successfully control the flame location to be stabilized inside the packed bed of the porous medium burner. By varying an opening area at the entrance of the packed bed to find the *OA* at which the burning velocity and flow velocity are well matched, thus flame stabilization can be achieved irrespective of the fuel type.

In addition, flame blow off can be avoided by increasing *OA* and vice versa decreasing *OA* to avoid flash back. Thus, a broad range of stable flame can be achieved with an implementation of the adjustable flame stabilizer. It is very useful when the calorific value of fuel gas was varied that affects burning velocity and stabilization of flame.

4.3Effect of gas inlet pressure

Fig. 8 shows effect of inlet pressure of LPG on measured temperature profiles along the packed bed at a fixed *OA* = 50%. It was found that flame location was not changed with inlet pressure of gas as high as 1.6 bar (or 55.2 kW). However, decreasing gas inlet pressure decreases temperature because heat input (firing rate) into the burner decreases, while the equivalence ratio is almost constant or not significant change as shown in Fig. 4, i.e.OA higher than 50%. Φ is nearly constant for all considered *FR*, therefore gas inlet pressure has low impact on flame movement. With *OA* = 50% is sufficient to stabilize the flame within the porous medium burner for the practical inlet pressure range of .2-1.6 bar (25.3-55.2 kW).

5. Conclusion

The objective of this research is to improve flexibility of a self-aspirating annular porous medium burner (SAPMB) by installation an adjustable flame stabilizer (FS) into the burner. It is found that FS is powerful to get the flame easily stabilized within the porous medium (PM) irrespective of the type of gaseous fuel (burning velocity).

Therefore, it can burn alternative fuels and get the flame stabilized inside the porous packed bed by tuning FS for proper opening area where flow velocity and burning velocity are well-matched.

It is also shown from the experimental results that *OA* has strong impact on Φ if *OA* is less than 50%, otherwise variation of *OA* does not modify Φ but has a strong impact on inlet velocity of the mixture. Φ is nearly constant for *OA* higher than 50%. Moreover, variation of *OA* affects flame temperature and stabilized location in the packed bed. Increasing *OA* increases temperature and flame moves upstream. Conversely, decreasing *OA* temperature decreases and flame moves downstream, in which primary equivalence ratio is a dominant parameter. However, at constant *OA* of 50%, variation of gas inlet pressure does not affect the location of maximum flame temperature, while the temperature increases with gas inlet pressure.

In addition, it can be inferred from the study that flame blow off can be avoided by increasing *OA* and vice versa, decreasing *OA* to avoid flash back. Thus, a broad range of stable flame can be achieved irrespective of the gaseous fuel type by FS installation to SAPMB.

6. Acknowledgement

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