A self-aspirating porous burner (SPB) with matrix-stabilized flame for Small and Medium Scale Enterprises (SMEs)

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Abstract

In the present work, a porous medium technology is used to improve a relatively low thermal efficiency of a self-aspirating conventional burner (CB) with free flame, which is widely used for small and medium scale enterprises (SMEs) in Thailand. A self-aspirating porous burner (SPB) with matrix-stabilized flame is proposed to replace the CB in the future. The SPB is designed and tested to understand its combustion phenomena and emission characteristics. A design criteria of the SPB is done by conserving some important characteristics of the existing CB, i.e. using the same mixing tube with the same pressure drop across the mixing tube and using the same pressure drop across a proposed porous burner to be equal to that of the multi-ports ring burner of the CB. The proposed porous burner is formed by a packed bed of randomly arranged alumina spheres. The Peclet number (*Pe*) combination with Ergun's equation are used to evaluated the pressure drop (ΔP) across the porous burner at different alumina sphere diameters which forms the packed bed of the porous burner. The designed and tested SPB yields favorable experimental results. With geometry and dimensions obtained from the calculation, the SPB can offer a matrix-stabilized flame with an intense thermal radiation emitted downstream at relatively high turndown ratio of 2.65 with the firing rate ranging from 23-61 kW. Emissions of CO and NO_x, respectively, are found at relatively low value of not more than 95 ppm and 85 ppm (corrected at 0% O_2) within the range of the firing rate studied.

***Keywords**:* Self-aspirating burner, Porous burner, Premixed flame, SMEs.

1. Introduction

For heating purposes in small and medium scale enterprises (SMEs) in Thailand, self-aspirating conventional burners (CB) are widely used owing to their simple construction, easy handling, high heating rate with directly impingement flame [1] and low cost. Although, the CB has more advantages but it has a relatively low thermal efficiency of about less than 30% [2]. Thus, it is not compatible with the energy crisis in the world today, which is not only a high price but also a reducing of fuel quantity. To remedy this drawback, a porous medium burner (PMB) technology is selected to replace than the CB. The advantage of PMB over the CB is that the PMB can allow for a self-preheating effect, resulting in a relatively high burning velocity, a wide flammability with relatively low level of pollutants [3-5]. The multimodes of heat transfer (especially radiation) with combustion within the PMB, that causes a higher efficiency than CB [6-7].

According to some advantage of the self-aspirating burner, it is not uses a force flow from air compressor or blower because a combustion air is naturally entrained by momentum transfer between the fuel jet and an ambient air [8-9]. The combustion with stabilized flame within packed bed has a higher radiation output than the surface combustion [10].

Following the several advantages of the PMB, this research aims to enhance the thermal efficiency of CB with porous medium technology. A new concept of design for a self-aspirating porous burner (SPB) is based on the basic characteristics of CB such as pressure drop across mixing chamber, using the same mixing tube to keep a primary aeration and the same range of firing rate. Ergun's equation [11] with Peclet number (*Pe*) [12] are employed to estimated the pressure drop in SPB and the packed bed geometries. This work is carried out for preliminary test of SPB to obtain fundamental data for further investigation.

2. Methodology

2.1 The SPB design procedure

An important in terms of the SPB design is to work as the CB, especially the pressure drop across the burner because it has highly affected to the primary air entrainment. So an empirical Ergun equation, as shown by Eq. (1), is used to calculate the pressure drop ΔP across the SPB. Here, ΔP is a given value from the experiment and is a function of the firing rate *CL*. Hence, various configurations of the SPB having given pressure drop ΔP can be formed depending on combination of the pertaining parameters of particle diameter d and the average packed bed diameter D_p.

$$\frac{\Delta P}{L} = aU + b^2U^2 \qquad (1)$$

Once the average packed bed diameter D_p and the particle diameter d are given, an average packed bed void fraction ε can be estimated from the empirical expression of Zou and Yu [13] as shown by Eq. (5). With knowing void fraction ε, the constant parameters of a and b can be calculated from Eqs. (2)-(3), respectively. Then the packed bed length L of the SPB can be calculated from Eq. (1) as a function of ΔP and superficial velocity U, which is proportional to the mixture volume flow rate Q (or firing rate *CL*) and the exit area at the mixing chamber A.

$$a = 150\frac{\mu}{d^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \qquad (2)$$

$$b = \sqrt{1.75\frac{\rho}{d}\left(\frac{1-\varepsilon}{\varepsilon^3}\right)} \qquad (3)$$

$$U = \frac{Q}{A} \qquad (4)$$

$$\varepsilon = \varepsilon_b + 0.01\left[\exp\left(\frac{10.686}{(D_p/d)}\right) - 1\right], \quad \varepsilon_b = 0.4 \qquad (5)$$

Peclet nuber (*Pe*) [12] in Eq. (6) is used to estimate a diameter of alumina sphere particle (d) that form the packed bed of SPB.

$$Pe = \frac{S_L d c_p \rho}{k} \qquad (6)$$

If $Pe > 65$, the flame can propagate and stabilize within the packed bed. On the other hand, the flame cannot propagate within the

Table. 1 The SPB Specification

Parameter	Value	Unit
$D_{p,outer}$ (see in Fig. 2)	0.18	m
$D_{p,inner}$ (see in Fig. 2)	0.12	m
d (diameter particle)	15	mm
L (packed bed length)	0.135	m
Net port area at mixing chamber exit	2015	mm^2
CL (firing rate)	23-61	kW

packed bed if Pe < 65 because of a strong quenching effect, preventing the flame from flashback. For the best of the SPB condition flame is stabilized within the packed bed, therefore, the packed bed of the SPB has to design basing on Pe > 65.

A calculation of exit area of SPB's mixing chamber has to rely upon the CB's net port area (see details in Table 1). The exit area of SPB's mixing chamber must be equal or less than the net port area of CB to avoid flashback phenomenon of flame from propagating into the mixing tube. This can be done by keeping the flow velocity through the exit port of the mixing chamber being higher than the laminar burning velocity of combustion within the packed bed.

Fig.1 shows a relationship between the firing rate CL and the interstitial velocity V_p and the packed bed length L at constant D_p = 0.15 m and d = 0.015 m. The interstitial velocity V_p is calculated by Eq. (7). Result from calculation (a black square-solid line) is higher than the velocity laminar flame speed S_L [14] by a factor of 1.15. Thus flame can be stabilized within the packed bed. At maximum firing rate CL = 70 kW, the packed bed length of L = 0.17 m (a white circle-dash line) is seem to be sufficient for

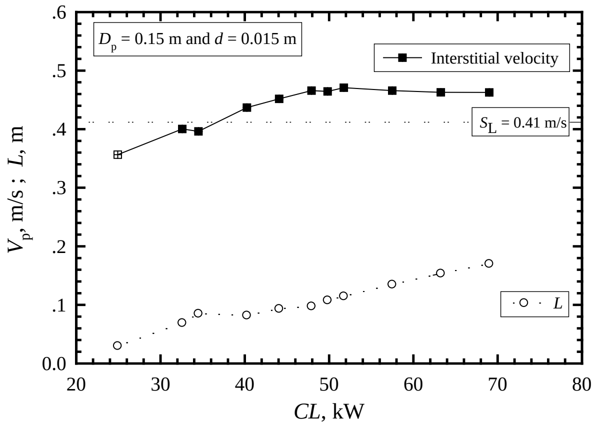


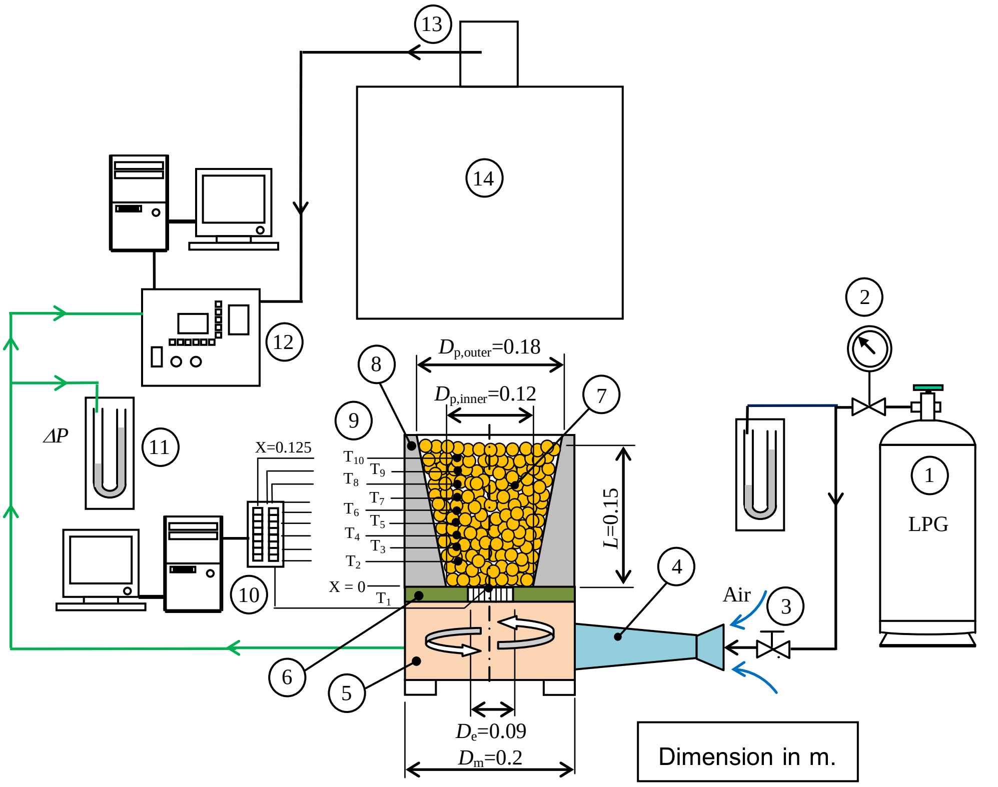
Fig. 1 A relationship between CL and L and V_p

flame stabilization while maintaining the primary air entrainment with the same pressure drop as is occurred in the CB.

$$V_p = \frac{U}{\varepsilon} \qquad (7)$$

2.2 Experimental procedure

Fig. 2 shows schematic diagram of the experimental setup. The SPB is comprised of four main sections: the mixing tube section **(4)**, the mixing chamber section **(5)**, the supporting perforated plate section **(6)** and the packed bed section **(7)**. The mixing tube section is made of a cast iron and is tangentially connected with the mixing chamber, which is constructed of a cylindrical steel of 3 mm in thickness wall and inside diameter of 0.2 m. The alumina spheres of diameter d = 15 mm are randomly arranged to construct the packed bed burner that is 0.15 m high. To improve flame stabilization within the packed bed, the theoretically obtained cylindrical packed bed is transformed into a conical shape with average diameter equivalent to that of the cylindrical one of D_p = 0.15 m. The packed bed burner is supported by the perforated stainless steel plate with a net flow area of about 2015 mm^2 at the plate to allow for the incoming flow of the air/fuel mixture from the mixing chamber.



(1) Fuel (LPG)	(2) Pressure gauge	(3) Ball valve	(4) Mixing tube	(5) Mixing chamber
(6) Perforated stainless steel plate	(7) Packed bed burner	(8) Refractory mortar	(9) Thermocouples	
(10) Data logger	(11) Manometer	(12) Exhaust analyzer	(13) Probe	(14) Hood

Fig. 2 Schematic diagram of SPB

Liquefied petroleum gas, LPG **(1)** is 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 [normal]. The LPG flow rates are controlled by a pressure regulator with calibrated pressure gauge **(2)**, mercury manometer and ball valve **(3)**.

The packed bed burner temperatures are measured by setting 10 locations of different thermocouples depending on location as denoted by T_1 - T_{10} as shown in Fig. 2. At the packed bed bottom has a highly quenching effect that it caused by a high velocity jet mixture from mixing tube. The temperature T_1 (X = 0) is located at the center of the interface between the packed bed and the perforated stainless steel plate. Within the packed bed where combustion zone takes place, the thermocouples are equidistantly located at T_2 - T_{10} as shown in Fig. 2.The tip of these thermocouples (T_2 - T_{10}) are not on the centerline of the packed bed burner but at about of 30 mm away from burner centerline. The temperatures at T_1 - T_4 are N-type sheath thermocouples with 1.5 mm sheath diameters and the temperature at T_5–T_{10} are B-type bare thermocouples (Pt/Pt-Rh 13%) with 0.1 mm wire diameters. The signals of thermocouple are digitized by a general-purpose data logger **(10)** (Delta model DT-600), and then transmitted to a personal computer.

The pressure drop across the packed bed (ΔP) is measured by manometer **(11)** at the side wall of mixing chamber. Meanwhile the oxygen sensor **(12)** is used to measure oxygen (O_2) concentration within the mixture with an accuracy of about 0.05%. An uncertainty analysis of oxygen sensor was carried out with the method proposed by Kline and McClintock [15]. The O_2 concentration is used for estimating the primary aeration (*%PA*) of the entrained air into the mixing tube [9] to monitor quality of the mixture.

Emission analysis of the dry air combustion products at the exit of exhaust hood **(14)** is carried out by using a portable exhaust analyzer (Messtechnik Eheim model Visit01L) **(12)**. A gas processing system of CO and NO_x is especially tuned for electrochemical sensors, ensuring long-time stability and accuracy of measurement. The measuring range of the analyzer is 0-10,000 ppm for CO and 0-4,000 ppm for NO_x with a measuring accuracy of about ±5 ppm (from the measure value) and a resolution of 1 ppm for both CO and NO_x. All measurement of emissions in the experiment is those corrected to 0% excess oxygen and dry-basis.

To start up the SPB, a surface-stabilized fully diffusion flame over the top surface of the packed bed burner is initiated first before switching to a matrix-stabilized rich premixed flame. The switch from surface-stabilized flame to matrix-stabilized flame was made by having a relative low firing rate (*CL*) of about 20 kW for the surface-stabilized fully diffusion flame so as to obtain a relatively low inlet velocity. Then the air shutter is gradually opened at the mixing tube inlet to decrease the equivalence ratio. At a certain value of opening of the air shutter, the flame over the packed bed burner propagates

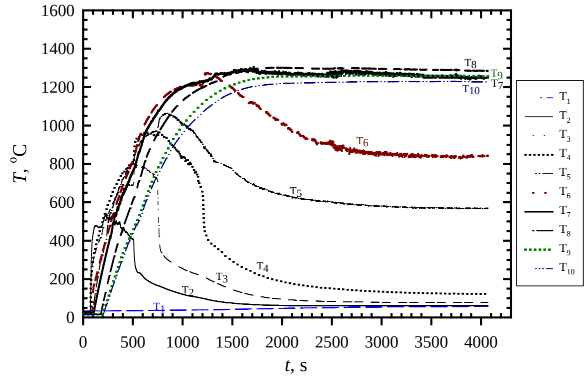


Fig. 3 Transient of SPB's temperature

automatically into upstream of the packed bed. Once matrix-stabilized premixed flame was established, the firing rate was increased to the desired values by increasing the LPG pressure. All temperatures were measured at the certain value of opening of the air shutter for studying the evolutions of temperature within the packed bed. At steady state condition, the temperature profiles and the emissions were measured.

3. Results and discussion

3.1 Transient temperature in packed bed

Fig. 3 shows typical transient changes of the solid phase temperature *T* within the packed bed burner at firing rate *CL* = 23.26 kW. A cool mixture temperature is represented by T_1. The interval $0 < t < 73$ s represents the surface-stabilized diffusion flame over the top packed bed burner surface that all temperatures is equal to the fresh mixture temperature, about 34°C, while the air shutter at the mixing tube inlet is gradually opened to increase the equivalence ratio. At t = 73 s, the opening of air shutter is optimized value, the flame is automatically propagated into the upstream of packed bed. T_2 is steeply increases that implies a diffusion flame moved from the top of packed bed into the packed bed inside and located at X = 25 mm. An inside of packed bed is heated by flame causing an increasing of packed bed temperatures T_3-T_{10}. At t = 540 s, the flame zone is shifted from T_2 (X = 25 mm) to T_3 (X = 37.5 mm) because a cool mixture from the mixing chamber is quench at the upstream of packed bed and the packed bed temperatures above this point are increased. So T_3 is steeply increases, whereas T_2 is sharply decreases. But the location at T_3, the flame cannot be stabilized because a high velocity of cool mixture at the upstream is quenched this area. At the time period 780 < t < 1800 s, the phenomena of changing the reaction zone location is from T_4 to T_5 and to T_6, respectively as time varied. After t > 1800 s, the temperature evolution profiles of $T_7 - T_{10}$ are steeply increased at the initial state and become constant afterward.

The radiation and convection heat transfer from the reaction zone are transferred to preheating the upstream region and the post flame. So the temperature T_7, T_9 and T_{10} are not sharply decrease with time. At t > 3300 s, the temperature evolutions are not changed as shown in Fig. 3. It means that the combustion in the SPB is a steady state condition and the matrix-stabilized flame is occurred.

3.2 Effect of *CL*

Fig. 4 shows the effect of *CL* on temperature profiles along the packed bed. Increasing *CL* from 23 to 61 kW yields a further increase in the temperature levels almost throughout the packed bed length. The upstream temperature value is relatively low (less than 150°C) after that it is steeply increase to maximum value at X = 0.10 m and slowly decrease in the downstream region. At *CL* = 23.26 kW, the quenching from cool mixture at

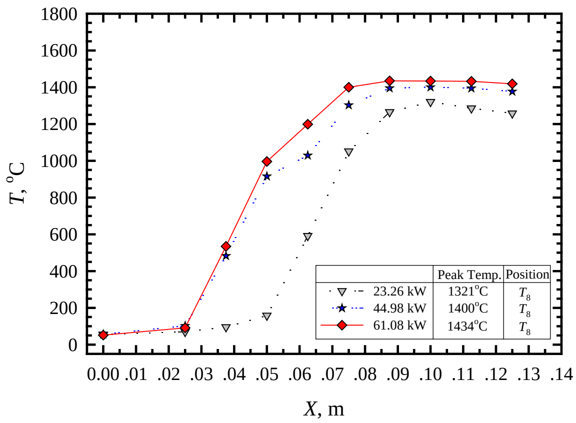


Fig. 4 Temperature distributions of SPB along the packed bed with *CL*

the exit mixing chamber has highly effect at upstream region that cause a low temperature in this region. At higher *CL*, radiant heat from high temperature zone, which is cause a steeply increasing of temperature at X = 0.025 - 0.0875 m. The flame zone is represented by the peak temperature as shown in Fig. 4.

3.3 Primary aeration and pressure drop

Fig. 5 shows variation of primary aeration (*PA*) and pressure drop (ΔP) across packed bed with *CL*. Within the range of *CL* studied, both *PA* and ΔP are almost linearly increased with *CL* because of a basic nature of the self-aspirating burner [8-9]. However, the *PA* has shown an asymptotic value as the *CL* is larger than 45 kW because it is limited by geometry of mixing tube. The measured primary aeration is range from about 40-50% that means the fuel-rich combustion regime (equivalence ratio is range from 2-2.5). In spite of this regime, the flame can be stabilized within the packed bed because of the unique characteristic of PMB in enhancing the burning velocity by a self-preheating effect.

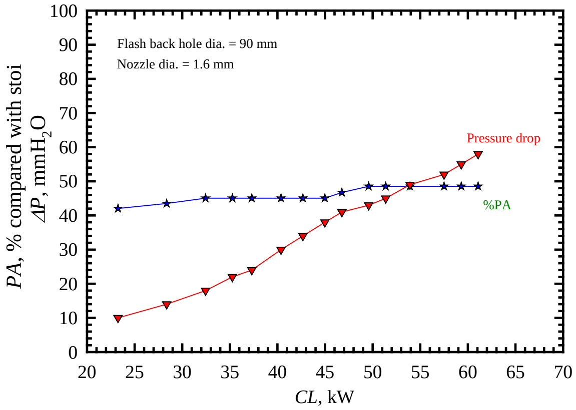


Fig.5 Primary aeration and pressure drop of SPB

The measured pressure drop across the packed bed is not differing from the CB [2] because a calculation of SPB is base on the basic characteristics of CB.

3.4 Emission characteristics

The variation of the emission pollutants (CO and NO_x) with *CL* are shown in Fig. 6. The measured emissions do not reflex actual combustion situation within the packed bed because the sample probe is placed at the exit of exhaust hood instead of within the packed bed. However, the out of bed probe measurement is adopted in this paper because this reflexes a practical application. Almost complete combustion with relatively low CO emission of less than 90 ppm (average value) can be achieved because the combustion takes place not only within the packed bed but also out of the packed bed with the secondary air entrainment.

NO_x in the present study is increase with *CL* but this is a relatively small in absolute value [2]. However, the maximum NO_x value does not exceed 81 ppm within the relatively wide experiment range of *CL*. This confirms an outstanding characteristic of the porous burner,

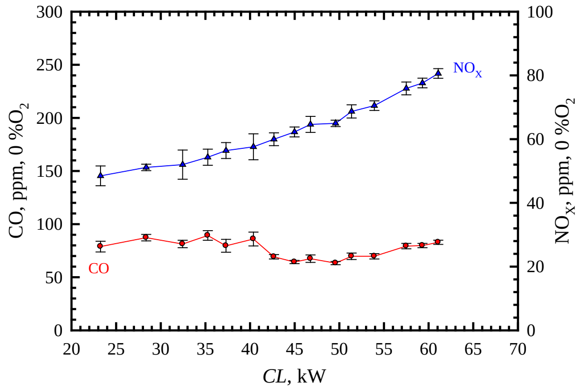


Fig. 6 Levels of CO and NO_x

which is capable of suppressing the formation of NO_x.

According to Sullivan and Kendall [16], it was considered that the thermal NO_x is sensitive to the firing rate and the prompt NO_x is much more sensitive to the theoretical air percent. Thus, at low *CL*, the prompt NO_x level in this experiment is expected to be a major contribution of the measured value because of relatively high equivalence ratio (2-2.5). The increasing of NO_x at high *CL* might be caused by thermal NO_x. Since the maximum temperature within packed with *CL* and the thermal NO_x will be suppressed if flame temperature is lower than a threshold value that below 1577°C [16].

4. Conclusion

4.1 The geometry of SPB from calculation can be operated in *CL*=23-61 kW and without the flashback phenomenon into the mixing chamber.

4.2 The SPB's turn-down ratio is widely range, about 2.65 that sufficient for SMEs in Thailand.

4.3 The main flame can be stabilized within the packed bed, which caused the low emissions.

5. References

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