CHAPTER 5 AN IMPINGEMENT FLAME OF SPMB WITH POROUS RADIANT RECIRCULATED BURNER

An effort for thermal efficiency improvement in the self-aspirating gas burner is succeeded by using a porous medium technology as shown in the chapter 4. It is a self-aspirating porous medium gas burner (SPMB) that it has a high thermal efficiency and high energy saving when compared with a self-aspirating conventional gas burner (CB) about of 57.64 and 21.48 percent, respectively. This is a new choice for a high performance gas burner in the SMEs. Although, the SPMB has a more thermal efficiency than the CB but a fossil fuel on the earth is running out that is truth. So an enhancement of thermal efficiency of the SPMB is the way to saving energy. From previous study, Jugjai et al. [6, 61-62] experimentally investigated the thermal efficiency improvement in the CB. They concluded that the heat recirculation technique can be increased the thermal efficiency by primary air preheating with radiation heat transfer from hot combustion products. Based on knowledge in Ref. [6], a possibility for thermal efficiency improvement of the SPMB can be achieved by heat-recirculating system [30]. Thus this chapter presents the experimental results of self-aspirating porous medium burner with porous radiant recirculated burner (hereafter referred to as PRRB) such as primary aeration, thermal efficiency and emission characteristics. Moreover the results of SPMB with PRRB are compared with the CB and SPMB.

5.1 Experiment setup

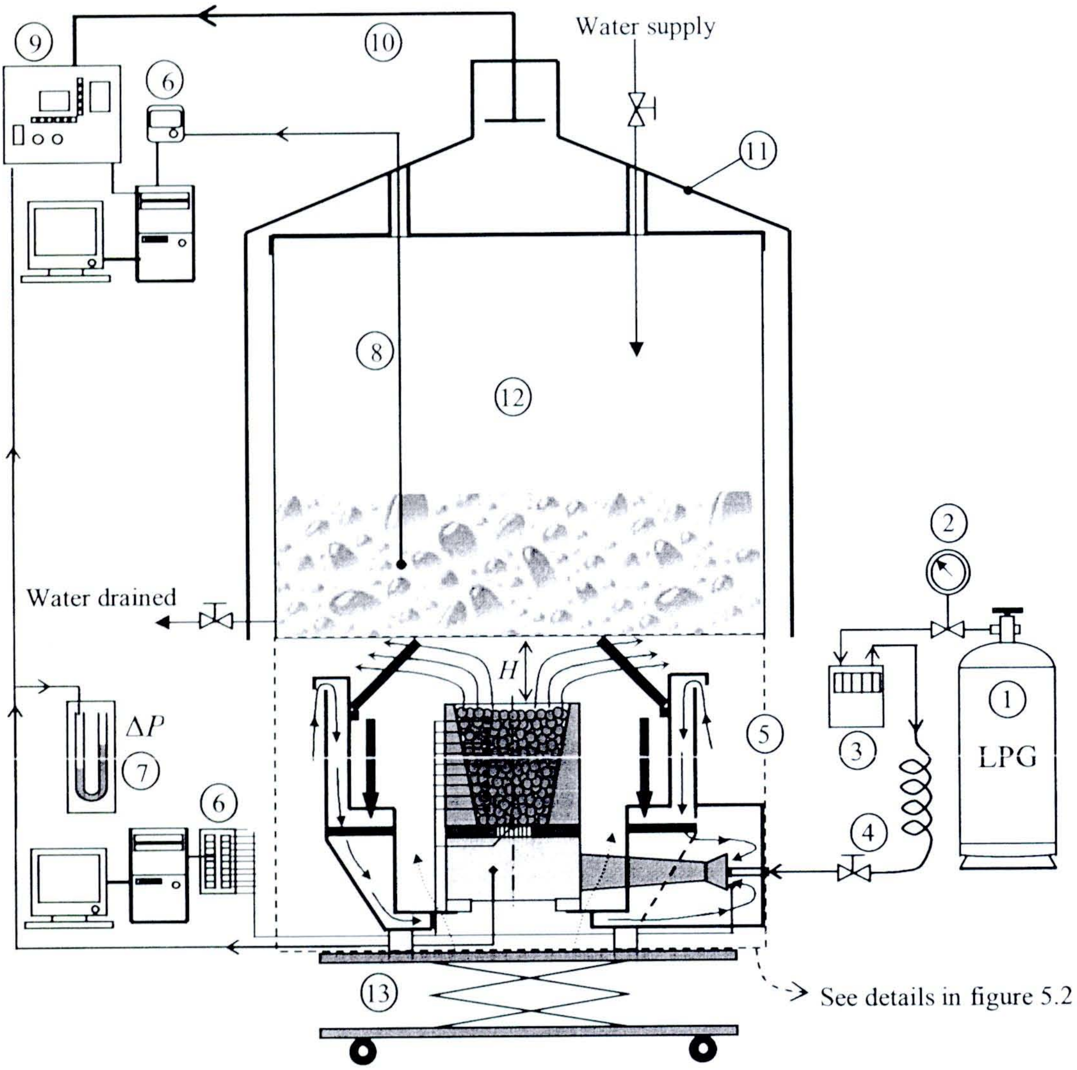
Figure 5.1 shows the schematic of the experimental setup for impinging flame of the SPMB with PRRB. A structure and direction of combustion air diagram of the SPMB with PRRB is shown in figure 5.2. The operational function, instrumentation, thermal efficiency calculation, emission measurement and energy saving are quite similar to those of the chapter 4. Specifications of the SPMB are same in chapter 4 and thus only a short notation is given here, which consist mainly composed of four parts: a mixing tube from the CB Ⓕ with gas fuel nozzle Ⓔ, a mixing chamber Ⓙ, a perforated stainless steel plate Ⓘ and a packed bed Ⓗ. The PRRB is modified from Ref. [6] that an inner volume of it has a same value. Heat recirculation in the PRRB is applied by porous technology, which have been made on the arrangement of a pair of the porous medium;

the emitting porous medium (EP) Ⓐ and the absorbing porous medium (AP) Ⓑ, through which the exhaust gas enthalpy part is recirculated to the primary air (combustion air) Ⓛ by thermal radiation as described in the chapter 2 in section 2.4 and Ref. [6]. EP Ⓐ is made by a perforated stainless steel (3 mm-thickness) and forming in conical shapes (see a photograph in appendix A) because it has a hot combustion products Ⓚ exit area when the SPMB with PRRB attached under a loading vessel (see in figure 5.1). AP Ⓑ is formed by a stack of four pieces of stainless steel wire net having 100 mesh per inch. An outer Ⓒ and inner Ⓓ housing is constructed by a steel plate of thickness 2 mm.

Combustion air is characterized in two parts; primary air Ⓛ and secondary air Ⓝ. At first, the primary ambient air is induced through a gap between outer Ⓒ and inner housing Ⓓ that likes an air jacket cooling. After that a cool primary air is heated up by hot AP Ⓑ and then preheated primary air Ⓜ is entrained into the mixing tube Ⓕ by momentum transfer from a high velocity of LPG jet [11, 42]. The preheated primary air temperature T_{pre} Ⓟ is measured by N-type sheath thermocouple at the mixing tube inlet, as shown in figure 5.2. The secondary air Ⓝ is induced into the PRRB by a combustion and it is not preheated. A hot combustion product Ⓚ impinges at a stagnation point of vessel bottom Ⓠ and then flow through EP Ⓐ that absorbs a heat from hot combustion product Ⓚ and radiates heat to AP Ⓑ and bottom vessel Ⓠ. Photographs and drawing of SPMB and PRRB are shown in appendix A and D, respectively.

A performance test methodology and parameter study of impingement flame of the SPMB with PRRB are similarly in the chapter 4. Except a distance between the burner top and the bottom of the loading vessel of the SPMB and PRRB (H) varies from 125 to 200 mm because minimum CO emission for the SPMB occurs at $H = 125$ mm (see in figure 4.3). Experimental conditions of the SPMB with PRRB shows in table 5.1.

The whole experimental was conducted under same conditions in the chapter 4. The thermal efficiency and emission characteristics of the SPMB with PRRB at $H = 125$ mm were compared with SPMB and CB.

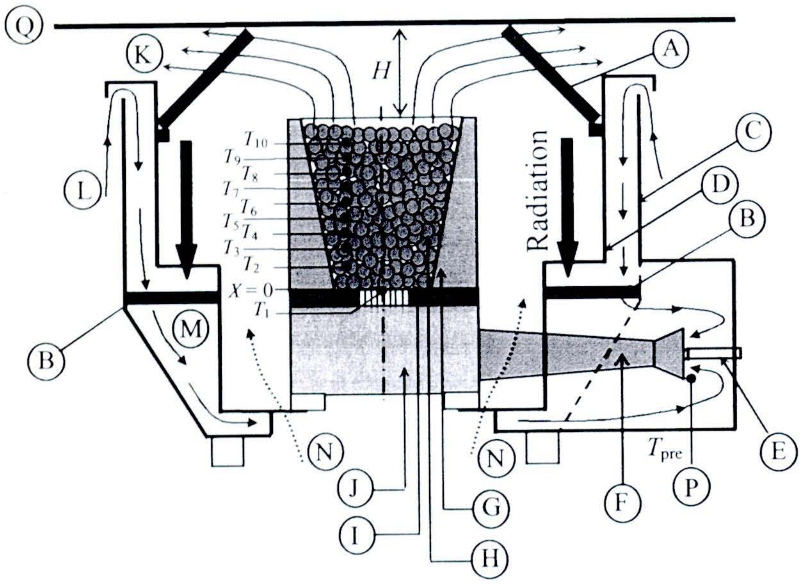


1. Fuel (LPG); 2. Pressure gauge; 3. High pressure gas flow meter; 4. Ball valve; 5. The SPMB with porous radiant recirculated burner (see details in figure 5.2); 6. Data logger; 7. Water manometer; 8. K-type thermocouple; 9. Exhaust gas analyzer & oxygen; 10. Sampling probe; 11. Hood; 12. Vessel containing water; 13. Adjustable base.

Figure 5.1 Schematic diagram of impinging flame test for SPMB with PRRB.

Table 5.1 Experimental conditions for SPMB with PRRB.

Parameter	Value	Unit
CL	21, 34 and 44	kW
H	125, 175 and 200	mm



A. Emitting porous medium (EP); B. Absorbing porous medium (AP); C. Outer housing; D. Inner housing; E. Gas fuel nozzle; F. Mixing tube; G. High temperature cement; H. Packed bed burner; I. Perforated stainless steel plate; J. Mixing chamber; K. Hot combustion products; L. Primary air; M. Primary air preheated; N. Secondary air; P. Preheated primary air temperature; Q. Bottom of water loading vessel.

Figure 5.2 Details of the SPMB with PRRB.

5.2 Results of impinging flame of the SPMB with PRRB

5.2.1 Preheated air temperature

A preheated air temperature, T_{pre}, is an important factor of the heat recirculation performance [6]. Figure 5.3 shows T_{pre} as a function of firing rate *CL* with different *H*. At constant *H*, T_{pre} is increased by increasing of *CL* because of a high heat recirculation performance by high exhaust gas temperature [6] (see in section 5.2.4). But T_{pre} decreases as *H* increases due to a heat transfer rate to AP is reduced by heat loss.

From Ref. [6, 20], an increasing of T_{pre} can enhances the thermal efficiency of burner. Unfortunately an increasing of T_{pre} is limited by auto ignition of mixture with safety working condition. So T_{pre} must not exceed the auto ignition temperature of mixture for safety in working area. From result in figure 5.3, the SPMB with PRRB can be preheated the primary air in range of 200 to 315°C that is a safety zone because it is lower than the mixture auto ignition temperature [63]. Moreover a combustion of the

SPMB with PRRB is a fuel-rich burn (see in section 5.2.2), therefore it has more safety due to the auto ignition temperature increases with an increasing of equivalence ratio [63]. Measured T_{pre} shows in Table 5.2.

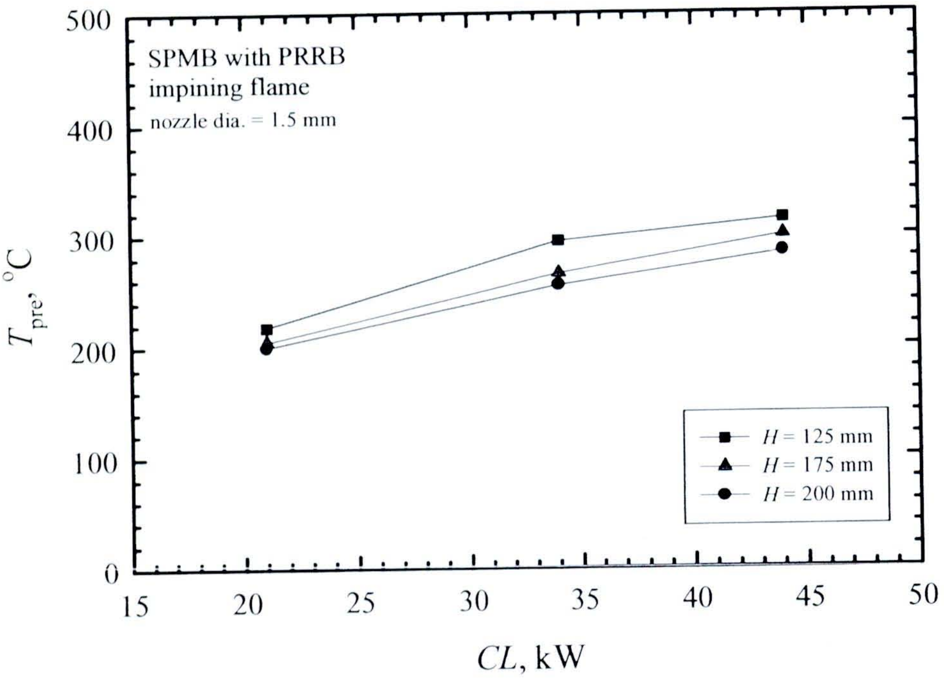


Figure 5.3 Preheated primary air temperature of the SPMB with PRRB.

Table 5.2 Temperature of preheated primary air of the SPMB with PRRB.

CL, kW	*H*, mm	Preheated air temperature, °C
21	125	218
	175	205
	200	199
34	125	295
	175	265
	200	254
44	125	314
	175	299
	200	284

5.2.2 Primary aeration

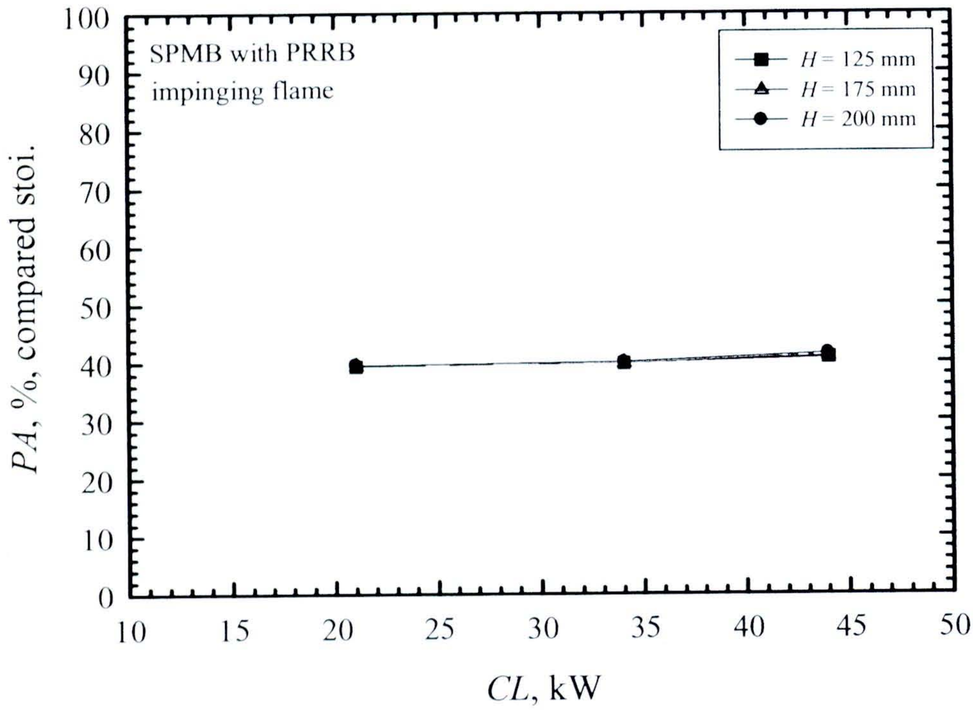


Figure 5.4 Primary aeration of the SPMB with PRRB.

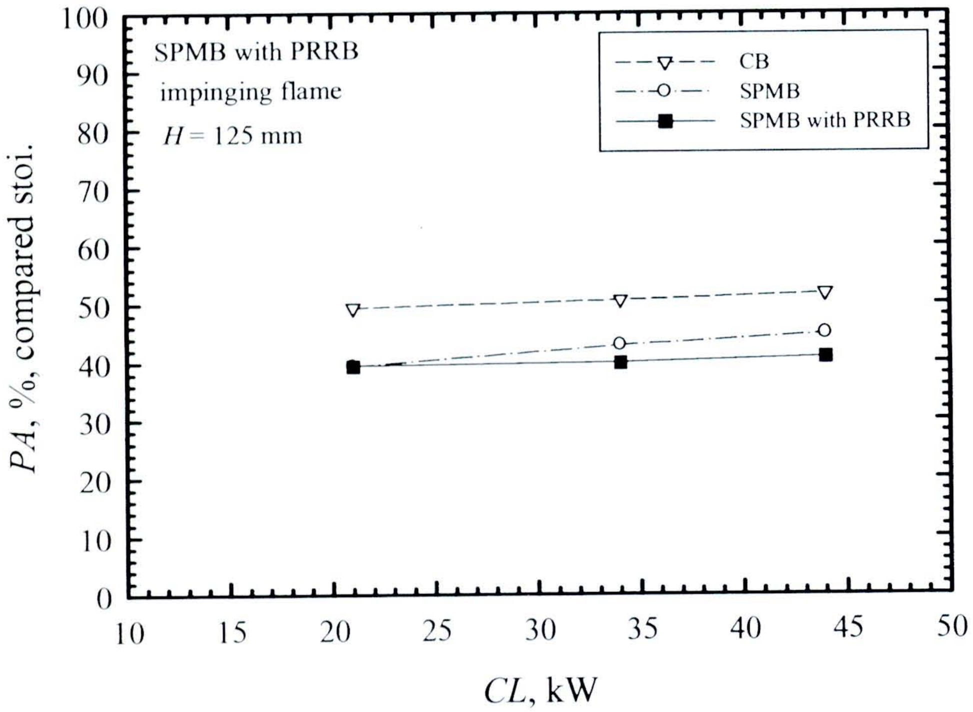


Figure 5.5 Comparison of *PA* at *H* = 125 mm.

Figure 5.4 shows the effect of *CL* and *H* on primary aeration *PA* of the SPMB with PRRB. The measurement technique and calculation of *PA* used by Namkhat and Jugjai [11] is applied in this section. Within the range of *CL*, the *PA* is almost linearly increased with *CL* because of a fundamental phenomenon of the self-aspirating burner [42]. But the effect of *H* is not significant on *PA*. It is seen in figure 5.4 that the *PA* slightly increases as *H* increases. Thus the viscosity of high temperature of primary air is a dominant parameter on *PA* in the SPMB with PRRB. Figure 5.5 shows the measured *PA* of the CB, SPMB and SPMB with PRRB as a function of *CL* at *H* = 125 mm. The measured *PA* of the SPMB with PRRB is slightly lower than the other burners because a primary air viscosity increases with temperature rising of it. The measured *PA* of the SPMB with PRRB is varying from 39 to 41 percent that implies a fuel-rich combustion regime. So the corresponding primary equivalence ratio is ranged from 2.42 to 2.54. This represents an advantage of combustion and heat recirculation with porous medium technology that can be operated with fuel-rich condition.

5.2.3 Emission characteristics

For a combustion with LPG, the prior pollutants in the flue gas are CO and NO_x [51]. The CO and NO_x emission levels are shown in figure 5.6 and 5.8, respectively. Error bars show range or span, which is a difference in maximum and minimum values of the experimental data. The measurement method of emission is similarly in the chapter 4 and all measured emission values are corrected to 0% excess air (0% O_2).

Figure 5.6 shows dependence of CO emission on *CL* for different *H*. The measured CO emissions decrease monotonically as *CL* and/or *H* increase, that has a same trend in the CB and SPMB, because of a more entrainment of secondary air and then more complete combustion [53]. Figure 5.7 shows a comparison of CO emission of the CB, SPMB and SPMB with PRRB at *H* = 125 mm. Although the CO emission of the SPMB with PRRB has a decreasing trend but it is still a high value as compared with the CO emission of the SPMB and CB (see in figure 5.7) since the secondary air is hard to entrained into the PRRB.

Figure 5.8 shows effect of *CL* on NO_x emission level with different *H*. NO_x emission is increased with *CL* and/or *H* because of more complete combustion and high flame temperature, as shown in figure 5.10 and 5.11. An increasing of NO_x emission might be caused by thermal NO_x. Except *H* = 125 mm, the trend of NO_x emission do not changes with *CL* because of a low flame temperature. A comparison of NO_x emission at *H* = 125 mm is shown in figure 5.9. The highest of NO_x emission occurs in the CB because of more the *PA* (figure 5.5) that causes a more complete combustion, that resulting in high flame temperature. For the SPMB with PRRB, that has the lowest of NO_x emission because of a low *PA* (figure 5.5) and not complete combustion. But the NO_x emission of the SPMB is higher than the SPMB with PRRB because the secondary can be easily induced into the flame. However the NO_x emissions of the SPMB and SPMB with PRRB provides a lower value than the CB because a unique characteristic of the porous medium technology that is capable to suppressing the NO_x formation [56-58]. The emission levels of the SPMB with PRRB are shown in table 5.3.

Table 5.3 Average emission levels of the SPMB with PRRB.

CL, kW	*H*, mm	Average emission, ppm at 0%O_2	
		CO	NO_x
21	125	15,149	16
	175	8,539	13
	200	7,662	19
34	125	10,265	14
	175	5,968	31
	200	5,334	35
44	125	7,513	16
	175	5,196	78
	200	4,163	78

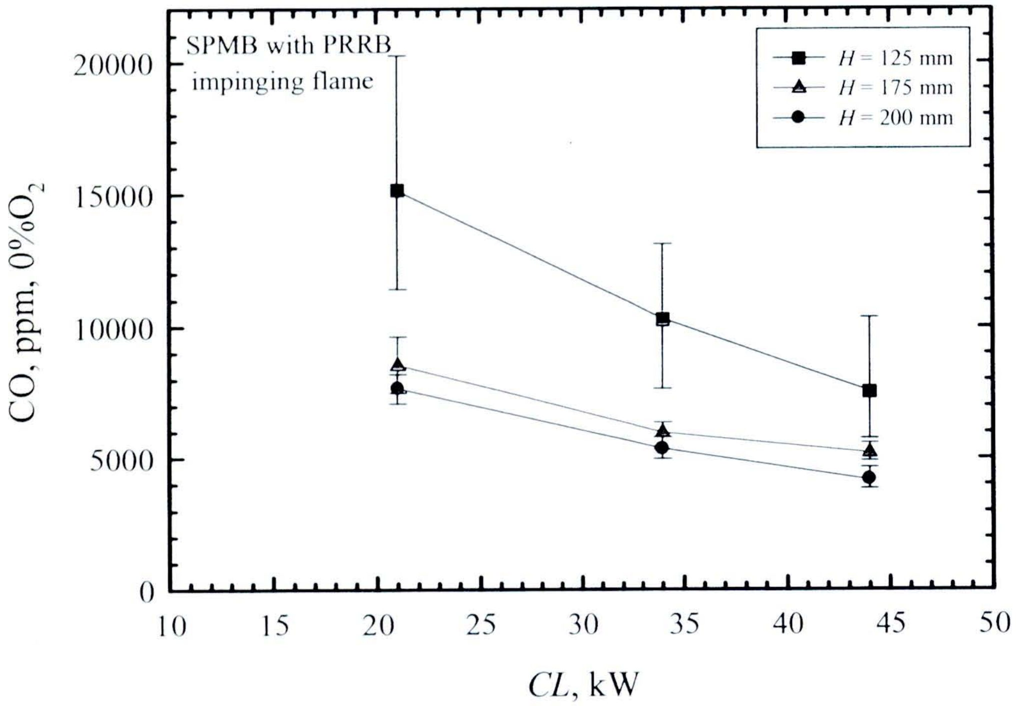


Figure 5.6 CO emissions of impinging flame of the SPMB with PRRB.

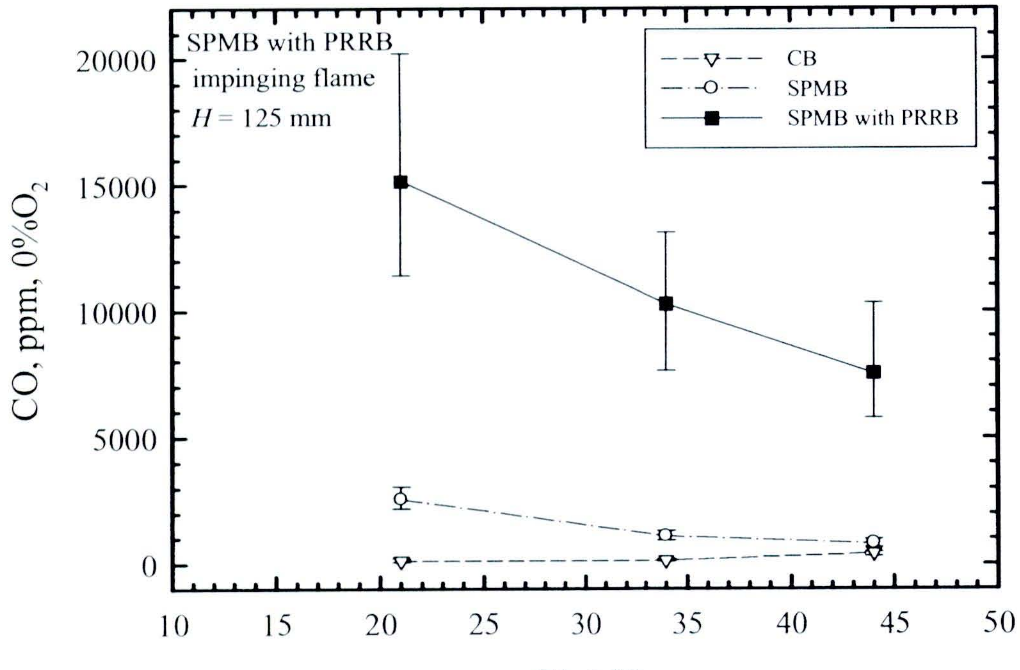


Figure 5.7 Comparison of CO emission levels at H = 125 mm.

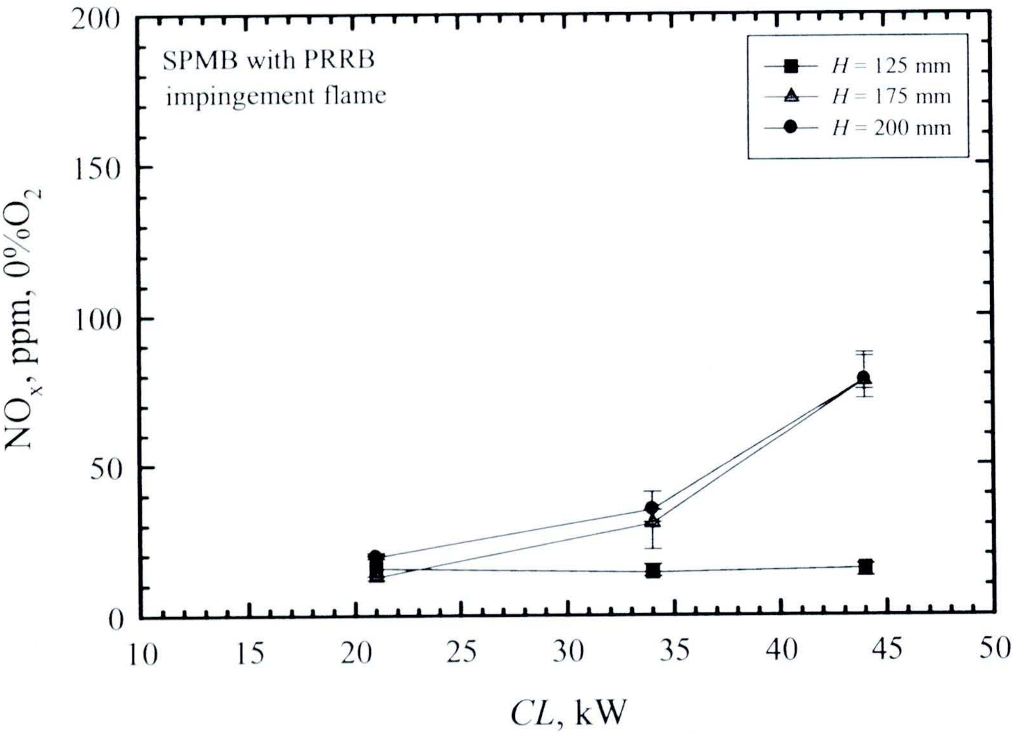


Figure 5.8 NO$_x$ emissions of impinging flame of the SPMB with PRRB.

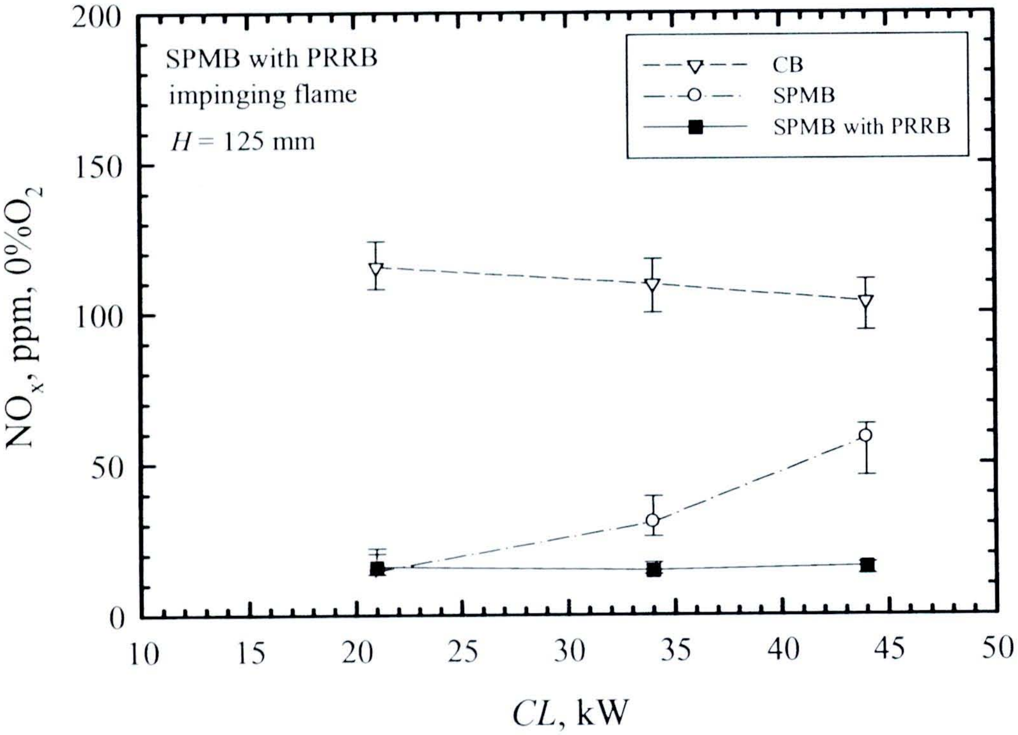


Figure 5.9 Comparison of NO$_x$ emission levels at $H = 125$ mm.

5.2.4 Temperature distribution

Figures 5.10 to 5.12 show an effect of *CL* on the temperature profiles along the axis *X* of the packed bed of SPMB with PRRB at *H* varying from 125 to 200 mm. Temperature profile has a same trend in the chapter 4. For $X < 0.0625$ m in every *CL*, the temperatures in this region are higher than the SPMB (figure 4.5 to 4.7) because of a strong preheating from self-preheating effect in combustion within the packed bed of the SPMB and a heat recirculation technology from the PRRB. Temperature at downstream region ($X = 0.125$ m) is dropped by heat loss to loading vessel and surrounding. The maximum temperature in the packed bed increases with *CL* and/or *H* and locates at $X = 0.1125$ m. As *X* increases from 0.075 m and small *H*, the temperature is low value because of non complete combustion (see in figure 5.7). The peak temperatures in figures 5.10 to 5.12 imply a reaction zone in the packed bed that the flame can be stabilized within the packed bed. There are shown in table 5.4.

Table 5.4 Maximum temperature in packed bed of the SPMB with PRRB.

CL, kW	*H*, mm	Maximum temperature, °C	Position
21	125	1,170	T_9
	175	1,213	T_9
	200	1,257	T_9
34	125	1,212	T_9
	175	1,291	T_9
	200	1,369	T_9
44	125	1,255	T_9
	175	1,307	T_9
	200	1,399	T_9

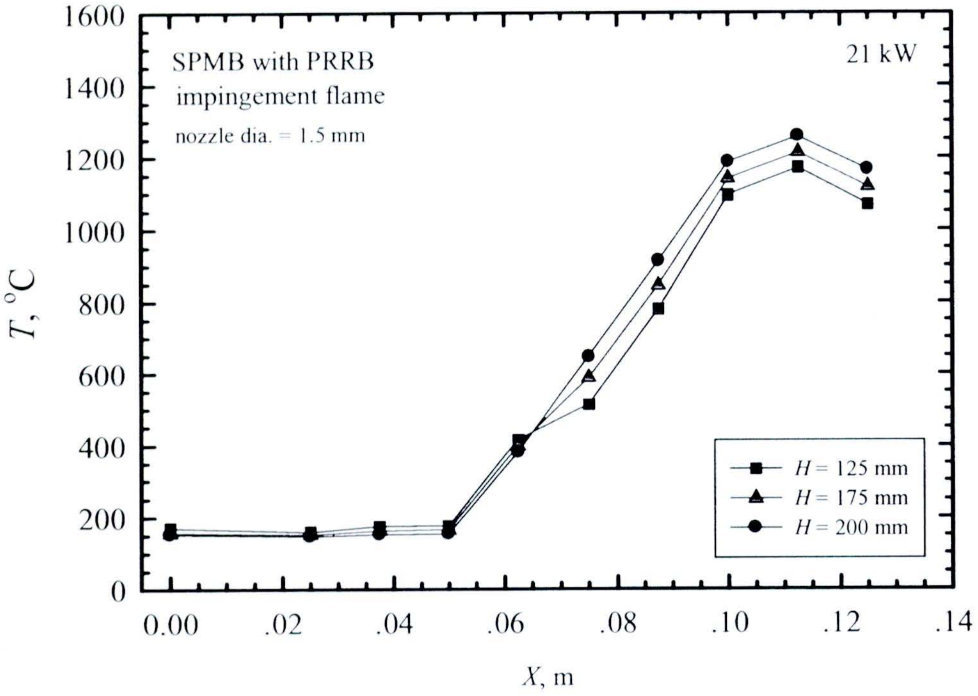


Figure 5.10 Temperature distributions in packed bed of SPMB with PRRB at 21 kW.

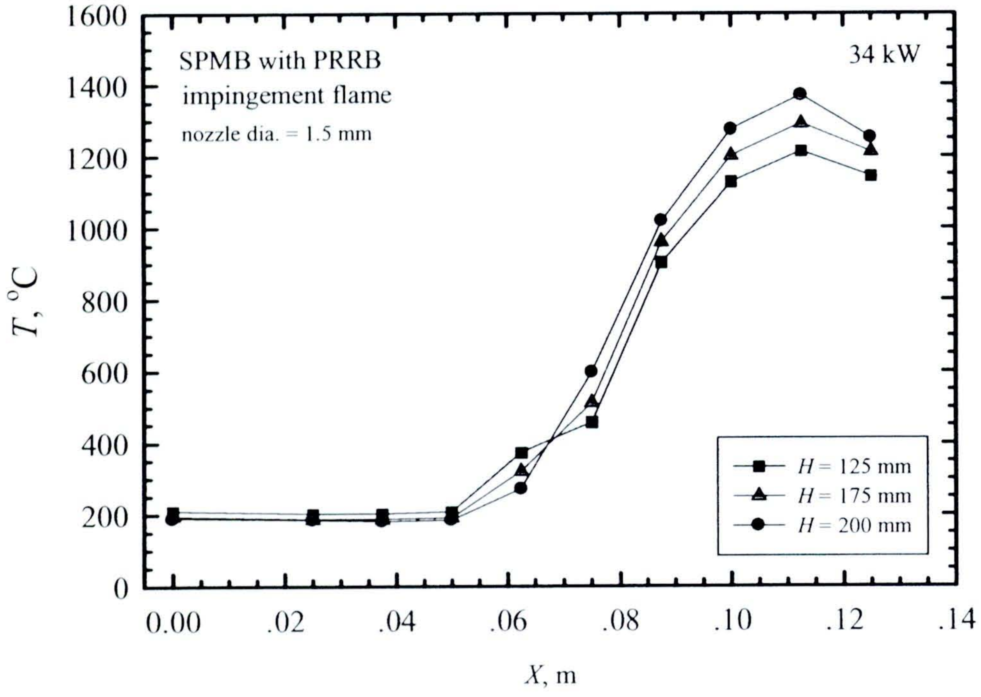


Figure 5.11 Temperature distributions in packed bed of SPMB with PRRB at 34 kW.

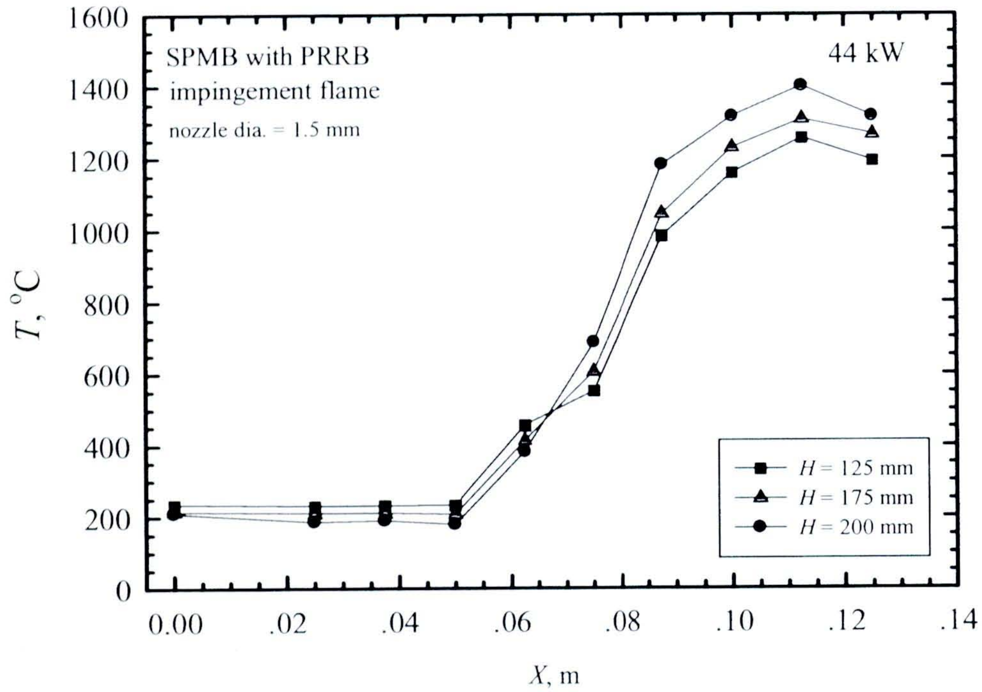


Figure 5.12 Temperature distributions in packed bed of SPMB with PRRB at 44 kW.

5.2.5 Thermal efficiency

Figure 5.13 shows the measured thermal efficiencies of the SPMB with PRRB as a function of firing rate *CL* and distance between the burner top and the bottom of the loading vessel *H*. From a result, the firing rate *CL* has a small effect on the thermal efficiency that it differs from the SPMB in the chapter 4 (see in figure 4.8) because a high preheating effect from the PRRB is more significant than a quenching effect of high flow velocity jet. But the thermal efficiency is decreased by increasing of *H* because of a low heat transfer from a hot combustion product [59]. The details of thermal efficiency is shown in table 5.5.

Table. 5.5 Thermal efficiency for the SPMB with PRRB.

CL, kW	η_{th} of the SPMB with PRRB, %		
	H, mm		
	125	175	200
21	52.86	50.65	48.84
34	51.48	50.07	46.13
44	51.28	49.96	46.04

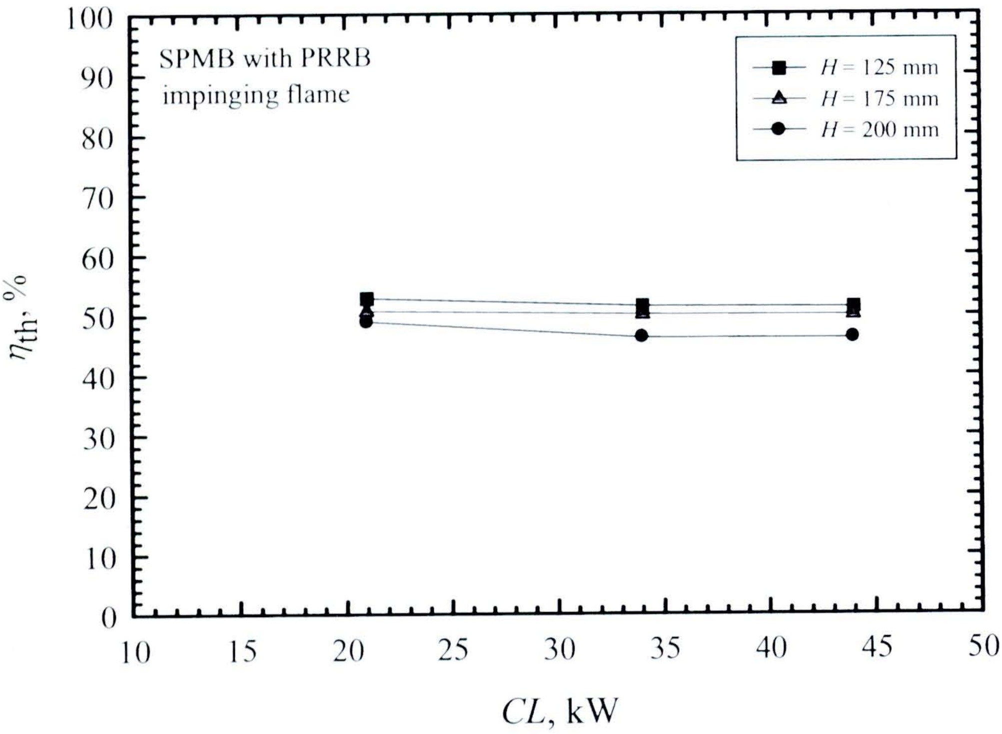


Figure 5.13 Thermal efficiency of impinging flame of the SPMB with PRRB.

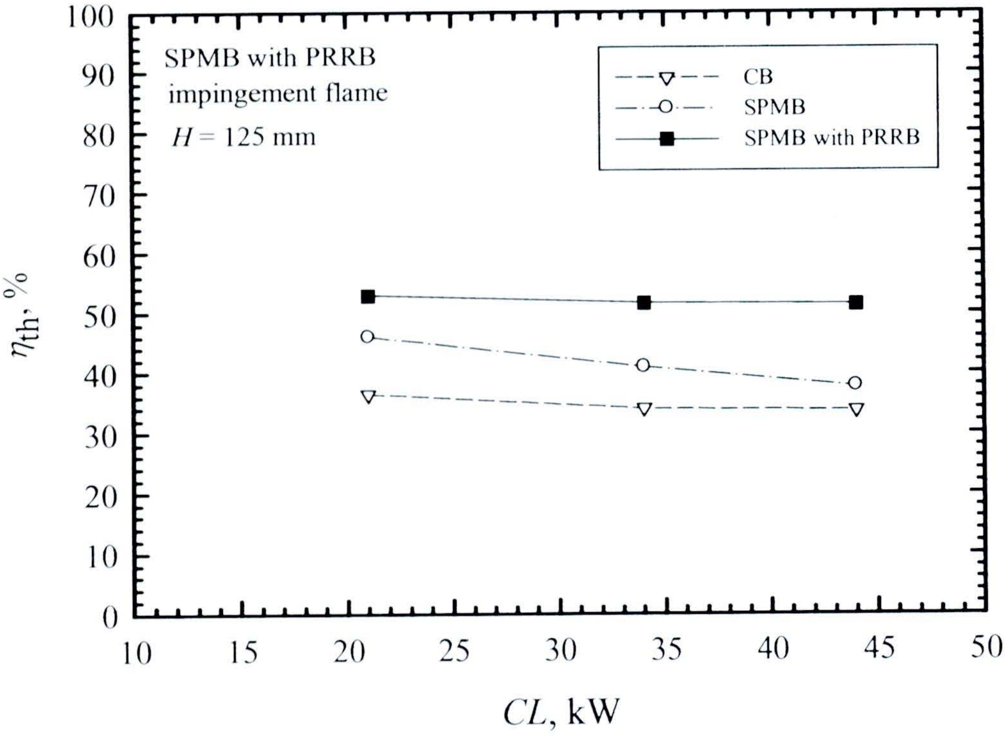


Figure 5.14 Comparison of η_{th} at $H = 125$ mm.

Figure 5.14 shows a comparison of the thermal efficiency of the CB, SPMB and SPMB with PRRB at $H = 125$ mm. For all conditions, the thermal efficiency of the SPMB with PRRB has a maximum value because of a heat recirculation from the PRRB. While the SPMB has only a self-preheating effect from a combustion within the packed bed burner and the CB is not an performance enhancement. This is clear that the heat recirculation technique [20, 30] can be improved the thermal efficiency of the SPMB [6] and the thermal efficiency contribution of the SPMB with PRRB is shown in appendix D. Although the thermal efficiency of the SPMB with PRRB is more than the CB and SPMB but it is sacrificed by a high CO emission level (see in figure 5.6) because of a lack of secondary air.

For more complete combustion in self-aspirating burner, the secondary air is very necessary. Appendix B shows an example of secondary air effect on the CB's combustion performance (thermal efficiencies and emissions).

5.2.6 Energy saving

Figure 5.14 shows a comparison of energy saving of the various self-aspirating gas burner at $H = 125$ mm. Energy saving (*EN*) for the SPMB with PRRB with respect to the CB and SPMB are calculated by Eqs. (5.1) and (5.2), respectively [6]. For increasing of *CL*, the *EN*s of SPMB with PRRB increase due to a high preheating effect from the heat recirculation. But *EN* of the SPMB and the CB (Eq. (4.3)) is reduced by increasing of *CL* because of a high heat loss from long flame of the SPMB. So the SPMB with PRRB provides a maximum value of *EN*. It is clear that the heat recirculation technique can be improved the thermal efficiency of the self-aspirating gas burner. The *EN* calculations at $H = 125$ mm are shown in table 5.6.

$$EN = \frac{\left(\eta_{\text{SPMB with PRRB}} - \eta_{\text{CB}}\right)}{\eta_{\text{SPMB with PRRB}}} \times 100\% \qquad (5.1)$$

$$EN = \frac{\left(\eta_{\text{SPMB with PRRB}} - \eta_{\text{SPMB}}\right)}{\eta_{\text{SPMB with PRRB}}} \times 100\% \qquad (5.2)$$

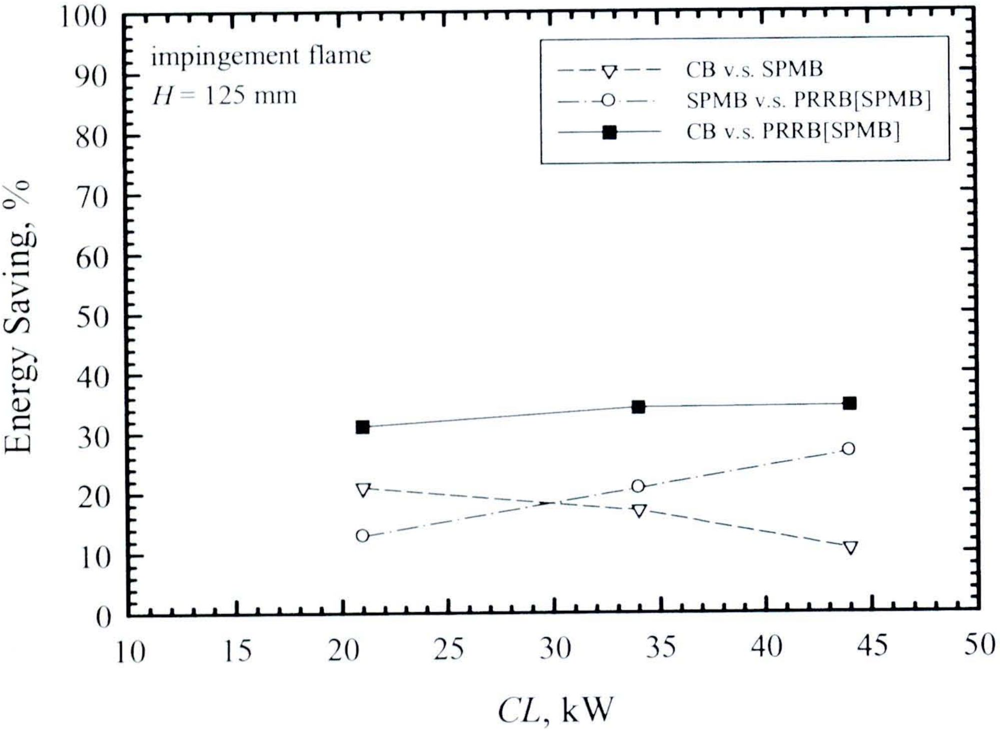


Figure 5.15 Comparison of energy saving at H = 125 mm.

From measured and calculation results, the SPMB with PRRB provides the highest thermal efficiency that causes a high energy saving [60]. An average of η_{th} of the CB, SPMB and SPMB with PRRB at H = 125 mm are about of 16.15%, 20.06% and 33.21%, respectively. Following the *EN* of the SPMB with PRRB that will reduce cost of LPG consumption for industry section in Thailand about of 2,730 million baht/year as compared with the SPMB and 1,649 million baht/year as compared with the CB (based on 2010) [10] that is not considered with economic costs.

Table. 5.6 Energy saving of the self-aspirating gas burner at H = 125mm.

CL, kW	*EN* at *H* = 125 mm, %		
	CB & SPMB	SPMB & SPMB[PRRB]	CB & SPMB[PRRB]
21	20.91	12.90	31.12
34	16.95	20.65	34.10
44	10.59	26.63	34.40

5.2.7 Development of the thermal efficiency

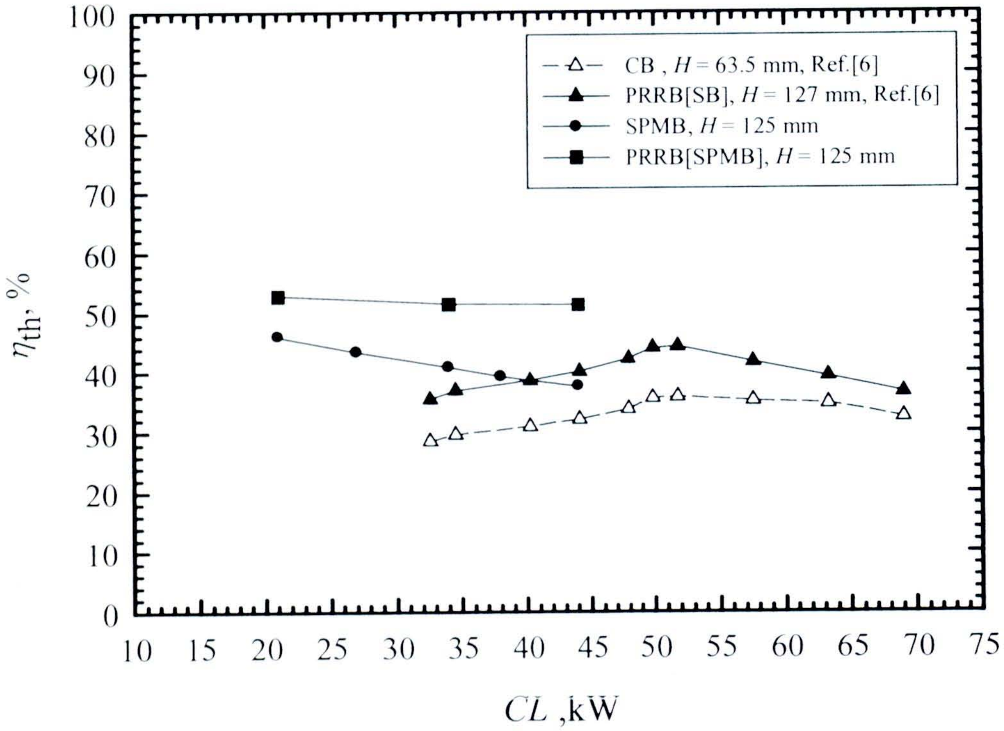


Figure 5.16 Development of thermal efficiency.

Figure 5.16 shows a development of thermal efficiency of the self-aspirating gas burner when H is similar about of 125 mm. Except the CB in Ref. [6], H is 63.5 mm because this condition obtain a best performance for the CB. In addition the firing rate CL is not a same range because of a different of fuel gas nozzle diameter. Diameter of gas fuel nozzle in Ref. [6] and this research is 1.8 mm and 1.5 mm, respectively. The thermal efficiency in Ref. [6] is the first effort of thermal efficiency improvement of self-aspirating gas burner for SMEs in Thailand. The results show that the thermal efficiency of the CB can be improved by changing a flow pattern from radial flow to central swirling flow and using the heat recirculation with porous technology, as shown in triangle symbol in figure 5.16. After that, the porous medium burner technology is adopted in the CB to replace a ring burner head. From many advantages of porous medium burner, that is clearly described in the chapter 3. So the SPMB has more an average thermal efficiency than the PRRB[SB] in Ref. [6], as shown in solid square symbol. Moreover, more enhancement of the thermal efficiency in the self-aspirating gas burner, the heat recirculation technique in the Ref. [6] is applied with the SPMB that the results are clearly shown in previous section. High preheating effect from the combustion within the packed bed and heat recirculated by PRRB that enhances the thermal efficiency [20]. As the result that the thermal efficiency of the SPMB with PRRB is the highest value as compared with other burners (circle symbol). The details of contribution of thermal efficiency are shown in appendix D. Although the firing rate *CL* is not a same range and the fact results in figure 5.16. It conclude that the thermal efficiency of the self-aspirating gas burner can be improved by the porous technology. An average of the thermal efficiency of the CB in Ref [6], PRRB[SB] in Ref.[6], SPMB and SPMB with PRRB in figure 5.16 is 32.87%, 39.94%, 41.44% and 51.87%, respectively.