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Performance and Investigation of a Self-aspirating, Liquid fuel, Annular Porous Medium Burner (SLAPMB)

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Abstract

This study is aimed at creating use of liquid ethanol as liquefied petroleum gas (LPG) substitute for household and industry uses. Design and development of a novel, self-aspirating liquid fuel annular porous medium burner (SLAPMB) is proposed. The SLAPMB is built in an annular shape with opening area at the center for more secondary air (*SA*) entrainment and a vaporizer for vaporizing the liquid ethanol is embedded inside the burner wall. Combustion characteristics of both free flame and impinging flame are studied. Transient period of the SLAPMB during the switching period from the LPG to the ethanol vapor is investigated for understanding the simultaneous combustion phenomena within the porous medium burner and the vaporization process within the vaporizer. Effects of firing rate (*FR*) on the flame stabilization, temperature profiles within the burner, and emission characteristics are investigated. Flame moves upstream as *FR* increases due to a strong effect of energy recirculation. The existence of *SA* inlet can significantly help to decrease CO emission and increase thermal efficiency. Thermal efficiency is 33.6 % on average that is comparable to that of the conventional KB-10 LPG burner. Temperature peak occurs at the middle region of the burner with relatively low CO and NO_x emission of about 100 ppm and lower than 50 ppm, respectively. The SLAPMB can offer a relatively wide turndown ratio with the firing rate (*FR*) ranging from 16 kW to 23 kW without the problems of flame stabilization and emission characteristics. Fuel decomposition within the vaporizer was not occurred, making this SLAPMB is very practical for industrial application to replace the liquefied petroleum gas (LPG).

***Keywords**:* Liquid fuel, Self-aspirating burner, Annular packed bed, Porous medium, LPG substitute.

1. Introduction

Thailand has to mainly rely on energy import because about 60% of primary commercial energy has to be imported to meet the domestic demand. Moreover, about 80% of the total energy demand is the use of fossil fuels that causes an increase in volume of CO_2, which is a primary greenhouse gas (GHGs). In order to reduce fossil fuels consumption, it requires a use of renewable energy resources such as wind, solar, and energy from garbage or municipal solid waste (MSW), biomass, biogas, and ethanol, which are produced from agricultural products.

Petroleum products consumption in terms of the liquefied petroleum gas (LPG), a major consumer comprised household sector and industry sector, which consumes LPG as fuel for cooking, has become the largest share of LPG consumption, i.e. about 40% of the total [1]. As aimed at strengthening energy security of the country and reducing the impact of climate change, a concepts of using ethanol as a replacement of the LPG is proposed, because the ethanol is made from the agricultures stuff, which is domestically produced.

A conventional self-aspirating cooking burner (CB), which is widely used in household, unfortunately, it is designed specifically to consume only LPG as gaseous fuel. More than that, thermal efficiency of the CB is relatively low [2], especially the high-pressure types, e.g. KB5, KB8, KB10, and KB15, in which, the consumption rates are relatively high, i.e., from 5 kW to 70 kW. For the KB10 and KB15 types, they have thermal efficiency lower than 35%, and they are rather used in the Small and Medium Enterprises (SMEs), such as food cooking industry. The number of such SMEs is increasing at a very fast rate [3]. Therefore, the share of energy by using these burner types in total energy consumption of the country has to be concerned.

The concept of heat recirculation combustion by using a porous medium technology is proposed for an improvement in the thermal efficiency [4, 5]. Porous medium has been applied for improving burner efficiency because of its self-heat recirculating recovery from the exhaust gas to the fresh reactant, which is resulting in the combustion temperature of higher than the adiabatic one [6]. Both combustion and radiation intensities are significantly increased along with the flammability limit [7]. Amanda J. Barra and Janet L. Ellzey [8] numerically studied heat recirculation within the porous medium wherein the premixed combustion of gaseous fuel is occurred. Results showed that increasing equivalence ratio will decrease heat recirculation efficiency. Yoksenakul W.

and Jugjai S. [9] designed and constructed a self-aspirating porous medium burner for gaseous fuel. 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, relatively high flame length is extended into the post flame region, at outside the burner, due to insufficiency of combustion air. Consequently, in order to improve secondary air entrainment, A. Petchsangkoon and S. Jugjai [10] 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 the stabilized flame inside the porous medium with relatively low emission of CO and NO_X can be achieved. However, its application is restricted to use only gaseous fuel.

Kaplan, M. and Hall, M.J. [11] examined the combustion of liquid fuel within the porous inert media (PIM). The fuel heptane was sprayed and impinged on the entrance of the porous medium section followed by combustion within it. Stable combustion within the porous medium was achieved at equivalence ratio of 0.57-0.67. Temperature inside the porous medium, at the equivalence ratio of 0.64, is as high as 1170-1370 ^{O}C with CO and NO_x varied from 3-7 ppm and from 15-20 ppm, respectively.

The literatures mentioned that the combustion locations can be stabilized within porous medium with paying attention on premixed combustion of a gaseous fuel. However, investigation of a self-aspirating burner using liquid fuel (ethanol) has not been studied before. Therefore, this research proposes a design and development of the high-pressure self-aspiration porous burner using liquid ethanol as fuel. CB burner KB-10 type was used as the reference ones. Porous medium burner with an annular in shape was applied to enhance combustion and thermal performances of the burner. A design of vaporizer tube for self-vaporizing the liquid ethanol was done by embedded the tube inside the burner wall. Flame stability within an annular porous medium has been focused. Effects of the secondary air (*SA*), and firing rate (*FR*) on the flame stabilization, temperature profiles within the burner, post flame length outside the burner and emission characteristics are investigated.

2. Design of the SLAPMB

Design of SLAPMB relies on the same parameter as that of CB, i.e. pressure drop across the burner (ΔP) and mixing tube dimension. Porous medium is an annular packed bed of alumina spheres (Al_2O_3). Diameter of the Al_2O_3 spheres can be calculated from Eq. (1) [12].

$$Pe = \frac{S_L d_m c_p \rho}{k} \tag{1}$$

Peclet number (*Pe*) of greater than 65 can get flame submerged within the pack bed of the Al_2O_3 spheres and vice versa according to the quenching effect.

2.1 Packed bed length of the SLAPMB

Length of the annular packed bed of the Al_2O_3 spheres is determined from suggestion of J.R. Sodre and J.A.R. Parise [4], the equations of which had been adapted from Ergun's equation [13]. Attention has been paid to the correction factor (C) that corrects the interstitial velocity of the cylindrical to annular shapes as stated in Eqs. (2) and (3). $\overline{\upsilon}_c$ is corrected total average flow velocity thought the packed bed For more accuracy calculation, the distribution of interstitial velocity profile had been divided into three regions keeping away from wall effects [4], i.e. at the internal wall region ($\overline{\upsilon}_{wi}$), at the transition region ($\overline{\upsilon}_t$), and at the external wall region ($\overline{\upsilon}_{we}$). While, $\overline{\upsilon}$ and A_b are the single region average flow velocity, and the single region area thought the packed bed, respectively.

$$\frac{\Delta P}{L} = 150\frac{(1-\bar{\varepsilon})^2}{\bar{\varepsilon}^3}\mu\frac{(C\overline{\upsilon})}{d^2} + 1.75\frac{(1-\bar{\varepsilon})}{\bar{\varepsilon}^3}\rho\frac{(C\overline{\upsilon})^2}{d} \tag{2}$$

$$C = \frac{\overline{\upsilon}_c}{\overline{\upsilon}} = \frac{\overline{\upsilon}_{wi}}{\overline{\upsilon}}\frac{A_{wi}}{A_b} + \frac{\overline{\upsilon}_t}{\overline{\upsilon}}\frac{A_t}{A_b} + \frac{\overline{\upsilon}_{we}}{\overline{\upsilon}}\frac{A_{we}}{A_b} \tag{3}$$

2.2 Vaporizer length of the SLAPMB

Vaporizer is designed and buried in the burner wall and turning around the burner for receiving heat by conduction (Eq.4) to vaporize the liquid ethanol. Burner wall has been constructed using refractory mortar.

$$\dot{Q} = sk\left(T_b - T_s\right) \tag{4}$$

An amount of energy (*Q*) that is utilized for vaporization process of the liquid ethanol is determined from a sensible heat, a latent heat and a superheated heat (Eq.5 and Eq.6).

$$\dot{Q} = \dot{Q}_{liq.,sensible} + \dot{Q}_{latent\ heat} + \dot{Q}_{super\ heat} \tag{5}$$

$$= \dot{m}C_p(T_{boil} - T_i)_{liq.} + \dot{m}L + \dot{m}C_p(T_o - T_{boil})_{gas} \tag{6}$$

Then length of the vaporizer can be calculated by using Eq. (7) to Eq. (9) [14] based on the following assumptions; combustion system is steady state, heat transfer is one dimensional calculation, wall temperature (T_s) is constant and, physical properties of ethanol are constant.

$$\dot{Q} = UA_s\Delta T_{lm} \tag{7}$$

$$UA\left(\frac{T_o - T_i}{\ln\left(\dfrac{T_s - T_i}{T_s - T_o}\right)}\right) = \dot{m}C_p\left(T_{boil} - T_i\right)_{liquid} + \dot{m}\mathrm{L} + \dot{m}C_p\left(T_o - T_{boil}\right)_{gas} \tag{8}$$

$$\frac{1}{UA} = \frac{1}{hA} + \frac{ln(OD/ID)}{2\pi kl} \tag{9}$$

Replacing *UA* from Eq. (9) into Eq. (8), in which the amount of energy is equals to the heat received by conduction as defined by Eq. (4), then the length of vaporizer (*l*) can be determined.

3. Experimental apparatus

Fig. 1 shows photograph of the constructed SLAPMB. As is clearly seen that the vaporizer is completely buried inside the wall of the packed bed of the porous medium for absorbing heat for vaporization. The porous medium is an annular in shape to allow for the central secondary air (*SA*) from the bottom flowing upwards and burned with the post flame combustion at the burner exit for more complete combustion.

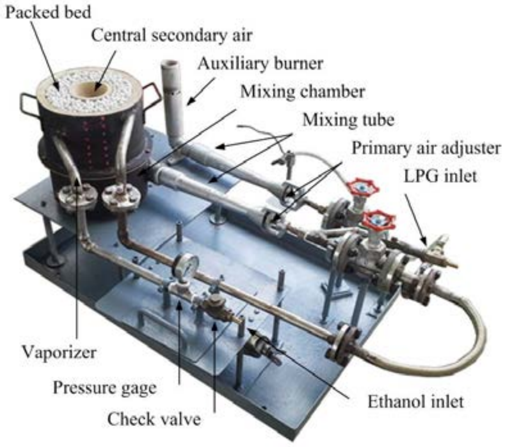


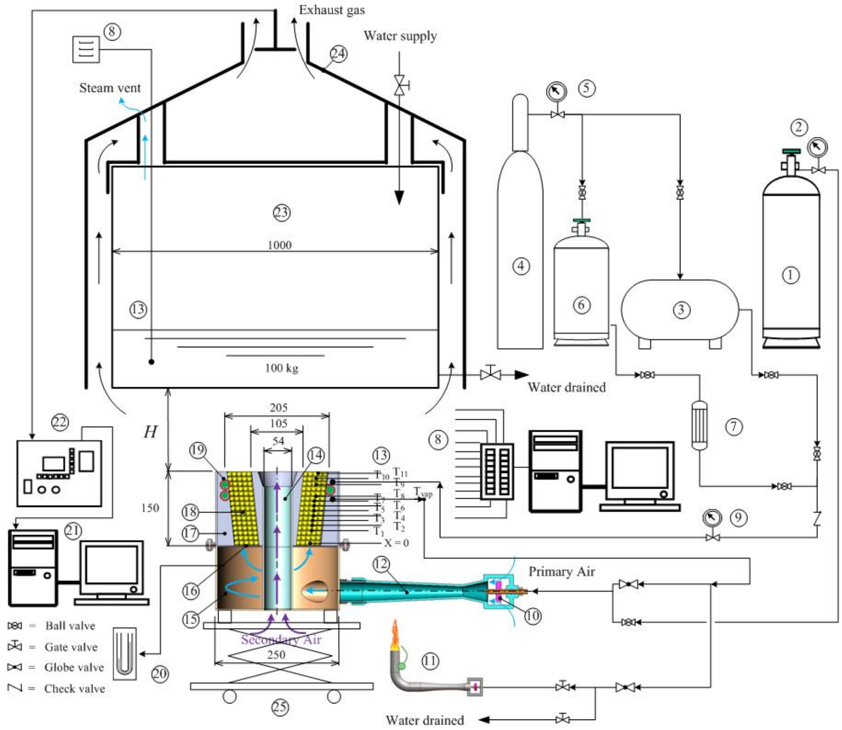
Fig. 1. Photograph of the SLAPMB.

Apart from the main burner of the packed bed porous medium, an auxiliary venturi-type burner is also connected with the outlet of the vaporizer on the right-hand side of the main burner.

This help to assure that the complete vaporization of the liquid ethanol is achieved before being switched to the main burner by controlling the nearby control valves.

Fig. 2 shows a schematic diagram of the experimental setup and details of the SLAPMB. It consists of five main systems, i.e. a fuel supply system, burner system, temperature acquisition system, water-boiling test, and emissions measuring system. The temperature has been acquired by DATA LOGGER (EQ 600) using thermocouples of types B and N. An exhaust analyzer (MESSTECHNIK EHEIM series Visit-01L) is used for analyzing CO, CO_2, O_2, and NO_x emissions. Thermal efficiency test is a water-boiling test, and it is calculated according to European standard [15].

To start the SLAPMB, a firing rate *FR* = 23 kW of energy input of the LPG is supplied into the main burner for warming up while liquid water is supplied into the vaporizer for cooling and drained at outside as the water turns into a hot steam. As steady state combustion is achieved at the main burner, the water is turned off and is switched to liquid ethanol with premixed combustion occurred at the nearby auxiliary conventional self-aspirating burner that is temporarily connected to the terminal of the vaporizer.



1. Fuel (LPG) 2. Pressure regulator (LPG) 3. Water tank 4. Liquid Nitrogen 5. Pressure regulator (N_2) 6. Fuel Ethanol 7. Flow meter 8. Data logger 9. Pressure gage 10. Primary air adjuster 11. Auxiliary burner 12. Mixing tube 13. Thermocouples 14. Secondary air pipe 15. Mixing chamber 16. Perforated stainless steel plate 17. Refractory mortar 18. Packed bed burner 19. Vaporizer 20. Manometer 21. Computer 22. Exhaust analyzer 23. Vessel containing water 24. Hood 25. Adjuster base

Fig. 2. Experimental setup of the SLAPMB.

As steady state combustion of ethanol is established at the auxiliary burner without any re-condensation, turn off the LPG at the main burner and switch to the ethanol vapor from the auxiliary burner, using the nearby control valves.

4. Results and discussion

4.1 Free flames

4.1.1 Flames stabilization within the SLAPMB

Fig. 3 shows transient behavior of temperatures within the packed bed of SLAPMB during switching from LPG to ethanol vapor at firing rate of 23 kW. The initial LPG submerged flame for warming up the SLAPMB is well stabilized with full opening of the primary air adjuster, assembled at the mixing tube inlet. The peak temperature occurred at T_9 is illustrated up to t = 2,200s before the primary air adjuster is completely closed followed by a small decrease in T_9 as depicted by point A. At point B, the LPG is completely turned off, resulting in further decreasing of temperature at T_9, and then increasing again when the ethanol vapor comes to replace the LPG at the point C. During this time the primary air adjuster of the SLAPMB mixing tube is carefully adjusted from fully closed with θ = 0° with strong temperatures fluctuation happening before flame stabilization with flat temperatures was achieved again at point D, where flame location occurred at T_7.

Note that the stabilized location of submerged flame is changed from T_9 with LPG to T_7 with ethanol because equivalence ratio of ethanol is nearer stoichiometric condition than LPG, because of a high oxygen content of ethanol. A porous medium burner that is operated with liquid ethanol has been successfully accomplished.

4.1.2 Effect of firing rate (FR) on T

Fig. 4 shows effect of firing rate on flame stabilization within the porous medium. Flame location moves upstream when *FR* is increased from 16 kW to 23 kW due to a strong effect of energy recirculation. The temperature of combustion is also increased. Relatively high turndown ratio is achieved with stable combustion from 16 kW to 23 kW.

4.2 Impinging flames

4.2.1 Effect of burner to pot distance (H) on emission characteristics

Fig. 5 shows effect of *H* on CO and NO_x emissions at constant firing rate of 23 kW. Amount of CO emission decreases as *H* increases because of more secondary air entrained toward to the flame and more residence time which lead to more complete combustion. On the other hand, the level of NO_x emission slightly increases as *H* increases because of more complete combustion and high flame temperature.

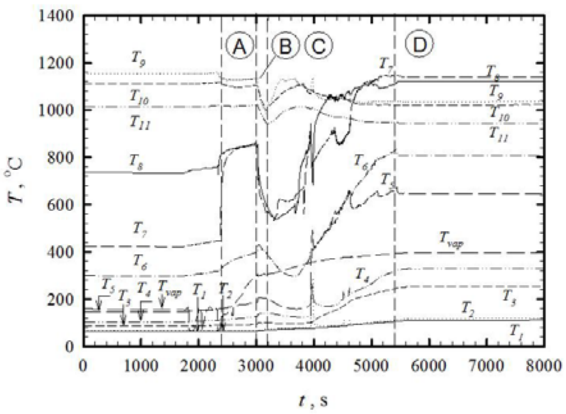


Fig. 3. Transient temperature within the SLAPMB.

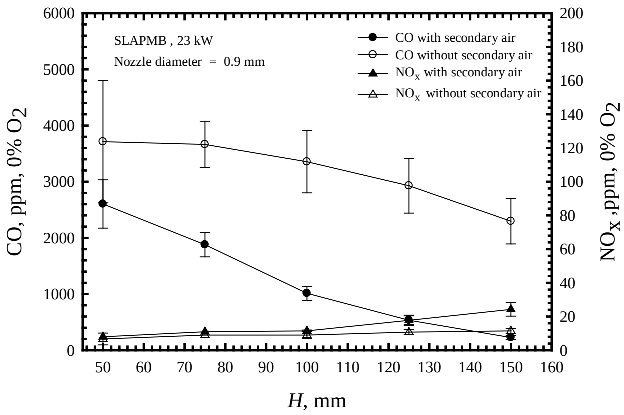


Fig. 5. Effect of *H* on CO and NO_x.

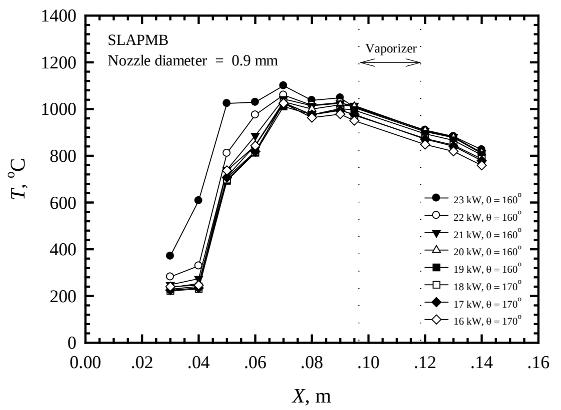


Fig. 4. Effect of firing rate (*FR*) on temperature profile along the annular packed bed of free flame.

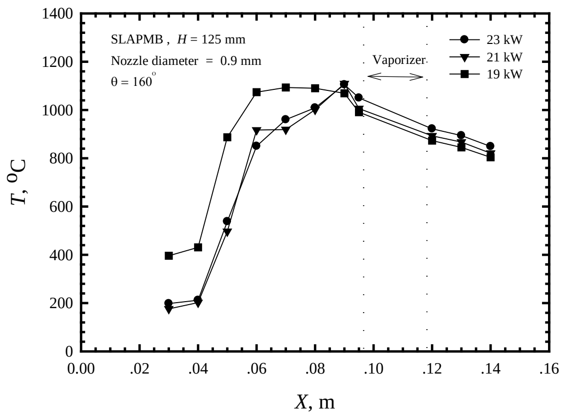


Fig. 6. Effect of firing rate (*FR*) on temperature profile along the annular packed bed of the impinging flame.

H = 125 mm was selected to estimate thermal efficiency of SLAPMB because it gives an acceptable emission level, i.e. CO lower than 1,000 ppm with *SA*.

4.2.2 Effect of FR on T along the packed bed

Fig. 6 shows effect of firing rate *FR* on temperature distribution along axis *X* of packed bed at varying firing rate from 19 to 23 kW for the impinging flame. The peaks imply reaction zones or flame locations within the packed bed. At a low firing rate, *FR* = 19 kW the location of flame is at x = 0.07 m with maximum temperature of about 1,100ºC. As firing rate increases to *FR* = 23 kW, flame location moves to x = 0.09 m with maximum temperature of about 1,155 ºC. The flame shows a trend of moving to the downstream region, because of increasing flow velocity of mixture with increasing gas input pressure. At downstream region, the temperature has a trend decreased because of heat loss to surrounding and water load.

According to the design, the SLAPMB can be operated at firing rate higher than 23 kW, but this is beyond the limitation of the apparatus. Thus, *FR* = 23 kW is maximum value in this research.

4.2.3 Effect of FR on CO and NO$_x$

Fig. 7(a) shows the effect of *FR* and secondary air (*SA*) on CO emission of SLAPMB.

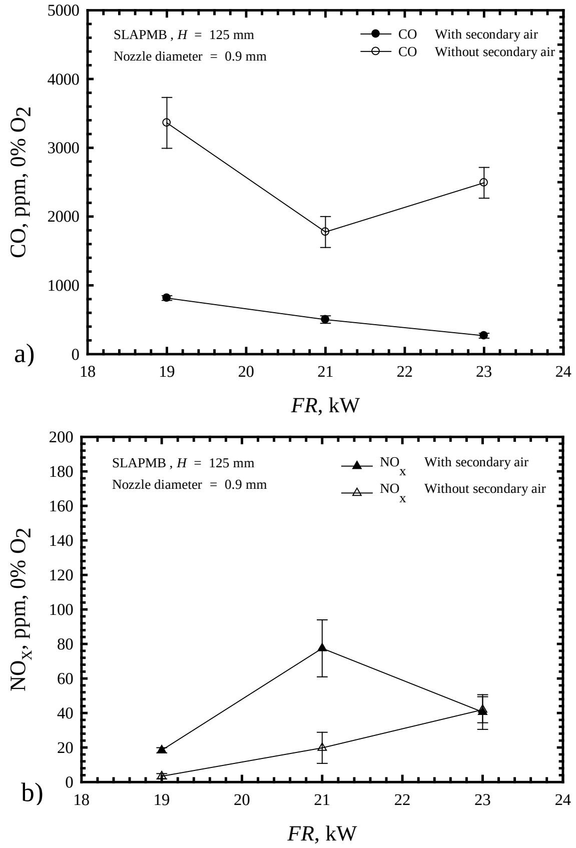


Fig. 7. Effect of firing rate (*FR*) on (a) CO and (b) NO$_x$ emission.

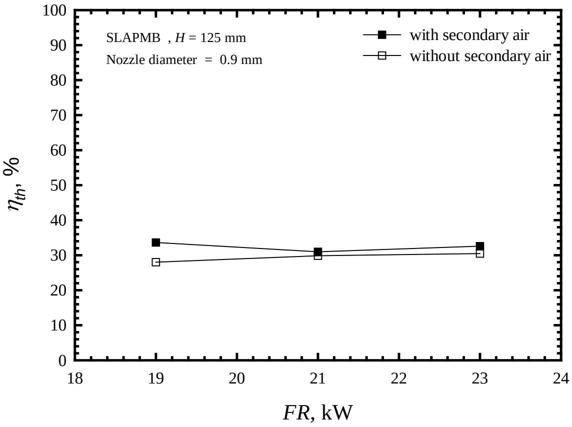


Fig. 8. Thermal efficiency of the SLAPMB.

CO emission decreases as *FR* increases because of more primary air entrainment due to basic nature of self-aspirating burner. The SLAPMB without secondary air emits more CO than the SLAPMB with secondary air because of lack of secondary air. This indicated that the existence of *SA* inlet can significantly reduce CO emission. Fig. 7(b) shows that NO$_x$ emission increases with *FR* and the existence of *SA* because of more complete combustion and higher flame temperature. The SLAPMB provides a lower NO$_x$ emission than the conventional burner (CB) [16] because of the advantage of the porous medium technology that is capable of suppressing the NO$_x$ formation [17].

4.2.4 Thermal efficiency of the SLAPMB

Fig. 8 shows thermal performance of the SLAPMB in terms of thermal efficiency as a function of firing rate (*FR*) and secondary air. Evaluation of the thermal efficiency, η_{th}, was guided by the European standard, i.e. EN203-1:1995[15]. As can be seen, the maximum thermal efficiency of SLAPMB is 33.6% obtained at *FR*= 19 kW and with secondary air. As a firing rate increases the thermal efficiency slightly decreases because of a higher heat loss to surrounding. As compared between SLAPMB with and without secondary air ones found that thermal efficiency with secondary air is higher than without secondary air.

It is clear that the advantage of porous medium and the existence of central secondary air (*SA*) can improve the thermal efficiency of the SLAPMB. This will help reducing LPG demand by the sectors and strengthening energy security of the country.

5. Conclusions

A design and development of a novel self-aspirating liquid fuel annular porous medium burner (SLAPMB) with stabilized flame inside a packed bed is accomplished by operating burner with liquid ethanol. Free flame and impinging flame were studied. From the experimental results, the following conclusions can be obtained.

5.1 For the free flame, transient period of flame stabilization during switching the fuels from the LPG to the ethanol vapor was observed.

5.2 The effect of firing rate was studied and it is very sensitive to the flame stabilization. Relatively high turn down ratio was found.

5.3 For the impinging flame, the central secondary air is very helpful in further enhancing combustion of the post flame at outside the SLAPMB with a decrease in CO emission and flame length.

5.4 Maximum thermal efficiency of about 33.6% can obtained with relatively low CO and NO_x of about 900 ppm and 5 ppm, respectively.

5.5 A problem of fuel decomposition within the vaporizer was not occurred, making this SLAPMB is very practical for industrial application to replace the liquefied petroleum gas (LPG).

6. Acknowledgement

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