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An Experimental Study on Combustion Performance of a Flexible Porous Medium Burner (FPMB)

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Abstract

A new design of Flexible Porous Medium Burner (FPMB) that can be efficiently operated as premixed and non-premixed combustion was studied to understand the effect of combustion mode on temperature profile and emission characteristics (CO and NO_X). The FPMB is a two-layer porous medium burner, i.e. an upstream Porous Burner (PB) and a downstream Porous Emitter (PE). The PB is used as a fuel distributor and a fuel vaporizer, while the PE is used as combustion chamber. Moreover, the PB is movable in a telescopic manner in relation to the fixed PE. The adjustable distance between the PE and PB is defined as X_{PB} (combustion mode controller, i.e., premixed and non-premixed combustion). Mixed fuel (50% Liquefied petroleum gas + LPG + 50% Kerosene by heat input) is supplied directly into the PB, while air is supplied into the air jacket surrounding the PB not only for cooling but also preheating air before combustion with the fuel in the PE. The result shown that for non-premixed combustion, the flame zone not only moves into PE but also enlarger as compared with premixed combustion. The combustion temperature is higher than adiabatic temperature due to the characteristic of porous medium yielding heat recirculating combustion. Moreover, thermal NO_X in the non-premixed combustion mode decreases due to the simultaneously heat of combustion absorbed by PE. CO also decreases due probably to the enlarged reaction zone yielding the oxidation time increases.

***Keywords**:* Two-layer porous medium burner, Premixed combustion, Non-premixed combustion

1. Introduction

Over the past several decades, combustion of fossil fuels has been the most important energy source for industry and household. Rapid depletion of such fuels and widespread concern about global warming have prompted researchers to invent new combustion techniques to improve combustion performance. Weinberg [1] first introduced the idea of heat recirculating combustion by using a heat exchanger to recirculate the heat from combustion product to preheat a fresh mixture in order to generate an excess enthalpy combustion. The benefits of such combustion technique are higher combustion temperature and higher combustion rate compared with conventional combustion. Due to such benefits, lean flammability limit is increased, likewise the lower heating value fuels can be efficiently used as a fuel of the burner using heat recirculating combustion technique.

Combustion within a porous inert medium (PIM) is the most interesting technique to achieve the heat recirculating combustion without heat exchanger requirement. The PIM in combustion zone not only uses for a combustion chamber but also uses for a heat exchanger due to the superior characteristic of the PIM, i.e., high heat transfer rate due to high surface area per volume ratio. Many researchers have achieved to use the PIM with gaseous fuels combustion and found that the combustion within PIM not only yielded a super adiabatic flame temperature but also emitted lower CO and NO_X emissions as compared with conventional burner. The heat of combustion in such combustion process is simultaneously absorbed by the PIM yielding the reduced combustion temperature and hence the suppression of NO_X formation. CO is also suppressed by the increased CO oxidation time caused by the enlarged reaction zone.

Early, the liquid fuels combustion required a large volume of combustion chamber which sufficiently high temperature to support the spray atomization and vaporization respectively. After-ward, a combustion within the PIM have been conducted to use with liquid fuels combustion as both a vaporizer and a combustion chamber to increase vaporization together with combustion performance [2], however, the combustion system still requires a high pressure fuel injector.

Takami et al. [3] achieves to invent a new porous burner for liquid fuel (kerosene) without the requirement of spray atomization, i.e., no requirement of a fuel injector. Such burner is operated by dropping kerosene on the hot PIM (absorbed heat from combustion zone), which is used as a vaporizer. After kerosene is completely vaporized within the PIM, such vapor mixes with the two-ways swirling air and then combustion starts. Their results show that flammability limit extends (0.1-01), turndown ratio increase (above 7.2). Moreover, NO_X emission decreases due to the heat of combustion is rapidly recirculated from combustion product to vaporize kerosene. Such combustion not only increases the combustion performance, but also decrease the requirement of combustion chamber volume. After that, **C**ombustion and **E**ngine **R**e-search **l**aboratory (CERL) has developed a burner using Takami's concept by Jugjai et al. [4-10] since 2002 until present. Recently, P. Toklip [10] develops this type of burner, which can be changed the combustion mode between premixed and non-premixed. The result shows both combustion mode, the combustion temperature is higher than adiabatic flame temperature and CO and NO_X emission decreases when changed the combustion mode from premixed to non-premixed. Moreover, this burner can be used with a fuel up to 3 types, i.e., liquefied petroleum gas (LPG), kerosene and mixed fuel (50% of LPG + 50% of kerosene)

However, the existing burner [10] is still far from using in real application due to the lack of durability caused by melting and thermal expansion problems. This leads to a new design of the Flexible Porous Medium Burner (FPMB), which is proposed to eliminate melting and thermal expansion problems of the existing burner. Moreover, the newly proposed burner is more compact.

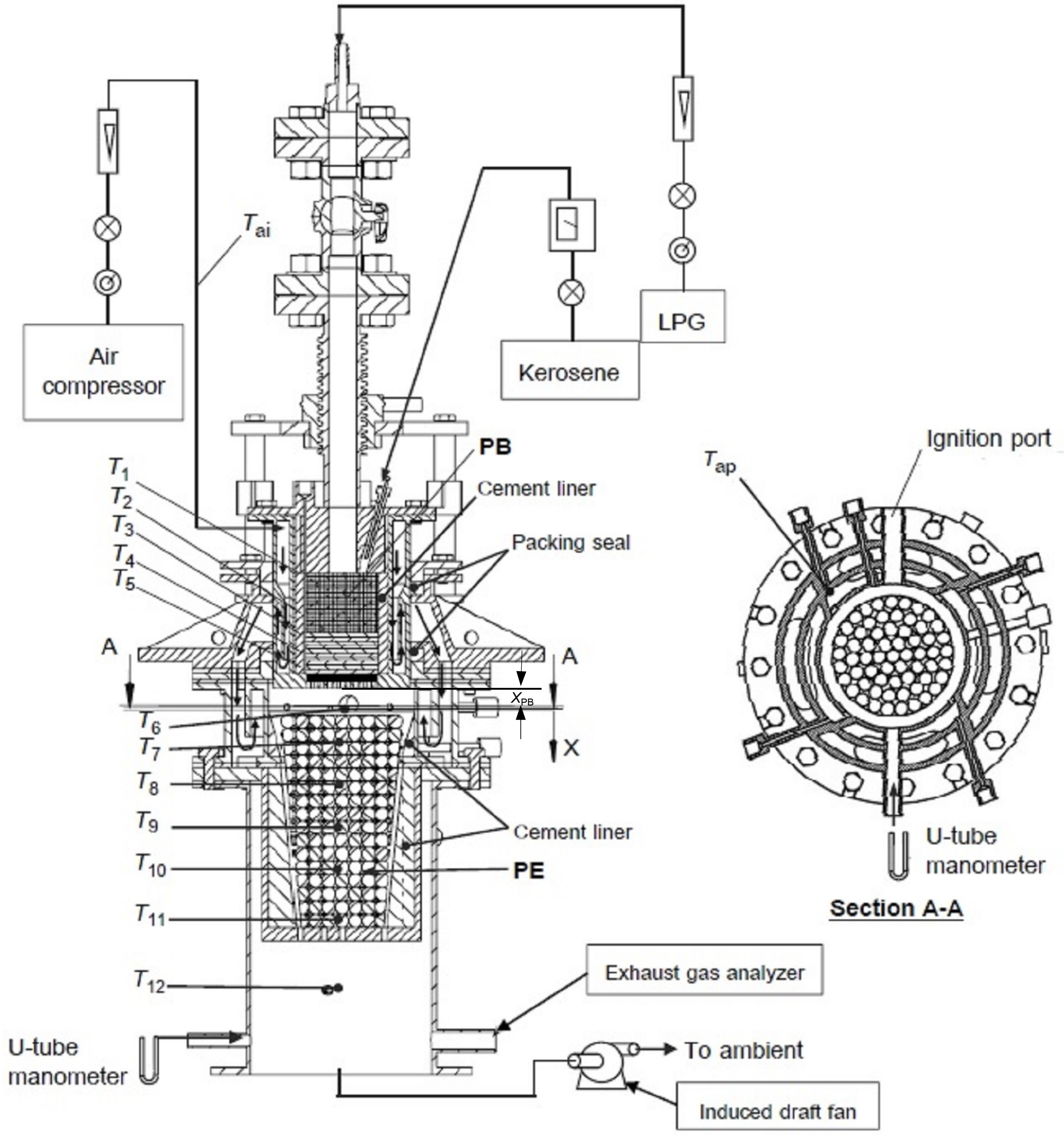

Fig. 1 Schematic diagram of the FPMB

2. Experimental apparatus

Fig. 1 shows a schematic diagram of the FPMB including data acquisition system. The FPMB consists of a two-layer porous burner, i.e., an upstream Porous Burner (PB), mixing chamber and a down-stream Porous Emitter (PE). The PB is made from the 80 mm height stack of 100 mesh/inch, 53 mm diameter stainless mesh. While the PIM packed bed within the PE is

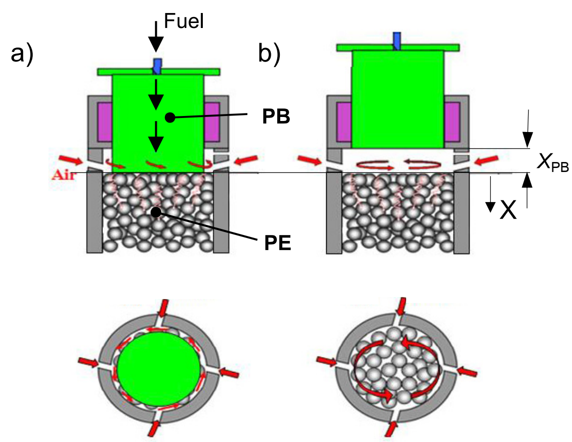

Fig. 2 Air flow characteristics

Nomenclature

FR	Firing rate (kW)	*Subscripts*	
T	Temperature (°C)	ai	Inlet air
x	Axial distance of burner (mm)	ap	preheated air
X_{PB}	Distance (mm)	1-12	Number of thermocouple
Greek symbols		PB	Porous Burner
Φ	Equivalence ratio	PE	Porous Emitter

made from 10 mm diameter alumina balls, which is used as combustion chamber. Moreover, the PB is movable in a telescopic manner in relation to the fixed PE. The distance between the PE and PB is defined as X_{PB} and this serves as a mixing chamber. The combustion mode can be controlled by the telescopic action of the PB. Where the X_{PB} = -20 mm yields the fully opened mixing chamber, air feeding is swirling flow (Fig. 2b), hence the premixed combustion is performed. While the X_{PB} = 0 mm yields the fully closed mixing chamber, combustion air feeding is annular flow (Fig. 2a), hence the combustion mode is non-premixed. Liquefied petroleum gas (LPG) and kerosene are supplied directly into the PB, while air is supplied into the air jacket surrounding the PB to cool the PB temperature down together with preheat combustion air prior to feeding into the mixing chamber with 4 ways tangential swirling flow and then combustion with the fuel in the PE.

The combustion characteristics are determined from the temperature profile and the composition of product gas at the burner exit. In order to know the temperature profiles, the 14 numbers of thermocouple (T_1 to T_{12},) are installed along the burner axis. Such thermocouples are separated into two type, i.e., 0.1 mm diameter N-type thermocouples (T_1 to T_5) and 0.5 diameter B-type thermo-couple (T_5 to T_{12}). T_1 to T_5 are positioned within the PB to study the vaporization mechanism, whereas T_6 to T_{11} and T_{12} are positioned within the PE and the burner exit respectively. These thermocouple are used to study the combustion temperature profile within the combustion zone. Moreover, the additional N-type thermocouples, i.e., T_{ai} and T_{ap} are installed in order to know the air preheating temperature The thermocouple signals are digi-tized by Data Logger model DT-600.

The CO and NO_X emissions is analyzed by the Messtechnik Eheim exhaust gas analyzer model Visit-01L, the measuring range of which is 0–4000 ppm for the NO_X and 0–10,000 ppm with $\pm$5 ppm for CO and resolution of 1 ppm for both NO_X and CO. All measured emissions are reported in 0% excess O_2 and dry-basis.

3. Experimental procedure

The operation of the burner is first started by preheating process using LPG as a fuel with appropriate Φ. The startup condition is X_{PB} = -20 mm and *FR* = 5 kW. The pilot flame (oxy-acetylene burner) is used as an igniter. Then, wait until the PIM within the PB is preheated to the sufficiently high temperature to complete the vaporization process of kerosene. Afterward, kerosene is supplied into the burning system and gradually increases the *FR* to 2.5 kW. together with decrease the *FR* of LPG to 2.5 kW. After the combustion reached the steady state, the variation of Φ (X_{PB} = -20 mm, *FR* = 5 kW) is then started by changing the air flow rate at the air rotameter to find out the flammability limit and the optimum Φ (lowest CO emission), which is used as a fixed parameter of the following variation.

The variation of the combustion mode (represented by X_{PB}) is started with X_{PB} = -20 mm and then gradually increases X_{PB} by 4 mm from -20 mm to 0 mm, while the Φ and *FR* are kept constant. All of the test conditions required a continuously steady state before recording the data.

4. Results and discussions

4.1. Flammability limits and the optimum Φ.

The flammability limits are represented by the range of Φ, which allows the combustion flame stable within the PIM, i.e., stability of CO emission and CO/CO_2 ratio $\leq$ 0.0002 [10]

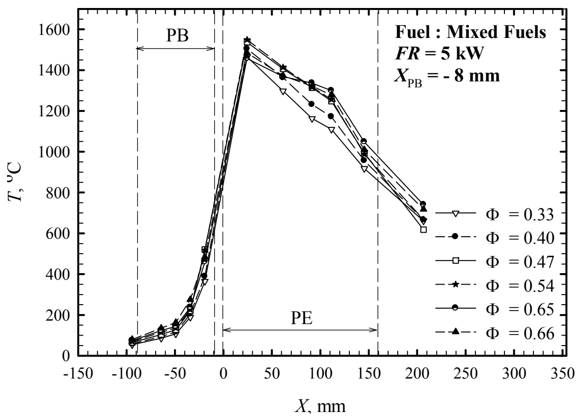

Fig. 3 Influence of Φ on temperature profile

Fig. 3 shows the influence of Φ on the thermal structure in terms of temperature profile along the burner axis using mixed fuel (50% of LPG + 50% of Kerosene, by heat input), which is received from the variation of Φ, whereas *FR* and X_{PB} are fixed, i.e., 5kW and -20 mm respectively. The result shows that when Φ is increased from 0.33 to 0.54, all measured temperatures along the axis of burner increase due to the amount of excess air (a combustion load representative) decreases. In other words, the combustion is closer to stoichiometry combustion. However, when Φ is increased from 0.54 to 0.65, the upstream temperature in the PE decreases, while the downstream temperature increases because the feeding air velocity is decreased, resulting in more mixing time requirement, and hence reaction zone widens.

Fig. 4 shows the influence of Φ on CO and NO_X emissions. The results shows the agreeable trend between CO and NO_X emission, and the temperature profile (Fig. 3). The condition of Φ = 0.40 is optimum due to the lowest CO emission, but at the lowest Φ (i.e., Φ = 0.33), CO increases and NO_X decreases due to the quenching effect. At higher Φ (i.e., Φ = 0.47, 0.54 and 0.65) yields the opposed trend due to poor mixing quality, however, the condition of Φ = 0.66, the CO emission steeply increases and the NO_X emission a little bit increases caused by fuel-rich condition, which generates prompt NO_X. Moreover, the amount of CO and NO_X emitted from burner is unsteady, implying Φ = 0.66 is the upper flammability limit of this burner. However, the lower flammability limit (Φ < 0.33) is still not clarify due to the temperature in the PB is not sufficiently high to complete the kerosene

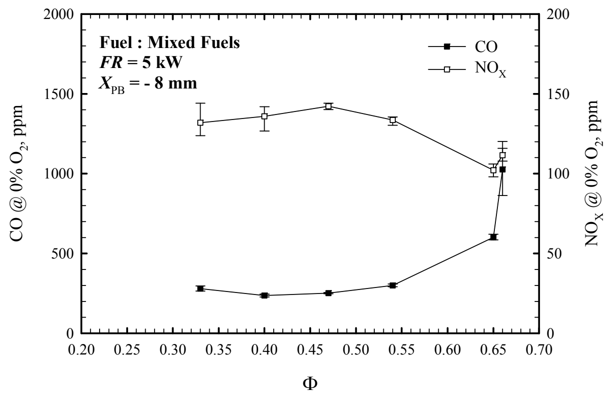

Fig. 4 Influence of Φ on CO and NO_X emissions

vaporization, resulting in unsteady combustion.

4.2. The influence of X_{PB} (combustion mode)

Fig. 5 shows the influence of combustion mode controlled by X_{PB}. The temperature profile within PE and the exit of the burner (T_7 to T_{12}) is lowest at the condition of X_{PB} = -20 mm and becomes higher when the X_{PB} is increased from -20 mm to -4 mm, whereas the temperature profile within the PB (T_1 to T_5) are low. These show the combustion zone is extended when the X_{PB} is increased, because the volume of the mixing chamber is decreased, hence combustion mode is changed from premixed to non-premixed. However, when the X_{PB} is increased to 0 mm, both the temperature profile within the PB and PE are decreased because of poor fuel/air mixing caused by the momentum of air feeding jet is lost to stagnation pressure at PB wall. This assumption is supported by the CO increasing and NO_X decreasing as show in Fig. 6.

Fig. 6 shows the influence of X_{PB} on CO and NO_X emissions. When the X_{PB} is increased, both CO and NO_X emissions decrease. The reduced CO caused by the enlarged reaction zone together with the sufficiently high temperature caused by heat recirculation generated from the PIM. While the reduced NO_X is caused by advantage of PIM, i.e., high surface area per volume ratio, which yields the improved heat transfer rate. The enthalpy from combustion product is instantly absorbed by the PIM yielding the reduced temperature which is the main cause of NO_X production. The optimum X_{PB} of this burner is -4 mm, which yields the lowest CO and NO_X emissions, i.e., 267 ppm and 110 ppm, respectively.

The preheated temperature shown in Fig. 7 also support with the assumption of the reaction zone being extended. The preheated temperature is decreased when the X_{PB} is increased due to

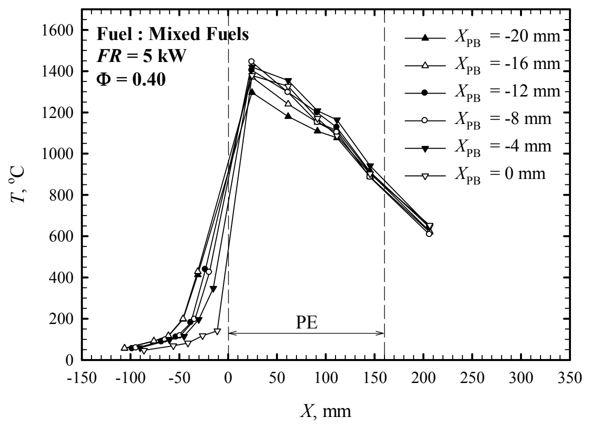

Fig. 5 Influence of X_{PB} on temperature profile

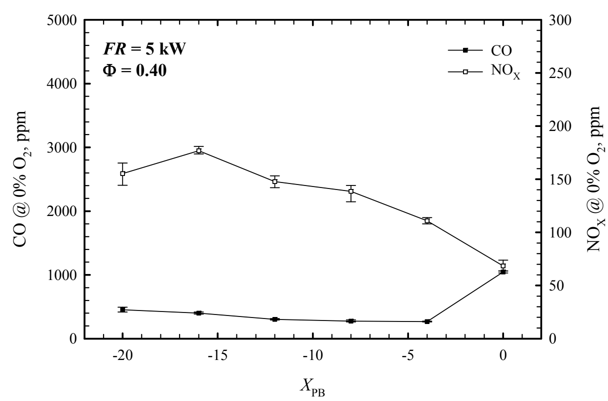

Fig. 6 Influence of X_{PB} on CO and NO_X emissions

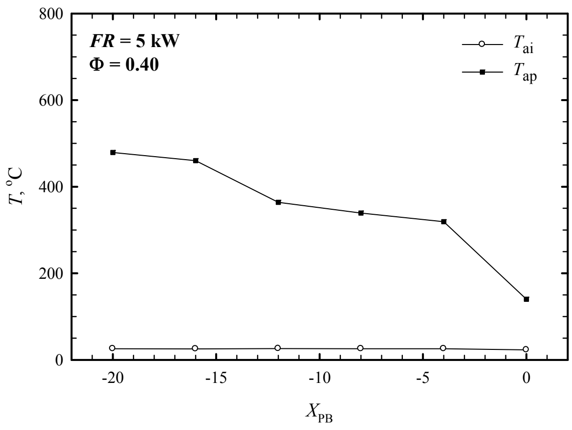

Fig. 7 Influence of X_{PB} on preheated temperature

the reaction zone is distributed to the downstream section, whereas the air jacket of preheater is installed at the upstream section of the burner. At the X_{PB} = 0 mm, the preheated temperature is the lowest due to incomplete combustion. The maximum preheated temperature is 490 °C with the condition of X_{PB} = -20 mm

5. Conclusions

A new design of FPMB can eliminate the thermal expansion and melting problem of the PB occurred in the existing burner efficiently. Moreover, using cooling air not only for cooling but also preheats the combustion air, which the maximum preheated air temperature is about 490 °C. The proposed FPMB is more compact than the existing burner. These shows the burner is practical to be used in the industrial. The FPMB can be used to study the influence of main variable parameters on the performance of the FPMB efficiently. The following conclusions can be drawn from the experimental results:

1. The influence of Φ on the combustion performance is elucidated that the lowest Φ, combustion temperature is relatively low, high CO emission and low NO_X emission, due to quenching effect. While at the highest Φ, combustion temperature, CO and NO_X emission is same as the lowest Φ, due to the fuel/air ratio is poor. At the optimum Φ (high combustion temperature and low CO and NO_X emission) of this burner is 0.4.
2. The influence of X_{PB} (a representative of combustion mode) is elucidated. The temperature profiles show the reaction zone is enlarged when the X_{PB} is increased due to the combustion is changed from premixed to non-premixed. CO and NO_X emissions are relatively low due to the reaction is enlarged with sufficiently high for CO oxidation and the heat of combustion is instantly absorbed by the PIM and emitted to surrounding, which suppress the NO_X formation from high temperature (thermal NO_X).

6. Suggestions

1. The problem of poor fuel/air mixing should be fixed by extending the combustion chamber length or corporating with the porous heat exchanger to use as both combustion chamber and heat exchanger.
2. The mechanism of NO_X formation should be further studies to well understood and for further improvement of low NO_X burner

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