Performance and Reliability of the Flexible Porous Medium Burner (FPMB)

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Abstract

Combustion and Engine Research Laboratory (CERL), King Mongkut's University of Technology Thonburi (KMUTT) has developed the Flexible Porous Medium burner (FPMB) that can burn liquid or gaseous fuel for more than a decade. However, when the FPMB is used to burn liquid fuel (kerosene) or gaseous fuel (Liquefied Petroleum Gas, LPG) for a long time, the stainless steel porous medium is clogged by the black carbonic like deposit affecting the reliability and performance of the burner. Therefore, the thermal decomposition of fuel in the FPMB is studied in order to understand process of blockage. The thermal decomposition of fuel in the FPMB is occurred at high temperature that cause of obstruction. Using the FPMB is necessary to control the temperature within the FPMB between the boiling and thermal decomposition temperature of the liquid fuel. In this research, the FPMB is designed with a cooling system to control the temperature inside the FPMB. Moreover, the fuel outlet port and area of annular flow is modified to improve the mixing of fuel and combustion air. The results show that the new design of FPMB can be operated at a wide range of equivalence ratio (0.4-0.85) without obstruction. The temperatures within the FPMB are lower than the thermal decomposition temperature of fuel. Emission of CO and NO_x are relatively low at 69 and 58 ppm (at 0% O_2), respectively, which are lower than those of the previous experiment.

Keywords*:* Annular flow / Porous Medium Burner / Thermal decomposition

1. Introduction

Porous medium burner is a burner that works on the principle of combustion within a porous inert medium (PIM). The combustion within PIM has many advantages compared with free flame combustion. Firstly, the porous, which has high surface area to volume ratio, enhances the thermal radiation and conduction though the porous matrix. For this reason, the combustion in PIM can provide a regenerative combustion, which has a peak temperature higher than the adiabatic flame temperature so-called 'excess enthalpy flame [1]. Thus, the higher burning speed and combustion intensity together with high radiant output can be achieved [2]. Secondly, the lean flammability limit is extended because of efficient internal energy recirculation. Thirdly, the heat of combustion in PIM was absorbed by porous material, thus, the peak temperature which is the causes of thermal NO_X, was reduced. Furthermore, CO and unburned hydrocarbon emission were also low due to preheating effect and the increased residence time of exhaust gases in a high temperature post combustion region. [3].

From the advantages of the combustion within PIM mentioned, research on the combustion within PIM burner has been the focus by numerous researchers. Earlier, the gaseous fuels were used in the combustion within PIM burner and later the concept of combustion within PIM has been applied to burn liquid fuels. Kaplan and Hall [4] built the liquid

Nomenclature

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

fuel porous ceramic burner and several design configurations were tested. The fuel heptane was impinged on the combustion section using an oil spray nozzle. The burner had an insulated combustion section that was 10 cm in diameter and 2.5 cm thick ceramic plate. Stable complete combustion was achieved at equivalence ratios of 0.57-0.67. Very low emissions of both CO and NO_X were measured and corrected for 3% oxygen; CO varied from 3 to 7 ppm and NO_X varied from 15 to 20 ppm. However, the combustion system still requires a high-pressure fuel injector.

Takami et al. [5] developed the porous ceramic burner using liquid fuels (kerosene) dropwise (instead of in droplet spray) to the top surface of the porous ceramic plate and ignited on the bottom surface. Their results show that flammability limit extended (0.1-1), turndown ratio increases (above 7.2). Based on the work of Takami et al[5] Jugjai et al. [6-11] have developed the burner, which can be changed the combustion mode between premixed and non-premixed combustion. Moreover, the burner can be used with liquefied petroleum gas (LPG), kerosene and mixed fuel (50% of LPG + 50% of kerosene by energy content)

Homraruen A. and Jugjai S.[12] designed the Flexible Porous Medium Burner(FPMB) that was a two-layer porous medium burner, i.e. an upstream Porous Burner (PB) and a downstream Porous Emitter (PE). The PB was used as a fuel distributor and a fuel vaporizer, while the PE was used as combustion chamber. Moreover, the PB was movable in a telescopic manner in relation to the fixed PE. The adjustable distance between PE and PB was defined as X_{PB} (combustion mode controller, i.e., premixed and non-premixed combustion). The result shown that for non-premixed combustion, the flame zone not only moves into PE but also enlarger as compared with premixed combustion. In addition, a new design of FPMB can efficiently eliminate the thermal expansion and melting problem of the PB that occurred in the past.

However, when the FPMB [12] was continuously operated for a long time, the stainless steel wire mesh porous within the PB was clogged by the black carbonic like deposit affecting the reliability and performance of the burner (Fig 1). In this research, the thermal decomposition of fuel in PB is studied and PB is integrated with a cooling system to control the temperature inside the PB. Moreover, the fuel outlet port and area of annular flow is modified to improve the mixing of fuel and combustion air. The temperature profile and the emission are compared with the previous work [12].

Fig. 1.The clogging of fuel outlet (left)
and stainless steel wire mesh(right) [12].

2. Thermal decomposition of fuel

Thermal decomposition is a chemical reaction in which a compound decomposes under the influence of heat into at least two other products. The decomposition of petroleum is induced by elevated temperature (>350°C) [13]. The FPMB works in combination with radiation of PE to aid the evaporation of liquid fuels in PB. The porous material provides the thermal radiation from the PE to PB as a result the temperature in PB higher than thermal decomposition temperature of hydrocarbon. From the Homraruen A. and Jugjai S. [12] experiments, temperature inside PB is higher than 350°C, thus, the stainless steel wire mesh porous and the fuel outlet port are inevitably clogged because of the thermal decomposition of hydrocarbon.

3. Burner design

Fig.2. shows the PB with a cooling system to eliminate the clogging problem of the PB. It is modified by adding a cooling pocket with swirling air flow inside the bottom of the PB to control the temperature inside PB and fuel outlet. Moreover, the fuel outlet port and area of annular flow are also modified to improve the mixing of fuel and combustion air.

4. Experimental apparatus and procedure

Fig. 3 shows a schematic diagram of the FPMB including data acquisition systems, which are the same as the previous work [12]. The FPMB consists of three sections, an upstream Porous Burner (PB), a mixing chamber and a down-stream Porous Emitter(PE).

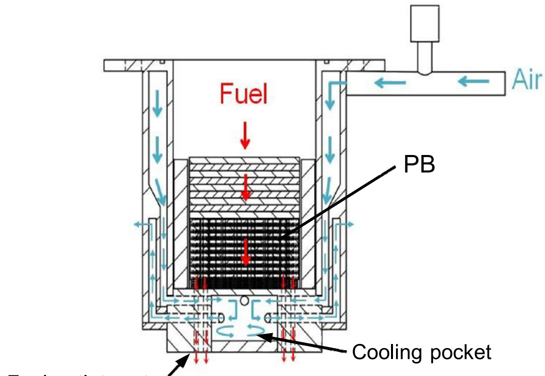

Fig. 2. Cooling system in PB.

The PB is made from the 60 mm height stack of 100 mesh/inch and 53 mm diameter stainless wire mesh. The PIM packed bed within the PE is made from 10 mm diameter of alumina balls which has 160 mm of length. The distance between PE and PB is called as X_{PB} (Fig.4). The combustion mode can be controlled by the telescopic action of the PB as shown in Fig.4. At X_{PB} = 0 mm yields the fully closed mixing chamber, and combustion air feeding was annular flow (Fig. 4a), hence the combustion mode was non-premixed. At X_{PB} = -20 mm, however, yields the fully opened mixing chamber, and air feeding was swirling flow (Fig. 4b), hence the premixed combustion was performed.

Liquefied petroleum gas (LPG) and kerosene were supplied directly into the PB from above (Fig.2.). The combustion air, however, was supplied into the air jacket surrounding the PB and flow into the cooling pocket at the bottom of the PB to reduce the temperature in PB. Then combustion air is fed into the mixing chamber through 4 ways tangential swirling flow outlet (Fig.3.).

The combustion characteristics were determined from the temperature profiles within PB and PE and the composition of product gas at the FPMB exit. Induced draft fan was used to assist a down flow of the burner. The temperature measurement was done by using 14 thermocouples (T_1 to T_{12}) installed along the burner axis. The 0.1 mm diameter N-type sheath thermocouples were positioned within the PB to study the temperature inside stainless steel porous (i,e.,T_1

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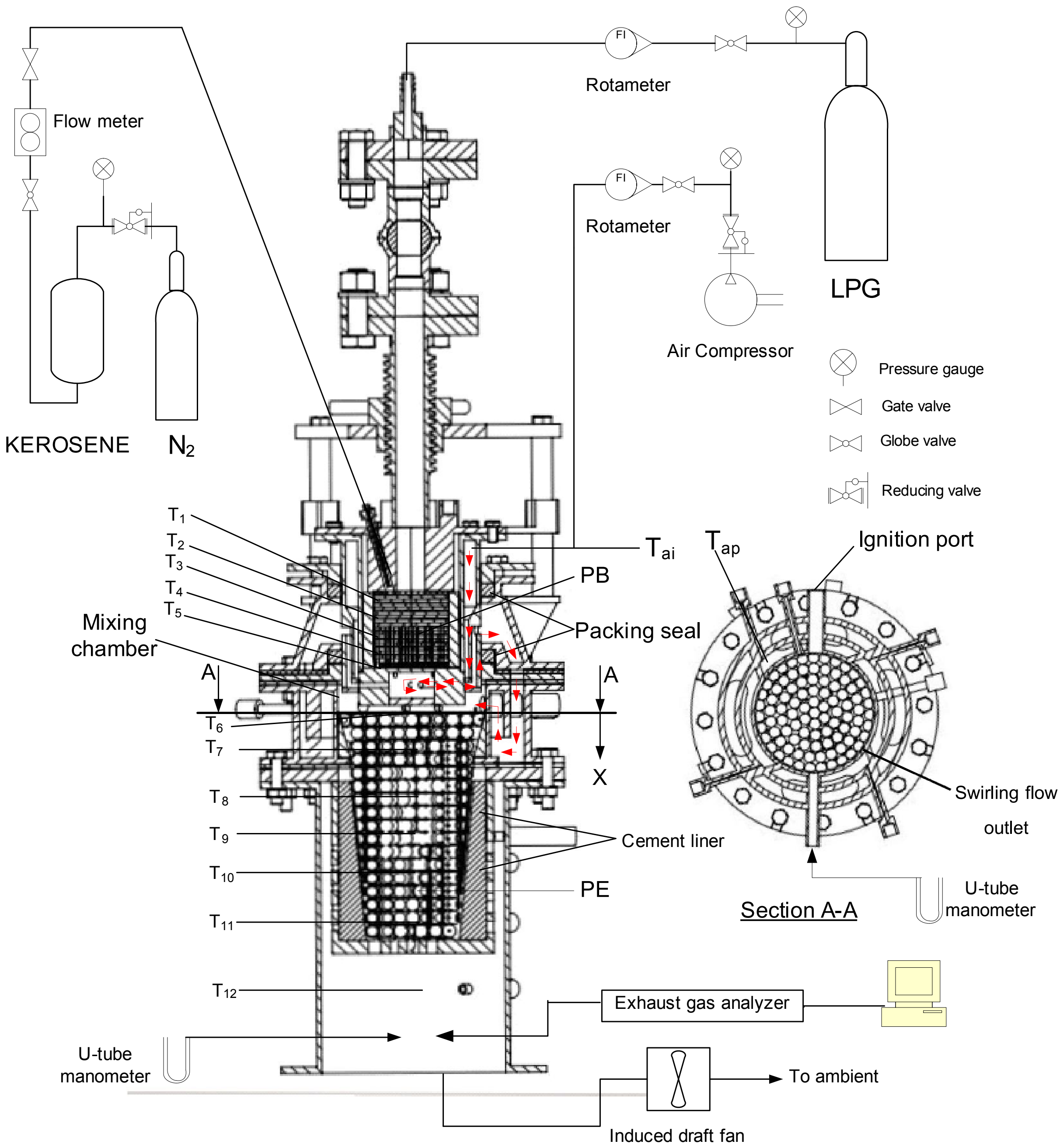

Fig. 3. Schematic diagram of the FPMB.

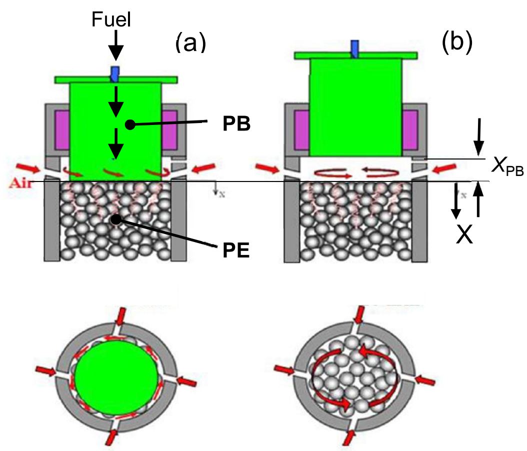

Fig. 4. Combustion mode control; (a) non-premixed and (b) premixed combustion.

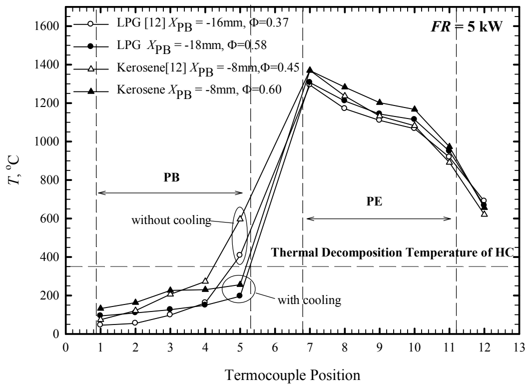

Fig. 5. Comparison of the temperature profile with and without [12] cooling.

to T_5). The 0.5 diameter B-type bare thermocouple were positioned within the PE and the burner exit to study the combustion temperature profile within the combustion zone (i,e.,T_6 to T_{12}). Moreover, two N-type sheath thermocouples were installed at the inlet and after preheated of combustion air (T_{ai} and T_{ap}), in order to know the air preheating temperature. The thermocouple signals were recorded by Data Logger model DT-600.

The CO and NO_X emissions were analyzed by the Messtechnik Eheim exhaust gas analyzer model Visit-01L, the measuring range of which was 0–4000 ppm for the NO_X and 0–10,000 ppm for the CO with measuring accuracy of about ±5 ppm and resolution of 1 ppm for both NO_X and CO. All measured emissions were reported at 0% excess O_2 and dry-basis.

The operation of the burner was started first using LPG as a fuel before switching to liquid kerosene when necessary to do so. The startup condition is X_{PB} = -20 mm Φ = 0.6 and FR = 5 kW. The pilot flame (oxy-acetylene burner) was used as an igniter by inserting it through the ignition port. Then the X_{PB} was increased from -20 to 0 to obtain a non-premixed combustion mode. After steady state combustion is reached, the variation of Φ was started by changing the airflow rate to find out the flammability limit and the optimum Φ (lowest CO

Fig. 6. PB and stainless steel wire mesh with cooling system.

emission) at constant FR. The variation of the combustion mode (represented by X_{PB}) was started with a non-premixed combustion (X_{PB} = 0 mm) and then switch to a premixed combustion by gradually decreases X_{PB} by 2 mm from 0 mm to -18 mm, while the Φ and FR are kept constant. The same experiment procedure was repeated with kerosene as a liquid fuel. All of the combustion required a continuously steady condition before recording the data.

5. Results and discussions

5.1 PB temperature

Fig. 5 shows the temperature profiles inside the burner with and without the cooling system using LPG and kerosene as fuels at the same X_{PB}. The temperature inside PE (T_7-T_{11}) of the two cases are similar but the temperature inside PB especially T_5 of PB with cooling (190-250 °C) is lower than without cooling (400-600 °C) due to cooling effect of the air. In addition, the temperatures inside PB are below the thermal decomposition temperature of HC (350 °C). The kerosene, however, can still be evaporated completely within PB. Therefore, the new design of PB can eliminate the clogging problem of PB (stainless steel mesh and fuel outlet) and can be operated with gases and liquid fuel.

Fig 6 shows the clean fuel outlet and stainless steel wire mesh of the PB with cooling system after

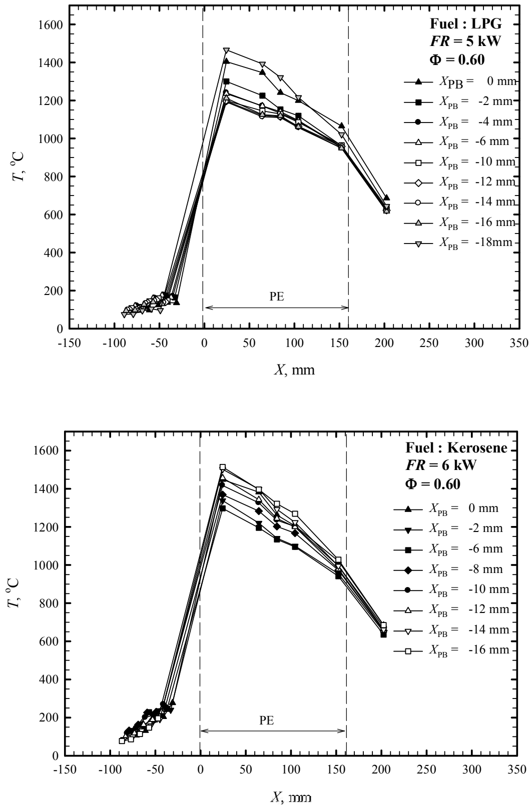

Fig. 7. Influence of X_{PB} on temperature profiles with LPG(top) and kerosene(bottom) as fuels.

24 hours of operation. No clogging of carbon deposit is not observed.

5.2. Combustion mode

Fig. 7 shows the influence of combustion mode controlled by X_{PB} on the temperature profiles using LPG (top) at FR=5 kW, Φ=0.60 and kerosene(bottom) at FR=6 kW, Φ=0.60. The reduction of the X_{PB} form 0 to -18 causes the temperature profiles and the maximum temperature (T_{max}) within PE decrease initially before increase again to almost the same value when X_{PB} = -18 mm and the same trend for both fuels as seen from Fig. 8, which shows the corresponding T_{max},T_{ap},T_{ai} of Fig.7. According to the theory, T_{max} at X_{PB} = -18 and 0 mm should be the same regardless of the combustion mode (Fig.8). It is clear that the burner can be operated both premixed and non-premixed mode while T_{max} is almost the same.

The preheated temperature (T_{ap}) shown in Fig. 8 is slightly varied between 400 – 500 °C when X_{PB}

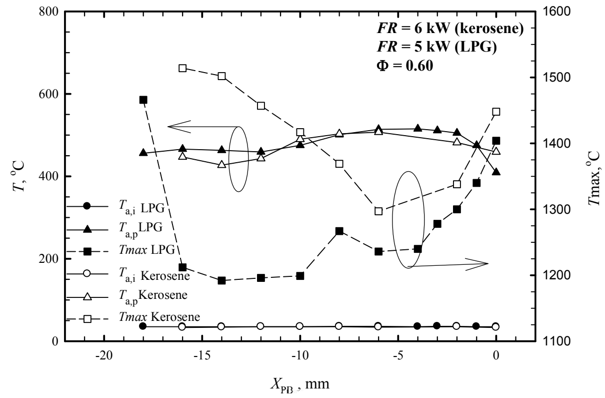

Fig. 8. Influence of X_{PB} on air temperature and T_{max}.

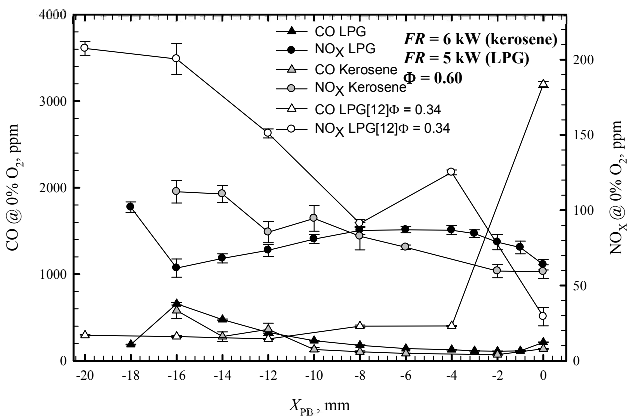

Fig. 9. Influence of X_{PB} on CO and NO_X emissions.

decreased; due to the temperature profiles of each X_{PB} are similar. However, at the X_{PB}=0 mm, T_{ap} is the lowest due probably to flame movement to the downstream. The maximum preheated temperature is 515 °C which occurs at X_{PB}=-4 mm.

Fig. 9. shows the corresponding CO and NO_X emissions as X_{PB} varied. When X_{PB} decreased from X_{PB}=0 mm CO increased, which is the same for both fuels. The CO is increased because of poor mixing of combustion air and fuel within the gap between PB and PE. This is supported by the initial decrease in T_{max} as X_{PB} decreases (Fig.8). At X_{PB}= -18 and 0 mm, as using LPG as fuel the CO emission are almost the same because the gap between PB and PE is large enough for good mixing and the complete combustion take place at X_{PB}=-18. At X_{PB}=0 mm the CO is reduced due probably to improvement in mixing of the fuel and air caused by the presence of the PE which acts as a turbulence promoter.

NO_X emission at X_{PB} =0(non-premixed mode) is significantly reduced by 37% and 47% for using LPG and kerosene as a fuel, respectively, when compare to at X_{PB}=-18(premixed mode). This may be explained by two reasons. Firstly, the maximum combustion temperature is reduced because the radiation losses in the combustion zone within the porous matrix of the PE and in the post-combustion zone within the PE where the concentrations of CO_2 and H_2O are produced play an important role in quenching the combustion gas. Thus, thermal NO_X and prompt NO_X could be reduced when the combustion temperature is reduced [9]. Secondly, the reduction of NO_X emission may be caused by the effect of a continuous staged combustion in the PE [9]. The continuous staged combustion can be established within the PE because the combustion air is continuously fed through the annular flow area (Fig.4.(a)). The annular combustion air flow is parallel mixed with the fuel flowing in the inner core of PE. The lean/rich or rich/lean combustion can take place. The combustion does not occur at stoichiometry which has high NO_X emission. Ones can clearly see that the non-premixed combustion mode within the porous medium is a good strategy to control the emission in the burner. The lowest CO and NO_X emissions are 69 ppm and 58 ppm, respectively as using kerosene as fuel. In comparison with previous experiments [12], the new design burner has lower emission especially at X_{PB} = 0, the CO emission decreased about 93% due to improvement in mixing of combustion air and fuel.

6. Conclusions

The cause of the obstruction in stainless steel mesh and fuel outlet of PB is the high temperature, in which, the thermal decomposition reaction take place at 350°C. A new design of PB with a cooling system can eliminate the clogging problem at stainless steel mesh and fuel outlet of the PB. Moreover, this can improve the performance and reliability of porous burner. By using the combustion air for cooling at the bottom of PE the combustion air is also preheated with the maximum preheated air temperature of about 515°C. The effect of the combustion mode on the burner performance has been investigated as temperature profiles of the premixed and the non-premixed mode are almost identical. CO and NO_X emissions however, are low at non-premixed combustion mode.

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