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# Reliability Improvement and Optimization of Condensing Porous Heat Exchanger (CPHE) integrated with Porous Medium Burner (PMB)

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***Abstract***

Improvement of porous medium burner (PMB) reliability and optimization of condensing porous heat exchanger (CPHE) performance were carried out. To improve durability and reliability of the PMB, combustion air was supplied laterally to cool down the burner head (porous burner, PB) in order to avoid thermal decomposition of fuel. Simultaneously, both air and fuel were preheated prior to combust inside the combustor (porous emitter, PE). The exit port of PMB was webbed with the ceramic sticks which have relatively high thermal resistance. The CPHE is a shell-and-tube heat exchanger, in which, the alumina balls with diameter of 15 mm. were fully filled inside the shell. Parametric study was carried out to optimize performance of the CPHE, which works by integrated with the PMB. Firing rate (*FR*) was varied from 5 kW to 20 kW of Liquefied petroleum gas (LPG). Flame stability limit was also investigated by varying fuel equivalence ratio ($\Phi$), emission of CO and $NO_x$ were measured. It was found that flame ability limit extended to relatively leaner condition compared to the conventional combustion limit of LPG. The CPHE integrated with PMB can be operated at $\Phi$ varied from 0.3 to 0.69 without thermal decomposition of fuel, even though the maximum temperature is as high as 1,650 $^{O}$C. The emissions of CO and $NO_x$ are lower than 100 ppm at 0% $O_2$ excess condition. Advantage of the porous media filled inside the heat exchanger is not only used to enhance heat transfer but also help enhance combustion due to heat recirculation within the packed of alumina ball. Therefore, near zero emission of CO was observed for wide range of operation. The optimum condition was achieved at FR of 15 kW and $\Phi$ of 0.5, in which, the outlet temperature of water at mass flow rate of 4.9 LPM. is 61 $^{O}$C. The corresponding thermal efficiency and effectiveness are 65.79% and 0.98, respectively. Condensation of water vapor in the products can be achieved, while the exit temperature of the exhaust was lower than 50 $^{O}$C.

***Keywords***: Porous medium burner; condensing heat exchanger; porous heat exchanger; air cooling system.

## 1. Introduction

Due to a fast-rise in world energy consumption today, driven by growth in developing countries, and the corresponding impact on environment, i.e. global warming problem caused by the release of Greenhouse Gases (GHGs), which is currently getting worldwide attention, intensively fundamental and applied research on advanced combustion technologies to increase efficiency or reduce energy (especially, derived from fossil fuel) consumption and minimize pollutants emission are needed. Concepts for combustion and waste heat recovery systems are considered for either heating or cooling appliances such as gas burner, boiler, combustor, and etc., and for saving in industry, heat exchanger is used. For heating propose, an exhaust gas heat exchanger, transferring heat generated by hot exhaust gases to the heating system, is widely used.

Among various technologies to improve combustion, heat recirculation combustion using a porous medium technology is extensively proposed. A porous medium has been applied for improving burner efficiency because of its self-heating recirculating recovery from exhaust gas to fresh reactant, resulting in a higher combustion temperature than an adiabatic one [1]. Both combustion and radiation intensities are significantly increased along with the flammability limit [2, 3]. Barra and Ellzey [4] numerically studied heat recirculation within a porous medium wherein a premixed combustion of gaseous fuel occurred. The combustion characteristics such as flame speed ratio, energy recirculation efficiency, preheat and reaction zones were defined. Porous medium burner has been developed to combust low calorific value fuels, e.g. lean premixed combustion of $H_2/CO$ mixtures has been investigated [5]. Moreover, porous media reformer has also been developed for reformation of methane [6-7]. The results showed that a large turndown ratio of the reformer and burning rate ratios greater than unity. Jugjai and co-workers have carried out experimental work on combustion within porous medium, both gaseous and liquid fuels without spray can be burned [8-10]. Recently, Homraruen and Jugjai [11] proposed the Flexible Porous Medium Burner (FPMB). A two layers porous medium burner was constructed, i.e. it is composed of a porous burner (PB) and a porous emitter (PE). The PB was used as a fuel distributor and a fuel vaporizer, while the PE was used as combustion chamber. The burner can be operated both in premixed and non-premixed combustion without problem of flame stabilization and pollutants emission. However, it was found that the porous was clogged by the black carbonic like deposit due to thermal decomposition of fuel when the burner was used for a long period of time, which is effecting on the reliability and performance of the burner. 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) [12].

In the present work, porous medium burner (PMB) is designed with cooling system to control the temperature inside the burner. Moreover, the fuel outlet port and area of annular flow is modified to improve the mixing of fuel and combustion air. By the advantages the porous medium can be both a combustor and a heat exchanger, the PMB will be applied to be used as heat source producing high temperature exhaust gases to heating device, i.e., by integrated PMB with condensing porous heat exchanger (CPHE). The CPHE is a shell-and-tube heat exchanger, which was filled with the packed bed of alumina balls to enhance heat transfer. Parametric study was carried out to optimize performance of the CPHE integrated with PMB. Effect of firing rate and water flow rate were investigated. Flame stability limit was also investigated by varying fuel equivalence ratio ($\Phi$), emission of CO and $NO_X$ were measured.

## 2. Experimental devices

In this work, the device is a composed of a porous burner (PMB) and porous heat exchanger (CPHE). The PMB was applied to produce heat source, i.e., high temperature exhaust gases (hot fluid), transferring heat to cold fluid (i.e. water) through the CPHE. Detailed designs and operating procedures are described in the following sections.

### 2.1 Porous medium burner (PMB)

The PMB ( Fig. 1) consists of three sections, an upstream porous burner (PB), a mixing chamber and a down-stream porous emitter (PE). The PB is made from the 60 mm height stack of 100 mesh/inch and 53 mm diameter stainless wire mesh. The PE section is 160 mm long and filled with aluminium balls with a diameter of 10 mm.

To improve durability and reliability, combustion air was supplied laterally (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 in order to avoid thermal decomposition of fuel. Simultaneously, both air and fuel were preheated prior to combust inside the combustor (PE) where the preheated combustion air is fed through 4 ways tangential swirling flow outlet. While, the fuel (liquefied petroleum gas, LPG) was supplied directly into the PB from above (Fig.1). The exit port of PMB was webbed with the ceramic sticks which have relatively high thermal resistance (improvement of Sompu et al. 2015 [13]). By these novel design, clogging inside PMB with the black carbonic like deposit was not occurred. Detailed description of this burner was given in Sompu et al. [13]

### 2.2 Condensing porous heat exchanger (CPHE)

Structure of the CPHE is shown in Fig. 2. CPHE is a shell-and-tube heat exchanger, which was filled by a packed of alumina balls with a diameter of 15 mm. (not shown) inside a lower housing part of the shell outer tube bank. The shell or housing was divided into three parts, i.e., upper housing water jacket as inlet of cold water, and then exits to flow laterally a lower housing, before flowing through a tube bank as the final step of heat exchange between cold fluid (i.e., water ) and hot fluid (i.e., combustion gases).

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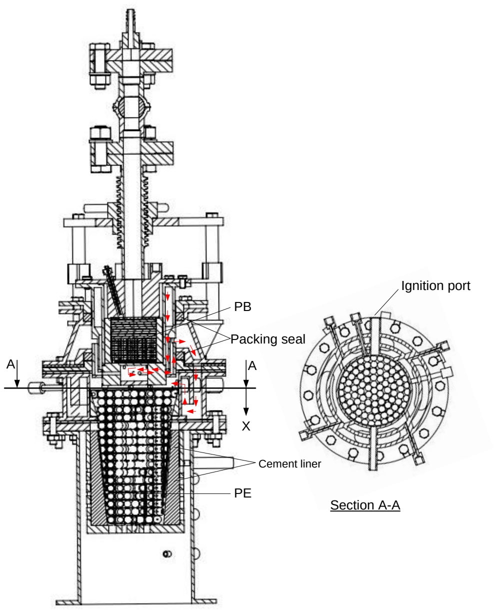



Fig.1 Porous Medium Burner (PMB).

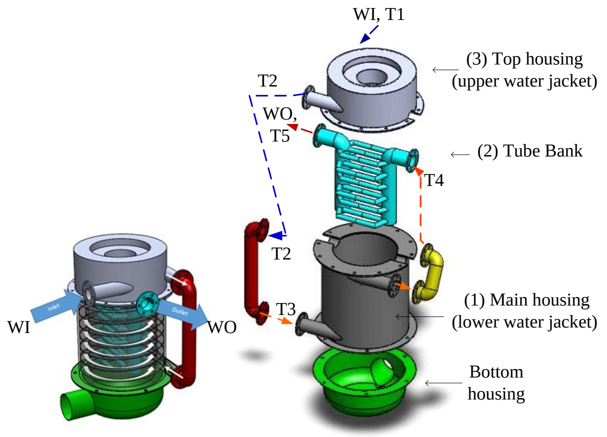



Fig.2. Condensing porous heat exchanger (CPHE).

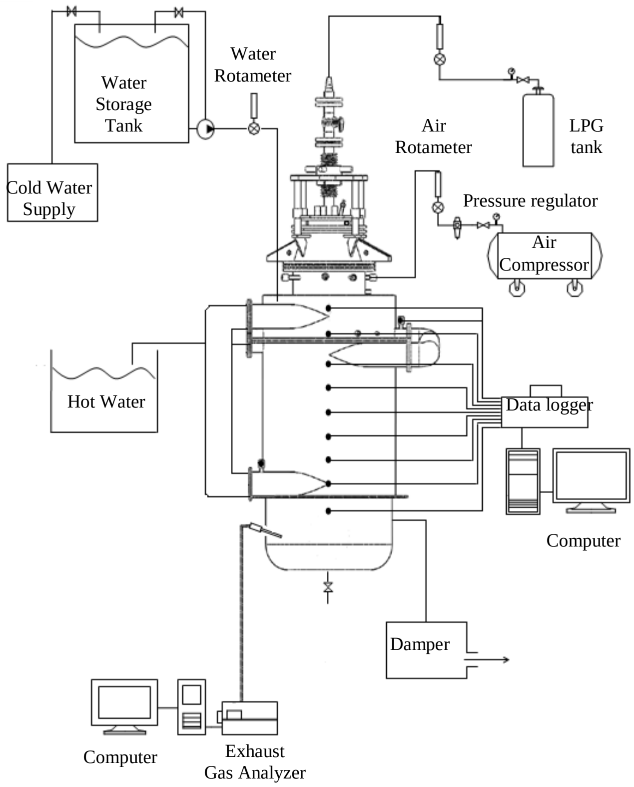



Fig.3 Schematic diagram of experimental set up of CPHE integrated with PMB.

The tube bank was staggered arrangement of six rows comprising an inside diameter (ID) of 9 mm and length (L) of 145 mm of the total 21 tubes, embedded inside a lower housing part.

### 3. Experimental Method

Fig.3 shows schematic diagram of experimental set up. The apparatus consists of three main parts: fuel, air and water supply system, data acquisition system and CPHE which works by integrated with PMB. Parametric study was carried out to optimize performances of the CPHE integrated with the PMB. Combustion takes place inside PMB, a combustor that produces heat for heating cold liquid flowing through tube bank inside heat exchanger CPHE. Combustion air and LPG are separately supplied into the PB. Air was supplied laterally into the air jacket surrounding the PB using an air compressor, while the LPG (composed of 60% v propane, 40% v butane; 49,840 kJ/ kg) was supplied directly into the PB from above. Gas and air flow rates were measured by calibrated rotameters. Firing rate (*FR*) was varied from 5 kW to 20 kW of Liquefied petroleum gas (LPG), and it was determined using high heating value (*HHV*) of fuel as show in Eq. (1).

$$□□ = \dot{□}_{□□□□} \times □□□ \quad (1)$$

where $\dot{□}_{□□□□}$ is the mass flow rate of fuel (i.e. LPG).

Flame stability limit was also investigated by varying fuel equivalence ratio (*Φ*), emission of CO and $NO_x$ were measured.

Temperatures of combustion gas were measured along the centerline of PMB and CPHE by using B-type thermocouples with measuring range of 400 to 1,700 ± 1 $^{O}$C (inside the burner) and N-type thermocouples (inside the heat exchanger), with measuring range of 0 to 1,260 ± 2.2 $^{O}$C, In addition, the inlet and outlet water temperatures for the top housing or the upper jacket (T1-T2), lower jacket or main housing (T2-T3), the tube bank (T4-T5), and flow path of water were also measured by using N-type thermocouples. Their signals are digitized by a general-purpose DT 600 Data logger, and then are transmitted to a computer. Pump of water supply system was used to ensure that the water is fully flowing through the cross-sectional area of heat exchanger. The water flow rate ($\dot{□}_{□}$) was measured by calibrated rotameter. The Messtechnik Eheim model Visit01L which is a portable emission analyzer designed especially for quasi-continuous measurement was used to analyze the emission of the dry combustion products at the exit of the CPHE. The measuring range is 0–4000 ppm for $NO_X$ and 0 – 10,000 ppm for CO with the accuracy of about ±5 ppm and the resolution of 1 ppm for both $NO_X$ and CO. All measured emissions in the experiment are corrected to 0% excess oxygen and dry-basis.

Performances of the CPHE in terms of thermal efficiency and effectiveness are reported as function of $\dot{□}_{□}$. The thermal efficiency is the ratio of the rate of heat absorbed by the water flowing in each part of the CPHE to the firing rate (*FR*), while the effectiveness is defined as the fraction of the actual heat transfer rate to the maximum possible heat transfer rate that can be given in Eq. (2).

$$□ = \frac{□_{□□□□□□}}{□_{□□□}} = \frac{□_{□}(□_{□,□} - □_{□,□})}{□_{□□□}(□_{□,□} - □_{□,□})} \quad (2)$$

where $□_{□} = \dot{□}_{□}□_{□,□}$ is heat capacity rate of hot fluid and $□_{□□□}$ is minimum heat capacity rate of fluid (hot fluid).

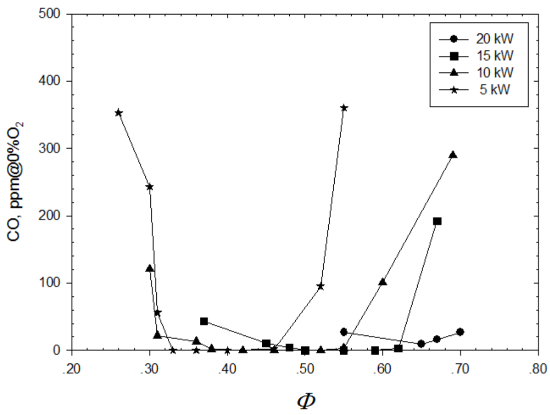
## 4. Results and discussion

### 4.1 Combustion performance of CPHE integrated PMB

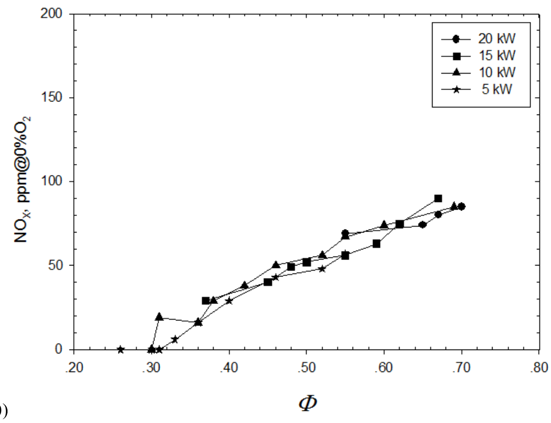
Fig.4 shows combustion performance of the CPHE integrated with PMB via a variation of CO and $NO_X$ emission by the effect of fuel equivalence ratio at the given firing rate varied from 5 kW to 20 kW. It was found that at any given firing rate, CO emission is varied as U-curve by varying Φ from lean to rich condition (see Fig.4a).

Increasing *FR* will extend operating fuel equivalence ratio, i.e., wider range of low CO emission can be obtained. Moreover, when increasing *FR* from 5 kW to 20 kW, the U-curve of CO emission shifts from fuel leaner to fuel richer side, i.e., and vice versa. However, varying of firing rate does not much effect on $NO_X$ emission (see Fig. 4b), while it was increased with increasing equivalence ratio.

These figures present wide range of equivalence ratio varied from 0.3 to 0.7 can be operated by this burner with very low emissions of CO and $NO_X$.




a)




b)

Fig.4. Effect of equivalence ratio on CO and $NO_X$ emissions at the given firing rate.

It is found that flame ability limit extended to relatively leaner condition compared to the conventional combustion limit of LPG, which shows the possibility of using this burner to burn low calorific value fuels.

### 4.2 Effect of firing rate (*FR*)

Fig.5 shows temperatures inside the PMB integrated CPHE. Temperatures of preheated air, combustion inside the combustor PE, and exhaust gases flow through the heat exchanger CPHE are revealed. Increasing *FR* will increase the temperatures along the burner and heat exchanger and the exhaust gases at exit

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of the appliance. The peak temperature reaches 1,600 $^{O}$C at firing rate of 15 kW, then steeply decrease along the heat exchanger due to high rate of heat transfer occurring inside the CPHE. The exhaust temperature exit with very low temperature, i.e., lower than 100$^{O}$C. Fig.6 shows temperature of water (cold fluid) flowing through the heat exchanger CPHE at constant water flow rate ($\dot{m}_w$) of 9.5 LPM. Temperatures of water continuously increase, step-by-step from the inlet at the top housing, the lower housing, and the outlet of tube bank. Increasing *FR* will increase water temperature owing to higher of heat input.

### 4.4 Effect of water flow rate ($\dot{m}_w$)

Fig.7 shows effect of water flow rate, $\dot{m}_w$, on water temperature, while firing rate was fixed at *FR*= 15 kW. It was found that water temperature decrease with increasing $\dot{m}_w$, because larger amount of cold fluid to absorb heat from the exhaust gases.

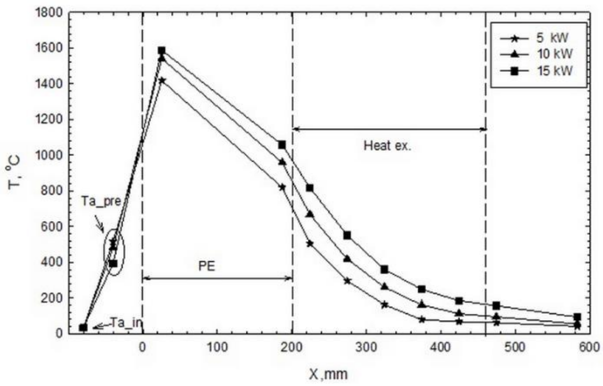


Fig.5 Effect of *FR* on gas temperature at $\Phi$ of 0.5.

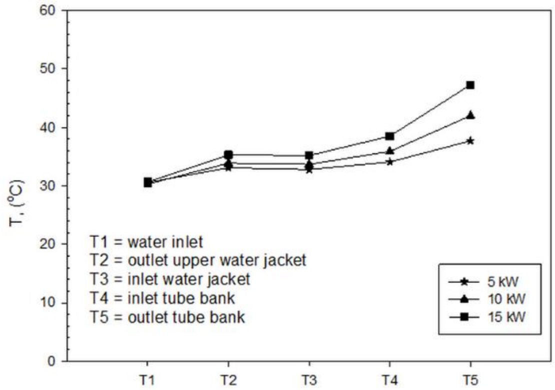


Fig.6 Effect of *FR* on water temperature at $\Phi$ of 0.5, and $\dot{m}_w$ of 9.5 LPM.

However, as determining performances of the device in terms of thermal efficiency and effectiveness (as shown in Fig.8), increasing water flow rate results to an increase in effectiveness, while thermal efficiency increase with increasing $\dot{m}_w$ till 12 LPM reaching the maximum thermal efficiency of 72%, then decreasing as $\dot{m}_w$ further increased, this might be due to strongly decrease in residence time of heat transfer. However, by using this device, CPHE integrated with PMB, the outlet water temperature of the maximum 61$^{O}$C at water flow rate of 4.9 LPM can be obtained, while a variation of water flow rate does not affects the emissions of CO and $NO_X$ (see Fig.9).

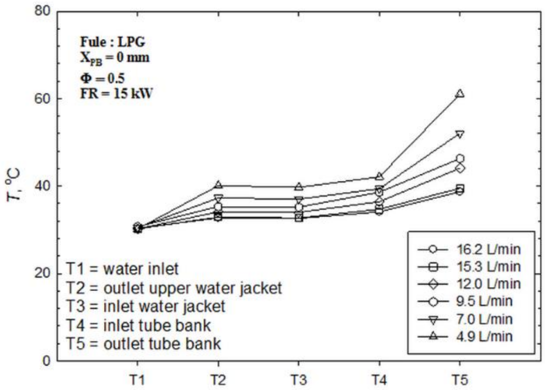


Fig.7 Effect of $\dot{m}_w$ on water temperature at *FR* of 15 kW.

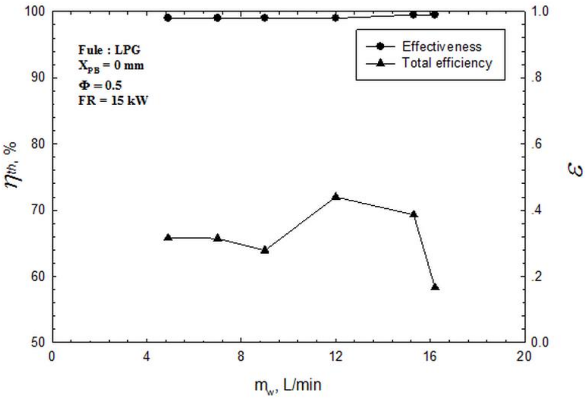


Fig.8 Effect of $\dot{m}_w$ on thermal efficiency and effectiveness.

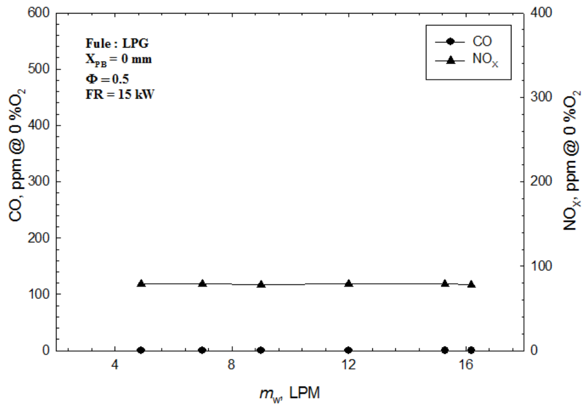


Fig.9 Effect of $\dot{m}_w$ on CO and $NO_X$ emission.

In addition, clogging inside PMB with the black carbonic like deposit was not occurred, even though the burner was continuously operated over a long period of time. It was confirmed that the combustion air cooling system is powerful to improve reliability of the burner by preventing fuel decomposition that will occur inside the PB due to over preheating temperature of fuel.

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Moreover, it is effectively used to enhance combustion due to the combustion air was preheated. Advantage of the porous media filled inside the heat exchanger is not only used to enhance heat transfer but also help enhance combustion due to heat recirculation within the packed of alumina ball. Therefore, near zero emission of CO was observed for wide range of operation.

### 5. Conclusion

This work is an implementation of the advantage of porous medium which can be both a combustor and a heat exchanger. The porous medium burner (PMB) was applied to produce heat source by producing high temperature exhaust gases to heating device, a so-called condensing porous heat exchanger, CPHE. The CPHE integrated with PMB can be operated over wide range of $\Phi$ varying from 0.3 to 0.7 without thermal decomposition of fuel and no clogs were found in the burner. Advantage of the porous media filled inside the heat exchanger is not only used to enhance heat transfer but also help enhance combustion due to heat recirculation within the packed bed of alumina balls. Even though the maximum temperature is as high as 1,650 $^{O}$C, however, the emissions of both CO and $NO_x$ are lower than 100 ppm at 0% $O_2$ excess condition. The optimum condition was achieved at *FR* of 15 kW and $\Phi$ of 0.5 in which the outlet temperature of water at mass flow rate of 4.9 LPM. is 61 $^{O}$C. The corresponding thermal efficiency and effectiveness are 65.79% and 0.98, respectively. Condensation of water vapor in the products can be achieved, while the exit temperature of the exhaust was lower than 50 $^{O}$C.

### 6. Acknowledgement

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