Heat Recirculation Using a Porous Medium for Air Pre-Heating in a Biomass Stove

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Received: 03/07/2021, Accepted: 10/11/2021

Abstract

The purpose of this research is to develop a biomass stove with a heat-recirculating approach that utilized a porous medium material to capture combustion heat and pre-heat the air inlet. Corn cobs were employed as the solid fuel. The combustion chamber of the biomass stove was 40 liters in volume, and the porous medium was made of alumina ceramic balls with an average diameter of 10 mm and a porosity of 41.21 percent. This substance has the ability to pre-heat and premix air, hence increasing the stove's combustion efficiency. The fuel consumption rate was 1.2 kg/h, and the operating time was four hours with a lean-burn ratio of 0.75 for the fuel/air ratio. The power input, power output, percentage of char created, burning rate, and temperature efficiency were determined to be 0.006 kW, 94.98 kW, 38.88 percent, 20 g/min, and 28.28 percent, respectively. In comparison to the conventional biomass stove without porous medium, the new biomass stove efficiently reduces ash by 38.88 percent. This study demonstrated the successes of integrating heat recirculation into a biomass stove to increase efficiency.

Keywords:

Heat Recirculation, Preheated-Air, Porous Medium, Biomass Stove.

1. Introduction

Biomass has been the traditional fuel to produce heat since the prehistorical period. Biomass can be converted into heat by direct combustion, a thermochemical conversion process. A biomass cooking stove is the most widely used equipment or device for energy conversion of biomass to heat. The merit of biomass stove is its low-cost and simplicity, particularly suited for serving the household cooking needs of the world population. At present, about 38% of the world population use biomass stoves for cooking. In India, the number of users is higher, which is about 66% of the total population using biomass stove [1-2].

Many researchers have developed various biomass stove designs for applications appropriate to the conditions of local communities. However, many factors should be considered in biomass stove design, such as (a) type of stove configuration, (b) type of combustion technique, (c) the application or purpose of the stove, (d) stove materials used, and (e) fuel type [2-3]. Typically, the research and development on biomass stoves focus on three main parts, (i) improvement of thermal efficiency, (ii) reduction of emissions, and (iii) ensuring ventilation [2,4].

Heat circulation is one approach that can be used to enhance thermal efficiency of biomass stoves. This has a positive effect on low-calorific value fuels [5]. Pre-heated by heat recirculation, can be used for combustion to generate high-temperature flame leading to energy savings [6-8].

Another approach to increase thermal efficiency is to improve the type of material used for making the stoves. One successful research used porous medium material technology for heat recirculation for combustion in stoves [9]. The use of porous medium (PM) material in stoves can effectively help in pre-heating the air input [10-11]. PM was used to fill up the outer chamber of the stoves to improve combustion efficiency, particularly when utilizing a low heating value fuel and thus enhancing combustion efficiency.

2. Objective of the Study

The purpose of this study is to develop the biomass stove designed using porous medium as a material for heat transfer media for pre-heating air to achieve higher thermal combustion efficiency and to reduce ash formation.

3. The experimental setup and methods for analysis

3.1. Biomass stove configuration

The biomass stove was designed to have three zones: combustion zone, porous medium zone, and insulator zone. The combustion chamber was made of an iron sheet with a thickness of 3 mm. The working volume of the combustion chamber of the biomass stove was 40 liters. Conventional castable cement No. CAST-15LW was used as an insulator material for a biomass stove.

3.2. Porous medium material

The porous medium used as heat transfer media consisted of aluminum oxide (Al_2O_3) balls of 10 mm of diameter. The porosity of the alumina ceramic balls was 41.21%, (which was calculated using equation 8). This material had a maximum service temperature of 1,500 °C. The thermal conductivity of the ball at temperatures of 400, 600, 800, and 1,000 °C were 0.59, 0.60, 0.61, and 0.63 $Wm^{-1} K^{-1}$, respectively.

3.3. Feeding of biomass fuel

Corn cobs were the fuel used in this study. They were collected from the Preserveago Products Co., Ltd., located in Mae rim, Chiang Mai, Thailand. The proximate analysis was performed using a thermogravimetric analyzer (TGA), PerkinElmer, Pyris 1 TGA. The ultimate analysis followed the in-house method based on ASTM D5373 – 16 and WI-03.Rev.01. The high and low heating values were analyzed using the bomb calorimeter, LECO, AC 350 following the automatic isoperibol (stirred-liquid bomb) method. Ash contents were determined based on the standard method ASTM2007d as presented in Table 1.

Table 1 Proximate and ultimate analysis results of corn cob used in this study.

Contains	Value
Moisture content: (%)	3.62 ± 0.52
Low heating value: (kJ/kg)	15,831.42 ± 109.29
High heating value: (kJ/kg)	17,355.23 ± 103.97
Proximate analysis	
Moisture contain: (%)	3.62 ± 0.52
Volatile matter: (%)	80.15 ± 0.34
Fixed carbon: (%)	14.16 ± 0.67
Ash: (%)	2.07 ± 0.29
Ultimate analysis	
C: (%)	47.14 ± 0.41
H: (%)	7.58 ± 0.01
O: (%)	42.67 ± 0.26
N: (%)	2.32 ± 0.04
S: (%)	0.29 ± 0.01

3.4. Experimental Set-Up

A data logger (GRAPHTEC bland model: mini logger GL820) with a K-type thermocouple was installed to continuously record the temperature profile of the biomass stove and the ambient temperatures. The primary air was supplied by a centrifugal air-blower (Norvax model NVT-020(2RB010-7AH16), and air volume was measured at the inlet tube by an anemometer (LINI-T model UT363). The 4-digitals balance (ADAM, model NBL 254i) was used to weigh the produced ash.

The experimental biomass stove, as mentioned earlier, has three main parts as follows: (i) combustion chamber zone, (ii) porous medium zone, and (iii) the insulator zone, see Fig. 1.

The velocity of the primary inlet air into the porous medium zone defined as V_{air}, the temperatures of the porous medium zone (T_{por}) on the top, medium, and bottom of the porous medium pack bed, the ambient temperature (T_{ab}), the inlet air temperature (T_{air}), and the combustion temperature (T_{com}) were all monitored and measured. The amount of the ash residue was also determined.

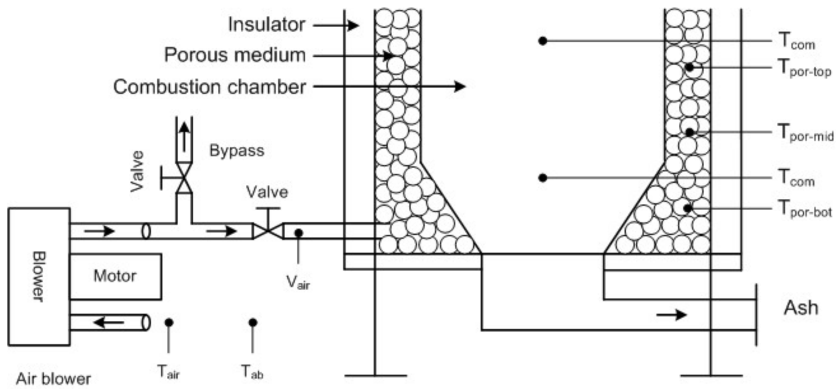

Fig. 1 The schematic diagram of biomass stove with a (PM) porous medium.

3.5. Experimental Methodology

The experiments were done in batch mode. For each batch, a total of 2.4 kg of corn cobs were manually fed to the stove. 0.7 kg of the corn cobs were first fed into the combustion chamber and ignited to start the experiments. Then, 1.7 kg of corn cobs were added to the chamber.

An anemometer, controlled through a motor (with an inverter of frequency between 0-120 Hz) was used to determine the air-mass flow rate $\dot{m}_{air}$. In this study, with the motor frequency of 50 Hz, the air mass flow rate was fixed at 11.53 kg/s, see Fig 2.

The Equivalence Ratio (ER), defined as the "fuel/air mix ratio", was calculated using equations (1), and (2). This study determined the effect of lean-burn combustion in which the ER = 0.75.

The duration of the study was set to 4 hours. The blower was turned on for the first two hours, which was the controlled fuel burning rate period. Then, the blower was turned off for the next two hours. The experiments were conducted three times to ensure repeatability.

Fig. 2 The biomass stove experimental setup.

4. Data analysis

In addition to the temperature measurements (as discussed previously), additional data collected for analysis included power input and output of the biomass stove, percentage of char produced, fuel-burning rate, energy consumption rate, the porosity of porous material, and the temperature efficiency.

Stoichiometric combustion determines the amount of the theoretical mix or ratio of oxygen (in the air) and carbon (in the fuel) for full combustion. The theoretical mix or ratio is the mass equivalence of carbon and oxygen needed in a complete combustion reaction. This can be estimated from equation (1) [13]. The equation includes all elements contained in the fuel and the air.

$$C_uH_vO_wN_xS_y + \left(u + \frac{v}{4} - \frac{w}{2} + y\right)\left(O_2 + 3.76N_2\right) \rightarrow uCO_2 + \frac{v}{2}H_2O + ySO_2 + \left[3.76\left(u + \frac{v}{4} - \frac{w}{2} + y\right) + \frac{x}{2}\right]N_2 \quad (1)$$

The respective subscripts *u, v, w, x, y* are the mole equivalent of C, H, O, N, and S, (the elements in the fuel and air) [13].

The air-fuel actual ratio $(F/A)_{act}$ can then be determined using equation (2) based on the fuel characteristics of the corn cobs obtained through ultimate analysis [14].

$$\Phi = \frac{(F/A)_{act}}{(F/A)_{stoich}} \quad (2)$$

Where Φ is equivalence ratio (%), $(F/A)_{act}$ is the actual Fuel/Air ratio, and $(F/A)_{stoich}$ is the stoichiometric Fuel/Air ratio. Then $\Phi < 1$ is fuel-lean mixture/ratio, $\Phi = 1$ is stoichiometric fuel-air mixture/ratio, and $\Phi > 1$ is fuel-rich mixture/ratio.

The *Power Input* (P_{in}) was the amount of energy supplied into the biomass stove based on fuel consumption. The P_{in} can be calculated from equation (3) [15].

$$P_{in} = 0.0012 \times FCR \times HVF \quad (3)$$

Where P_{in} is power input (kW), *FCR* is fuel consumption rate (kg/h), and *HVF* is heating value of fuel (kcal/kg).

The *power output* (P_{out}) was the amount of useful energy released by the biomass stove for heating. The P_{out} can be calculated by using equation (4) [15].

$$P_{out} = FCR \times HVF \times TE \quad (4)$$

Where P_{out} is power output (kW), *FCR* is fuel consumption rate (kg/h), *HVF* is heating value of fuel (kcal/kg), and *TE* is the thermal efficiency (%). *TE* in this research was assumed to be 18% as recommended by the previous researchers [16,17].

Ash is the inert material produced during combustion. The amount of generated ash depends on the moisture content, combustion temperature, and combustion efficiency. The extent of ash production is expressed as the ratio of the amount of ash produced to the amount of biomass used, which can be calculated using equation 5 [15].

$$P_{char}=\frac{W_{char}}{W_{fuel}} \tag{5}$$

Where P_{char} is a percentage of char produced (%), W_{char} is the weight of char (kg) , and W_{fuel} is the weight of used solid fuel (kg).

The *Burning rate*, (R_b) used in the experiment can be calculated using equations (6) [16,17].

$$R_b=\frac{f_d}{\Delta t_m} \tag{6}$$

Where R_b is a burning rate (g/min), f_d is mass of fuel (kg), and Δt_m is the duration of combustion (min).

The *porosity* is given by the surface area of the porous medium and can be calculated using equation (7) [17,18].

$$\phi=\frac{V_S}{V_T} \tag{7}$$

Where ϕ is the porosity of porous medium, V_S is void-space volume, and V_T is total or bulk volume.

Temperature efficiency (η_T) reflect the ability of the porous medium to transfer energy by convection (see Equation 8). This is influenced by the heat absorption of the porous medium for radiated heat transfer [18,19].

$$\eta_T=\left[T_R-\frac{T_s(0)+T_s(x_0)}{2}\right]\Big/\left(T_R-T_0\right) \tag{8}$$

Where η_T is temperature efficiency (%), T_R is radiation temperature (˚C), T_s is the porous temperature (˚C), T_0 is the air-inlet temperature (˚C), x_0 is porous pack bet thickness (m).

The *dry air sensible heat input* ($Q_{in\text{-}air}$) can be calculated based on the PM zone temperature and the inlet air temperature, using equation (9):

$$Q_{in-air}=\dot{m}_{air}Cp_{air}(T_{por}-T_{air-in}) \tag{9}$$

Where $Q_{in\text{-}air}$ is the dry air sensible heat (kJ), $\dot{m}_{air}$ is air mass flow rate of air inlet (kg/s), Cp_{air} is the specific heat capacity of air (Cp_{air}= 1.02 kJ/kg K), T_{por} is porous medium zone temperature (˚C), $T_{non\text{-}por}$ is non-porous medium zone temperature, and $T_{air\text{-}in}$ is an air-inlet temperature (˚C).

5. Results and Discussions

5.1. Effect of the PM on heat-recirculation

The temperature of the pre-heated inlet air, $T_{air,inlet}$ was the most critical factor in the performance of the biomass stove with PM, with heat recirculation. The measurement of the $T_{air,inlet}$ was done near the pipe blower inlet. This was used to calculate and compare the sensible heat input Q_{in-air} for the two set of experiments conducted, the stove with PM and the stove with NPM (no PM or without PM).

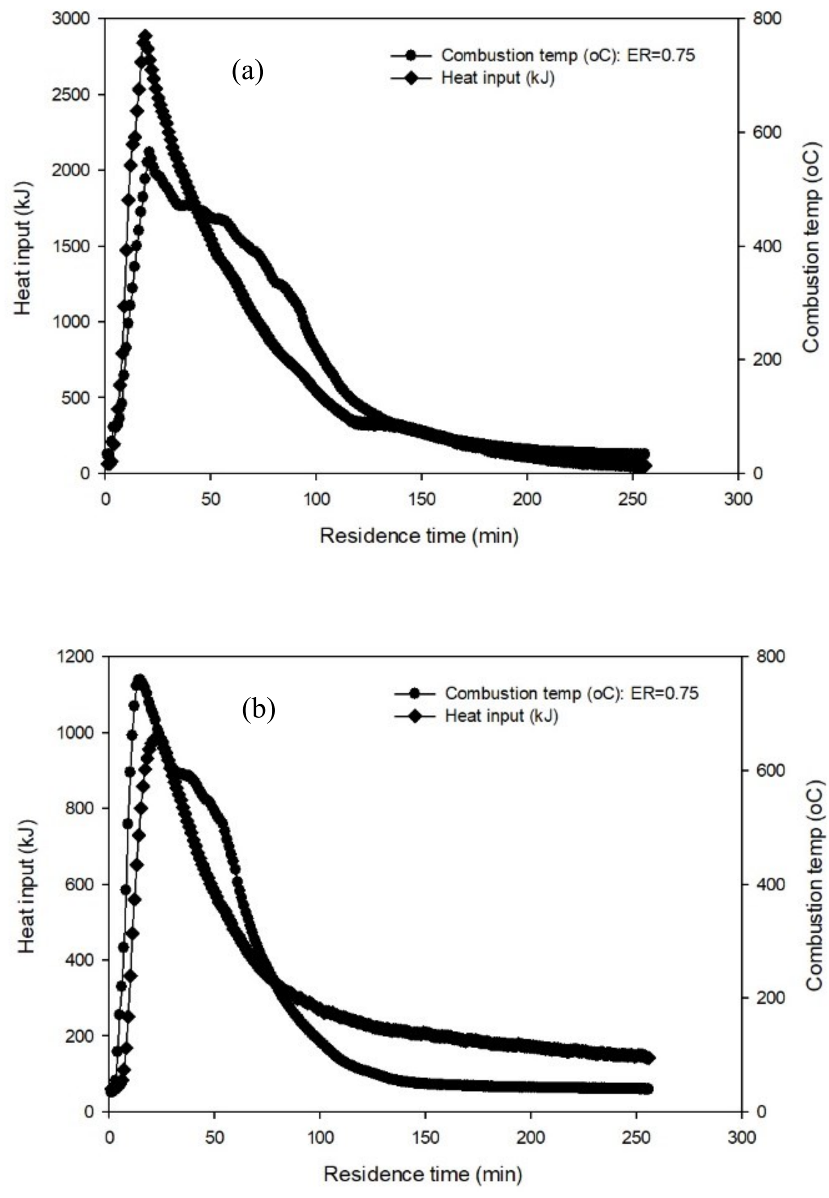

Fig. 3 The effect of heat-recirculation on the combustion temperature.

Fig.3(a) shows the maximum combustion temperature in the stove without PM, and the results indicated that the $T_{com,\max\text{-}non}$ increased from the ambient temperature up to 564.67 ˚C within 21 minutes. After that, the temperature decreased as the fuel in the combustion chamber was used up.

The maximum combustion temperature $T_{com,\max\text{-}non}$ (= 564.67 ˚C) for the stove with NPM was lower than the maximum combustion temperature in the stove with PM, $T_{com,\max\text{-}por}$= 758.47 ˚C, see Fig.3 (b)). This might be because, in the stove with PM, the PM absorbed the heat released from the combustion and then that heat was transferred by recirculation into the inlet air. As a result, the inlet air temperature increased, and this led to less dense air that enhanced the mixing between air and fuel.

Comparison of Figures 3(a) & 3(b) shows that the maximum dry air sensible heat input in the stove with NPM,$Q_{in,\max\text{-}non}$was 2,885.92 kJ which was higher than the maximum dry air sensible heat input in the stove with PM, $Q_{in,\max\text{-}por}$. This might be because the amount of $Q_{in,\max\text{-}non}$in the stove with NPM, was not reused as there was no recirculation of the exhaust gas to pre-heat the inlet air for combustion.

Fig. 3(b) shows the maximum combustion temperature for the stove with PM, $T_{\max,com\text{-}por}$ increased from the ambient temperature up to 758.47 ˚C within 15 minutes, and it was higher than that of the stove with NPM. The maximum sensible heat input in the stove with PM, $Q_{in,\max\text{-}por}$ was 986.45 kJ which was lower than the maximum sensible heat input of the stove with NPM, $Q_{in,\max\text{-}por}$ because the energy was used to heat up the PM which then heated and increased the inlet air temperature. The high surface area of the PM could have further enhanced heat transfer.

5.2. Effect of the PM on the pre-heating of inlet air

The comparison on the effect of PM on the inlet air temperatures in the stove with NPM with that of the stove with PM is shown in Fig. 4 (a) & (b). The average inlet air temperature $T_{air,inlet}$ was 29.90 ˚C for both. The maximum air temperature in the stove with NPM was 274.09 ˚C which was higher than that of the stove with PM at 113.81 ˚C. This might be because the stove with NPM had higher heat losses.

The PM (porous material) effectively absorbed the heat resulting to a lower temperature in the porous medium zone. In addition, the PM could reduce the heat loss in the combustion chamber because heat energy was transferred for storing in the porous material.

The combustion characteristic in the biomass stove with PM to pre-heat the inlet air is presented in Fig. 4(b). The inlet air- temperature was constant with an average value of 33.92 ˚C. However, the conventional biomass stove (i.e., stove without PM) without air pre-heating had higher heat losses because the temperature of a porous zone raised depending on the amount of heat of combustion (see Fig. 4 (a)).

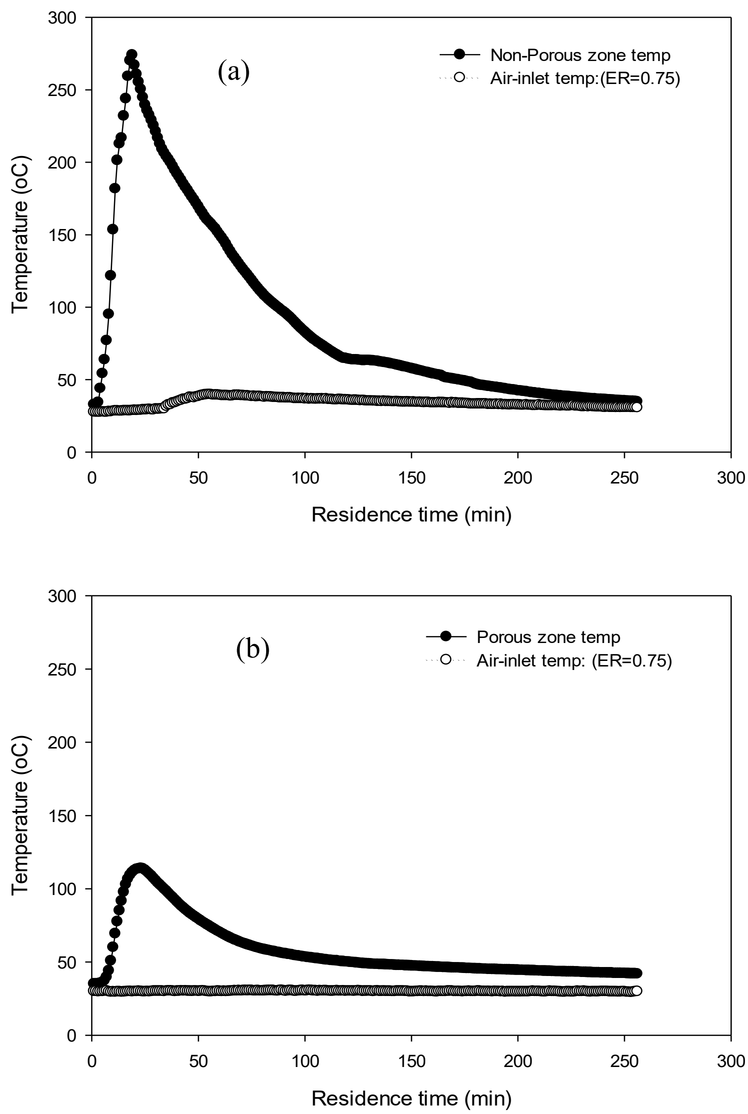

Fig. 4 The effect of air pre-heating on the porous zone temperature: (a) non-porous medium, NPM, and (b) Porous medium, PM.

5.3 The effect on the combustion temperature

The temperature of the pre-heated air in the stove with PM was higher compared to that of the stove with NPM, see Fig. 5 (a) & (b). The reason might be because the temperature of primary air, $T_{pri\text{-}air}$ was increased by the heat transfer from the installed porous medium. The temperature of the primary air $T_{pri\text{-}air}$ increased to the warm air, $T_{war\text{-}air}$ and enhanced air-fuel mixing in the combustion chamber.

In the stove with NPM, the temperatures of the non-porous zone were, $T_{\max,\,non\text{-}por}$= 274.09˚C and, the average temperature of NPM, $T_{ave,non\text{-}por}$ = 90.65˚C, see Fig. 5(a). On the other hand, in the stove with PM, the temperature in the porous zone were higher the $T_{\max\text{-}por}$ at 113.81 ˚C and $T_{ave\text{-}por}$ at 57.04 ˚C, see Fig. 5(b).

In the stove with PM, the temperatures in the combustion zone were, $T_{\max,\,com\text{-}por}$ of 758.47 ˚C and $T_{ave,com\text{-}por}$ of 194.10 ˚C (see Fig. 5 (b)). The temperatures in the stove with PM were higher than those in stove with NPM, and this due to the effect of the porous medium, which reduced heat loss and but allowed heat recirculation to pre-heat the inlet air. Reversely, the temperatures in the stove without PM can be describe in term of maximum temperature $T_{\max,\,com\text{-}por}$ at 564.67 ˚C, and $T_{ave,com\text{-}por}$ at 188.35 ˚C, see Fig. 5(a).

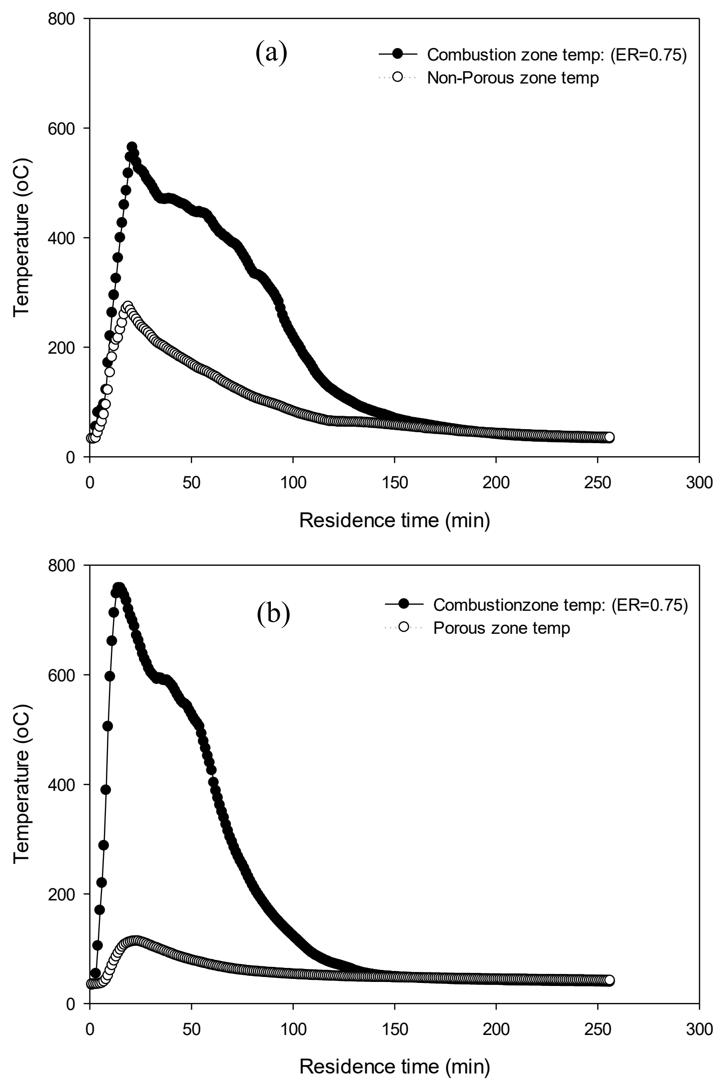

Fig. 5 The effect of pre-heated air on the combustion temperature profile: (a) non-porous medium, NPM, and (b) Porous medium, PM.

This study showed that pre-heating of the inlet air led to the increasing of combustion chamber temperature. However, the temperature in the PM zone decreased because the input heat was transferred to the PM, as shown in Fig. 3(b). This was because the PM acted as heat absorber during the combustion. In addition, the use of the PM had additionally effectively improved the thermal efficiency because the ash production was reduced by about 38.88%, thus also decreasing overall heat loss in the biomass stove.

Table 2 Comparison of ash production between a stove with non-porous medium (NPM), and a stove with a Porous medium (PM).

No.	Ash weight (g)		Ash reduction	NPM/PM
	NPM	PM	(%)	ratio
1	75.00	43.00	42.66	0.57
2	71.00	46.00	35.21	0.65
3	80.00	49.00	38.75	0.61
Average	75.34	46.00	38.88	0.61

Table 2 presents a comparison of ash production between the stove with PM and the stove with NPM. The comparison of the ash weight reduction between the stoves with PM and with NPM, is given by the ratio PM/NPM, which has an average value of 0.61. The average weight of ash from the stove with PM was almost half of the ash from the stove without PM.

The power input and output were calculated from equations (3) & (4). The power input was 0.006 kW, while the power output was 94.98 kW. Power input strongly depends on the fuel consumption rate (FCR) and the heating value of fuel (VHF). This research used a corn cob with VHF of 17,355.23 kJ/kg and the FCR of 1.2 kg/h.

The burning rate calculated from equation (6) was 20 g/min. The burning rate of other research were between 4 and 25 g/min [20,21] because the fuel burning rate depends on the air-fuel mixture rate, bulk density, and the size of the solid fuel e.g. biomass.

The temperature efficiency of 28.28% was determined using equation (8). However, other research have a value of temperature efficiency at 97% [22]. This could be from the enhanced heat radiation from the installed porous medium, resulting in higher temperature efficiency.

6. Conclusion

This study successfully presented the positive effects of using PM on the combustion temperature, which led to higher combustion efficiency. In addition, ash production was reduced by almost 38.88%. The results in this study can be used as a guideline for designing new biomass stoves and modifying existing ones. The advantage of using porous medium is its effectiveness in pre-heating primary or inlet air for direct combustion. It enhances the combustion reaction in the biomass stove and in addition, also act as an insulator to reduce heat loss in the biomass stove.

Acknowledgments

We gratefully acknowledge the Preserveago product Co., Ltd. Mae rim, Chiang Mai Thailand for support a corn cob this study. Also, we would like to thank you The School of Renewable Energy and Smart Grid Technology, Naresuan University, Thailand for support the data logger to collect the data of this study. Finally, this research was funded by Chiang Mai Rajabhat University (Research Fund for the Fiscal Year 2020) under grant number: CMRU 64/63.

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