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Improvement of Heat Transfer on Solid Fuel Combustor System Using Waste Steel Nuts as Porous Media

Buncha Puttakoon*, Boonrit Prasartkaew *, [1] and Kitipong Jaojaruek[#]

Abstract *– This study investigated the performance and efficiency of a hot water combustion system by applying the concept of porous media technology using waste stainless steel nuts and by using wood charcoal as solid fuel. In the experiment, the useful heat output of the product gas was extracted from the reactor to the heat exchange chamber in order to heat the water inside the water tubes packed within the porous media. Results showed the feasibility of using solid as fuel for combustors applied with porous media technology, and the possibility of heat recuperation using porous media. Temperature and heat rate profile fluctuation, however, were noticeable during the experiment as compared to the configuration without the porous media. Furthermore, the effect of using varying sizes of porous media was explored by using 8, 10, and 12 mm stainless steel nuts in the study. With the porous media technique, the 10mm size stainless steel nuts with the porosity of 0.53 greatly improved the performance of the proposed solid fuel porous media combustor (SFPMC) system. At steady state combustion condition, the maximum average combustion temperature reached 1,002℃ and the average thermal efficiency of 67 %, was obtained with heat balance error less than 10%.*

Keywords *– combustor, heat transfer, porous media, solid fuel, waste stainless steel nut.*

1. INTRODUCTION

Energy seems to be the most important factor for human survival; for all human activities depend on energy. Most of the energy resources consumed by countries around the globe are fossil-based wherein its combustion is the primary energy consumption of about 90% in all countries [1]-[2]. Its excessive use caused a growing concern of its supplies depleting soon and of polluting the environment. With fossil fuels as the primary energy resource, it is a compelling issue to know the most effective way of utilizing it. This is due to the increasingly significant demand for an eco-friendly energy management and for various efficient schemes to be implemented in industrial commercial purposes [3]. Porous media has been used in various combustion applications and it has gained more attention from researchers in the applications such as biomass combustion, incineration of solid waste, catalytic combustion, coal gasification, in situ combustion for the recovery of oil, diesel engine and pollution control, hydrogen production, grounds polluted by toxic organic shedding recuperation, destruction of volatile organic compounds (VOC) in air [4].

Over the past few decades, the porous media combustion (PMC) has been one of the most well-known technologies to increase the system efficiency and reduce emitted pollutants, and one of the best techniques widely used for an energy efficient combustor. Regarding this technique, Yumlu [3] has presented the experimental study on the performance of a porous flat flame burner. Past studies focused on heat extraction, hydrogen–oxygen and hydrogen-air flames.

Various types of researches attempted to improve the performance of PMC over the years, which can be categorized into the phase of fuels used: gaseous, liquid and solid fuels. Most studies focused on gaseous fuel, liquid fuel, and porous combustor as presented in [5]-[12]. Kaplan and Hall [13] studied the characteristics of solid fuel combustion by comparing the porous burner installed with a porous emitter and with a nonporous emitter. The combustion behavior between the porous emitter and non-porous emitter was compared and found the thermal efficiency to be around 28% and the combustion efficiency to be around 99.5%, respectively [14]. Further studies regarding thermal efficiency improvement was studied in a newly designed cooking stove using wasted vegetable oil (WVO) as fuel. It was suggested that the performance of the WVO burner can be further improved if the H/D ratio was increased to 1.5, yielding thermal efficiency of up to 42% [15].

The PMC technique has been studied and applied to steady combustion with great success for the past decades of research. This technique was used for both gaseous liquid fuels and solid fuels (coal powder) and the effect of the combustion feature of such technology is its distinctive performance. Earlier studies of many researchers, focused on both experimentally and theoretical developments of reactors for gas and liquid. [16]-[17]. But in order to address the environmental problems of fossil fuel utilization, renewable-energy based systems should be encouraged as well as the development of new combustion techniques. Therefore, new renewable energy or biomass energy sources must be explored to remedy this crisis and environmental problems for the near future [12].

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Industries produce a lot of waste materials that can be a potential source of renewable energy. One common source is in the form of firewood that is usually used in rural households. However, when burnt it produces smoke and has low heating value. By converting the firewood into charcoal, its disadvantages are resolved. The charcoal obtained will approximately contain 50% of the wood burnt which still varies depending on the process. Nowadays, due to the progress in using wood as energy, it can now be used to directly produce product gas that can run engines successfully [28]. One of which is wood charcoal; it is a solid biomass fuel that can reduce green house gas (GHG) emissions which is said to be one of the culprits of climate change and global warming problems [29]-[30]. Studies also showed several advantages of renewable energy systems such as its safer operation, worldwide availability, contribution to a clean environment, and production of non-polluting energy [16]-[17]. Also, using solid biomass as fuel is much simpler in preparation compared to using biomass gas. Furthermore, it is also usually used in agricultural communities. However, the information of applying solid fuel in combustor with porous media is lacking in data and is quite rare to be studied. Therefore, this work would like to fill that gap of information reported.

In this study, waste stainless steel nuts served as the porous media since these can be collected easily from many factories. This alternative idea may be another useful option of how to dispose the waste rather than recycle [2]. Moreover, the heat recovery from the steel nuts was expected to be better than using it in recycling process. The nuts were packed inside tubes chamber (outside tubes bundle) so as to enhance heat transfer between hot gas outside the tubes and the flowing water inside the tubes. The study also investigated the nut sizes impact to the heat transfer between two fluids as mentioned.

This research studied several hot water production volumes from the porous-media combustor for solid fuel utilization. A porous material is a kind of material with connected voids, where airflow and hot airflow can easily penetrate through the media. Porous materials will cause the circulation of exhaust heat to the intake by conduction and effective heat radiation. The research is a comparative study of solid fuel burners with and without the porous media. The primary objectives of the present study are to reveal the effects of stainless steel nuts size and comparison of heat transfer to water tubes between with and without the porous media filled up in the tubes of the chamber.

2. MATERIALS AND METHODOLOGY

2.1 Experimental Setup

Figure 1 shows the proposed solid fuel porous media combustor (SFPMC) setup with a water heating system. The experimental system consists of a proposed reactor that was equipped with an air blower, a water pump, fittings, other plumbing and a 0.15 m^3 hot water storage tank. The water was stored in an insulated storage tank and can be supplied as heating load. The flow rate of air and water were manually controlled by its respective flow control valves. A pump circulated water through the heat exchanger (water heater) inside the reactor. To avoid the water evaporation under atmospheric pressure, the water temperature at the middle level of the tank was manually controlled at about 60°C by means of draining hot water at the top and filling the tap water at the bottom of the tank.

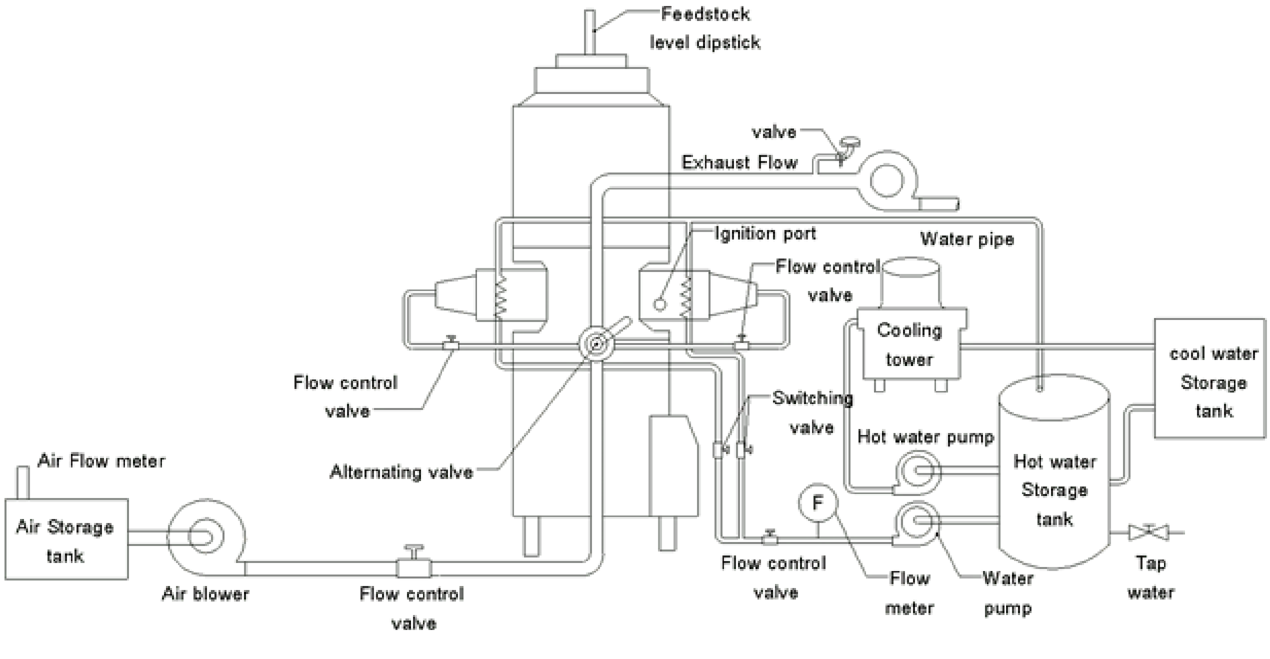

Fig. 1. Solid fuel porous media combustor (SFPMC).

2.2 Data Acquisition System

The water temperatures, at the inlet and outlet of heat exchangers were recorded using a data logger (Data Logger model GL820midi Logger) equipped with Type-K thermocouples. On the other hand, the internal temperature of the combustor was recorded at 6 points (T1 to T6) as shown in Figure 2. Point T1 measured the air supply temperature. Points T2-T4 measured the combustion temperature inside combustor along the air flow from left to right. While points T5 and T6 measured the temperature at the hot gas before and after water tubes, respectively. All temperature data were recorded in 30- second intervals. The water flow rate and fuel consumption rate were manually measured and recorded every half an hour.

2.3 Fuel

The charcoal used in this study is from wood and is usually used for cooking (as shown in Figure 3). This served as the fuel for the combustor lower heating value of 28.18 kJ/kg. The average size of charcoal is 2inch. Primarily, the quantity of feedstock used were weighed and recorded before loading into the reactor and beginning the test. The instantaneous feedstock consumption rate was approximately measured using the level dipstick, installed at the top of the reactor.

2.4 Porous Media

This research used waste stainless steel nuts as the porous media which were categorized into three sizes: 8, 10 and 12 mm. These were used because it does not change its shape when exposed to heat, can easily bend, and can easily be found and bought from the market. The porous media chamber was square in shape as shown in Figure 4. The width, length, and height are measured as follows: 190 mm. 210 mm. and 420 mm. It has 21 water pipes inside that is made from stainless steel. The pipe has an outside diameter of 22 mm. The side and backside of the porous media chamber has a 5 mm steel grating to prevent the porous media from falling out as the gas flows. The porosity of 8 mm nuts is 0.42, 10 mm. 0.53 and 12 mm. equal to 0.62 calculated as Equation 7.

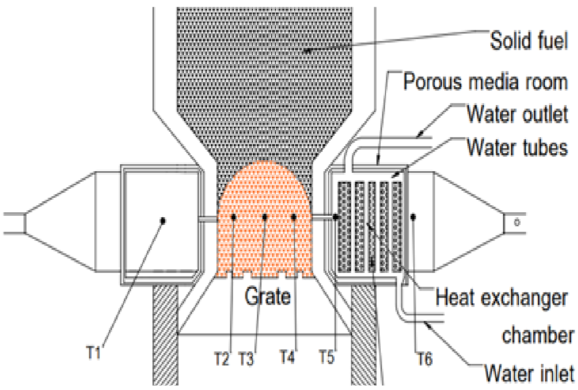

Fig. 2. Temperature measurement points.

Fig. 3. Wood charcoal used in the study.

Fig. 4. Porous media used in this study.

2.5 Heat Exchange

Figure 5.1 shows the case without porous media wherein hot gas transfers heat to the water tube surface by heat convection and heat radiation. In this case, it does not contain porous media for heat storage so, heat is conducted and radiated to the water tube. There is only hot gas and air inside, resulting in low heat transfer capability. As a result, the thermal efficiency is lower than that of with porous media.

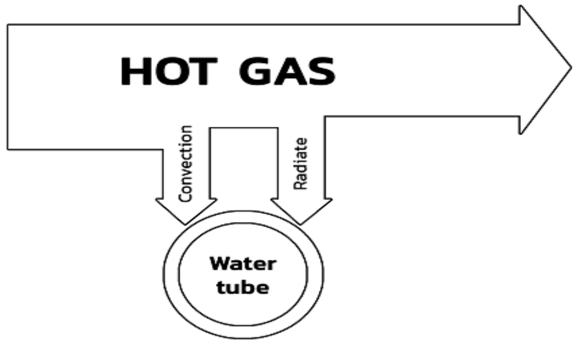

Fig. 5.1 Heat exchange of without porous media.

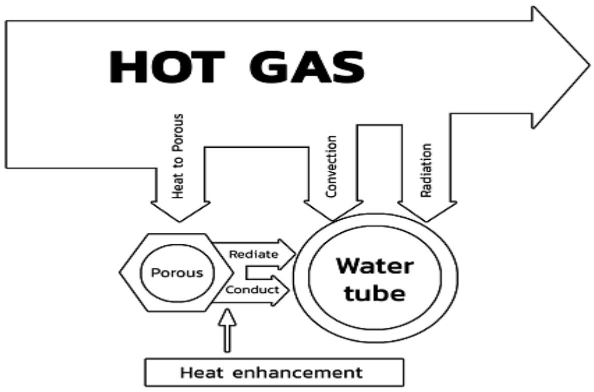

Fig. 5.2 Heat exchange of with porous media.

The case with porous media is shown in Figure 5.2, where the hot gas is transferred to the water tube by convection. Porous media as a material helps collect heat from the hot gas, thereby exchanging the heat from the porous media to the water tube. As a result, it conducts and radiates heat, causing increased heat to the water tube hence, promoting efficient heat transfer. The thermal efficiency is higher than in the case where the porous media is absent. The main characteristic of stainless steel nuts used as porous media is its high surface area to volume ratio giving good heat transfer capacity as well as its solid appearance. Hence, it has high absorption and radiation coefficient enabling it to transform energy well. It can be said therefore, that the porous media using stainless steel nuts is a high efficiency but compact heat exchanger.

2.6 Performance Evaluation

The efficiency of hot water production kiln using solid fuel with and without the porous media in unidirectional gas flow of the (SFPMC) proposed was calculated as:

$$\eta = \frac{\dot{Q}_u}{[\dot{m}\ \text{fuel x LHV fuel}]} \tag{1}$$

where $\dot{Q}_u$ is the rate of heat transferred to hot water. This useful energy that is increasing water enthalpy can be expressed as:

$$\dot{Q}_u = \dot{m}_w C_p (T_{w,o} - T_{w,i}) \tag{2}$$

Fuel consumption rate ($\dot{m}_{fuel}$) can be calculated from the amount of fuel used during the time being considered or estimated from the total amount of fuel divided by the total time spent in the experiment from the start of the experiment until the fuel runs out. The fuel used in this study is wood charcoal (or cooking charcoal) with a calorific value of 28.18 kJ/kg. Therefore, the fuel consumption rate was calculated as:

$$\dot{m}_{fuel} = \frac{\text{Total amount of fuel used per batch (kg)}}{\text{Total operationg time per batch (s)}} \tag{3}$$

Heat transfer improvement on the basis of hot product gas can be evaluated as follows:

Water side:

$$\Delta H_{im,\ water} = \dot{Q}_{water,\ PM} - \dot{Q}_{water,\ w/o} \tag{4}$$

Gas side:

$$\Delta H_{im,\ gas} = \dot{Q}_{g,\ PM} - \dot{Q}_{g,\ w/o} \tag{5}$$

and the improvement in terms of efficiency is,

$$\eta_{im} = \frac{\dot{Q}water,PM - \dot{Q}water,W/O}{\dot{Q}water,W/O} \tag{6}$$

Where ΔH_{im} is the heat transfer improvement and η_{im} is the heat transfer improvement efficiency.

$$\varepsilon = (V_t / V_s) \times 100 \tag{7}$$

The porosity (ε) of porous materials by water substitution method was calculated using Equation 7.

2.7 Experimental Procedure

The experiment evaluates the SFPMC with and without the porous media (stainless steel nuts) by determining the improvement in the heat transfer from product gas to the water tubes. The effect of porous media used was further investigated by varying its sizes: 8, 10, and 12 mm. The combustor was initially loaded with 40 kg of solid fuel. Airflow and water flow rates were equally set. The airflow control valve was adjusted to flow only from one direction. The air flows along the airway duct from left to right then through the combustion chamber. As the solid fuel burns and the temperature rises, the heat from the combustion chamber is brought to the right, at the heat exchange chamber containing the water pipelines. For the first setup, the heat exchange chamber was not filled with porous media .The other setups were then filled with porous media in which each setup was packed with the mentioned variation in sizes. The water pipeline then receives the heat energy from the combustion chamber .At the same time, water flowing through the pipe is also receiving the heat from the combustion causing the product gas temperature to decrease as it exits the heat exchange chamber. The heat absorbed by the water is then pumped back to the water tank, and then the water in the tank with lower temperature is circulated in the heat exchange chamber in a cycle. The results were collected and the data acquired delivering the highest calorific value was determined.

Table 1. The cases observed during the experiment for the proposed SFPMC with water heating system.

Case no.	Case	Air flow rate	Water flow rate	$\dot{m}_{fuel}$	Temperature: water inlet and water outlet
		(m^3/h)	(kg/s)	(kg/s)	(ΔT)
I	Without *PM	318	0.833	0.00206	5.3
II-A	8 mm PM	318	0.833	0.00206	9.8
II-B	10 mm PM	318	0.833	0.00206	11.2
II-C	12 mm PM	318	0.833	0.00206	7.8

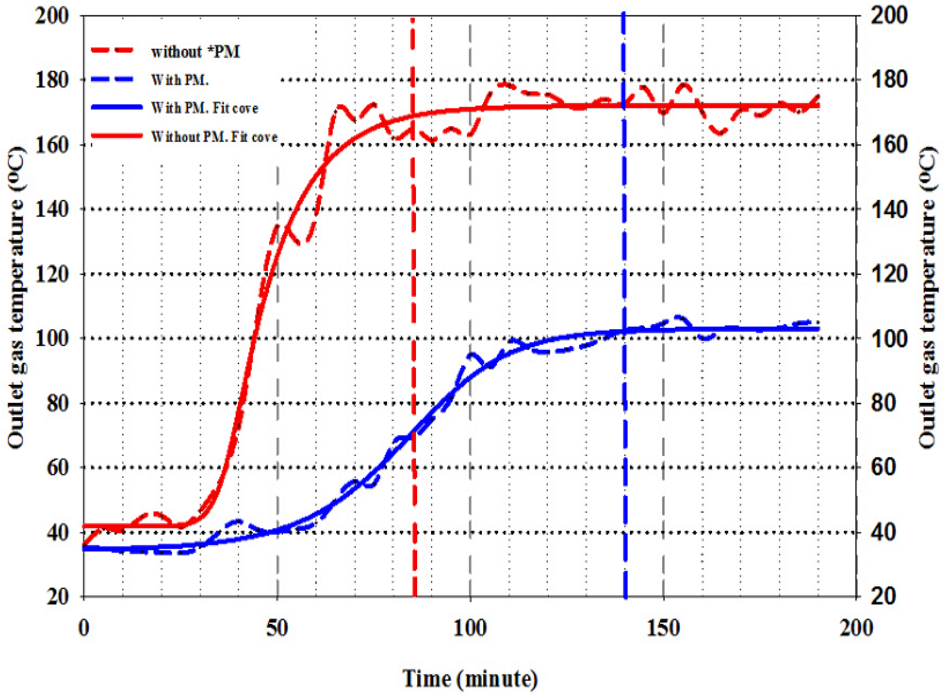

Fig. 6. Temperature profile of product gas at the outlet point with and without the porous media.

3. RESULTS AND DISCUSSION

Typically, porous media acts as a heat emitter and a heat absorber. Therefore, it was proposed as a water heating system. The heat extraction between the porous media was taken into account and noted as an important parameter. Hence, the experimental procedure was divided into four cases, which is shown in Table 1, for both with and without porous media configurations.

The temperature profile of the product gas at the outlet was compared with and without the porous media as seen in Figure 6. The temperature was plotted from 0 – 190-minute duration of the experiment. The red line graph shows the outlet gas temperature without the porous media whereas the blue line shows the outlet gas temperature with the porous media. As seen from the figure, the profile of the outlet gas without the porous media reached a maximum temperature of 178ºC but the temperature profile of the one with the porous media only peaked at 106ºC. Hence, outlet gas temperature is higher without the porous media compared to the one with it. The reason is attributed to the ability of the porous media to absorb some of the heat energy released from the product gas as it flows out of the temperature exchange chamber.

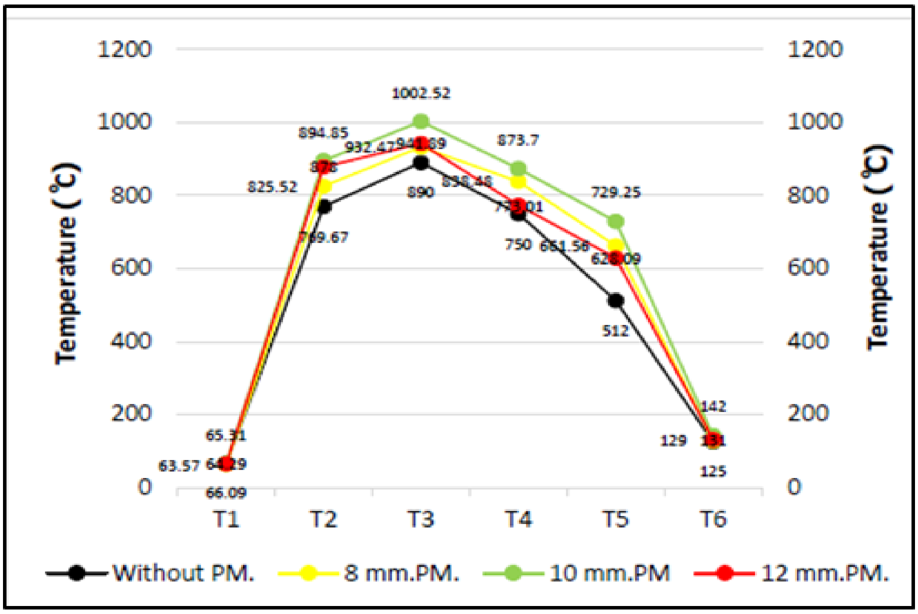

Fig. 7. The gas temperature at different points for the four experimental cases.

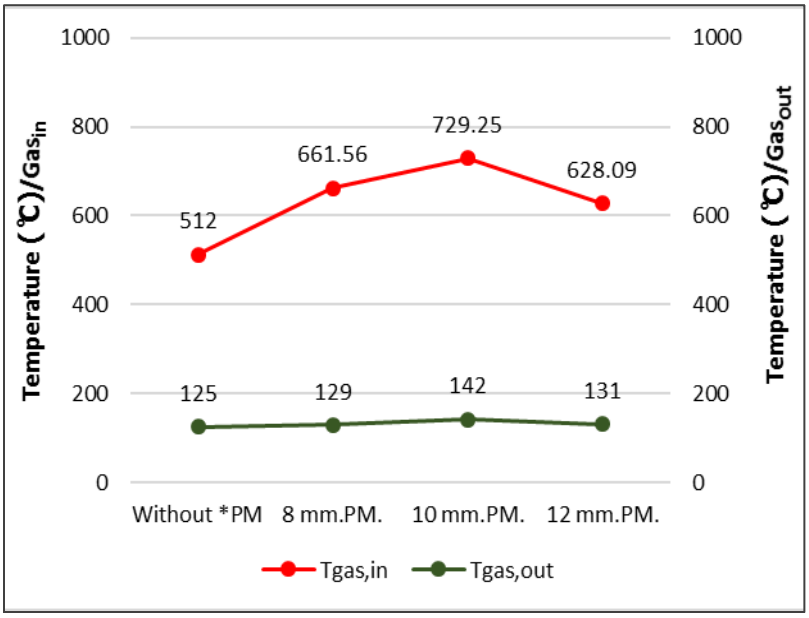

Fig. 8. The average gas temperature taken at the inlet and outlet points of the four cases at steady state condition.

Figure 7 shows the gas temperature at various points for the four different cases stated in Table 1. The heat exchange chamber was installed on the right hand sides of the combustor chamber, and having water pipelines that can be filled with porous media (shown in Figure 2). The water flow rate is 318 m^3/h all throughout the duration of the experiment and the gas flow direction is unidirectional. The results from the experiment found that the average temperature in the middle of the combustion area is approximately 1,002 °C.

The average inlet ($T_{gas,in}$) and outlet ($T_{gas,out}$) gas temperature shown in Figure 8 was taken within the 85 to 190 minutes duration of the experiment. Between this timeline, the steady state condition was observed .The average inlet gas temperature was observed to be 512ºC, 661ºC, 729ºC, and 628ºC for cases I, II-A, II-B, and II-C, respectively. Whereas the average outlet gas temperature observed for cases I, II-A, II-B, and II-C were 159ºC, 106ºC, 96ºC, and 80ºC, respectively. The graph shows that without the porous media (case I), the $T_{gas,\ in}$ = 512ºC, and $T_{gas,out}$ =125ºC. Whereas for the other 3 cases with the porous media the average inlet gas temperature ($T_{gas,in}$) were recorded as 661ºC, 729ºC, and 628ºC for cases II-A, II-B, and II-C, respectively. On the other hand, the outlet gas temperature ($T_{gas,out}$) observed were 129ºC, 142ºC, and 131ºC for cases II-A, II-B, and II-C, respectively.

Figure 9 shows the average temperature of inlet gas and outlet gas, and the inlet water temperature (W_{in}) and outlet water temperature (W_{out}) in all four cases; namely, the case without the porous media and with porous media of 8, 10, and 12 mm. sizes. The difference (ΔT) of the average inlet and outlet gas temperature for each case was calculated. The 10mm size porous media (case II-B) showed the highest with ΔT= 587ºC, followed by the 8 mm. size porous media (case II-A) with ΔT = 532ºC, the 12 mm. size porous media (case II-C) ΔT = 497ºC and without*PM (case I) the lowest with ΔT = 387ºC. For the recorded data without the porous media (case I), the inlet and outlet water temperature were 49.5ºC, and 54.8ºC, respectively. The other cases II-A, II-B, and II-C (8mm, 10mm, and 12mm sizes) with porous media, reported 48.7ºC, 49.6ºC, and 48.6ºC, respectively at the inlet water temperature (W_{in}). As for the outlet water temperature (W_{out}) cases II-A, II-B, and II-C recorded 58.5ºC, 60.8ºC, and 56.5ºC, respectively. Based on the recorded data, the case with the highest average temperature difference (ΔT) of the inlet and outlet gas temperature was found in 10 mm size (case II-B) porous media at about 587ºC. Moreover, the highest average temperature difference of the inlet and outlet water temperature was also seen on case II-B (10 mm size) having ΔW = 11ºC followed by the 8 mm. size porous media (case II-A) with ΔW = 9ºC, the 12 mm. size porous media (case II-C) ΔW = 7ºC and without*PM (case I) the lowest with ΔW = 5ºC.

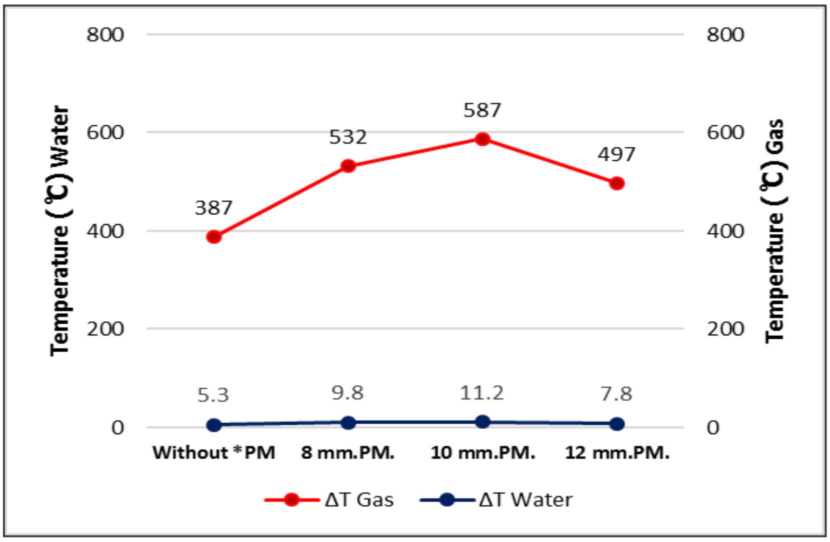

Fig. 9. The difference of the average inlet and outlet temperatures of the gas and water for the four cases.

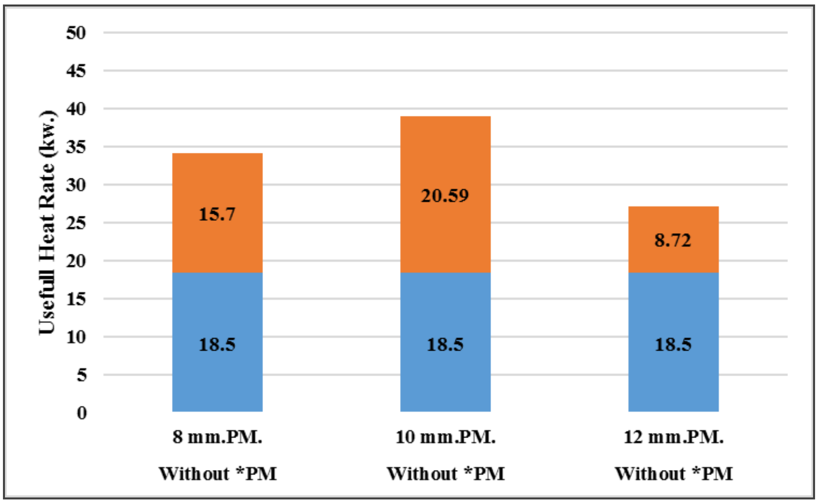

Fig. 10. The absorbed useful heat rate of the four cases (without*PM, 8mm PM, 10mm PM, and 12mm PM).

The water temperature profile at the inlet and outlet points of the heated water (within the porous media pack) presented in Figure 10 through the calculated absorbed heat rate using Equation 2 for each of the four cases. Since the storage tank was controlled to a relatively constant temperature of 60ºC, there were no observed fluctuations concerning the water temperature. Hence, the absorbed heat rate was plotted instead. The maximum absorbed useful heat rate during the quasi-steady state occurred when the 10 mm (case II-B) steel nuts were used as porous media with a highest value of 39.09 kw.

The thermal efficiency of the proposed SFPMC for the four cases: without porous media, 8mm porous media, 10mm porous media, 12mm porous media, and compared with the research of Arwut and Jarruwat references number 15 are shown in Figure 11. Results showed that the maximum and the highest average value of thermal efficiency calculated was obtained from using steel nuts porous media that is 10mm in size. It solved achieved the highest value of 39.09 kw of absorbed useful heat rate, and thermal efficiency of 67.32 % thermal efficiency compared to the one without the porous media (shown in Figures 10 and 11). With regards to the combustion stability of the system, the use of solid fuel resulted to a high fluctuation rate, which might be due to the high flowrate and combustion rate of the solid feedstock.

The error evaluation by heat balance was also presented on Figure 12. It shown that the hot-side (hot gas side) heat has around 6-9% more than that in cold-side (water side) heat. These errors may be due to the errors of instruments itself and effects of boundary layer at tube surfaces and chamber surfaces that not included in the experiment measuring.

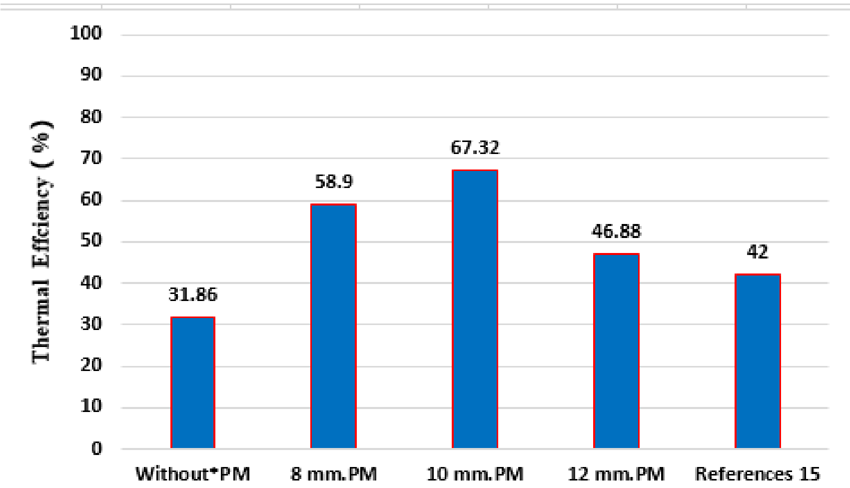

Fig. 11. The thermal efficiency of the SFPMC system.

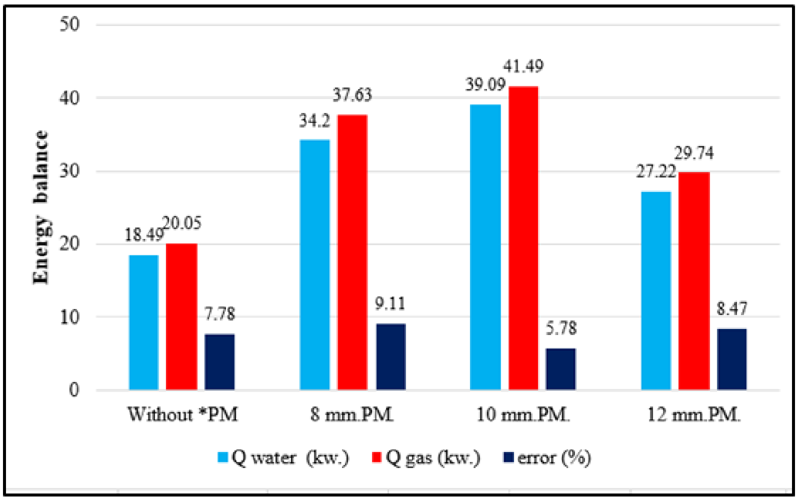

Fig. 12. The heat balance between hot and cold sides.

4. CONCLUSION

This research studied the effect of using waste stainless steel nuts as porous media on the efficiency of a hot water combustion system. The combustor used wood charcoal as fuel thereby coining the term solid-fuel porous media combustor (SFPMC). The experimental setup was done for two main cases: with (case II) and without (case I) the porous media. The setup with the porous media was further configured according to sizes: 8mm (case II-A), 10mm (case II-B), and 12mm (case II-C). The collected data were used to determine the setup with the highest heat transfer efficiency to the water tubes during combustion thereby giving a higher calorific value to the system and then comparing it to a nonporous kiln.

Based from the results, porous media encourages higher heat transfer efficiency as observed from the rise in the temperature of water at the heat exchange chamber during the experiment. This was also seen after comparing the water temperature at the inlet and outlet points of the two main setups. Porous media induces both the occurrence of conduction and convection heat transfer to water tubes resulting to higher heating temperatures as compared to the one without. Moreover, it was also noted that the size of the porous media affects the efficiency of the heat transfer occurrence to the water tubes. Based from the experiment, the size of the 10mm nut porous media was found to have the greatest thermal conductivity rate among the other tested sizes. The heat balance results has shown that the maximum error was within 10%.

So, it can be concluded that the using of waste nuts as porous media can improve thermal efficiency in the heat transfer application. It may be applied in economizer to improve heat recovery in the varying of thermal processes especially the factory that have a lot of waste nuts.

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NOMENCLATURE

SFPMC	Solid fuel porous media combustor
Without*PM	Without porous media
w/o	Without porous media
PM	porous media
W_{in}	Water in
W_{out}	Water out
$T_{w,o}$	Outlet water temperature
$T_{w,i}$	Inlet water temperature
$T_{gas,in}$	Inlet gas temperature
$T_{gas,out}$	Outlet gas temperature
LHV fuel	Lower heating value of fuel

Greek Letters

η_{SFPMC}	The efficiency of hot water production kiln using solid fuel for unidirectional gas flow
η_{im}	The improvement in terms of efficiency
$\dot{Q}_u$	The rate of heat transferred to hot water
C_P	Specific heat
$\dot{m}_{fuel}$	Fuel consumption rate
$\dot{m}_w$	Water flow rate
$\Delta H_{im,\,water}$	Heat transfer improvement of water
$\Delta H_{im,gas}$	Heat transfer improvement of gas
$\dot{Q}_{g,PM}$	The rate of heat transferred to hot gas with porous media
$\dot{Q}_{g,w/o}$	The rate of heat transferred to hot gas without porous media
$\dot{Q}_{water,PM}$	The rate of heat transferred to hot water with porous media
$\dot{Q}_{water,w/o}$	The rate of heat transferred to hot water without porous media
ε	Porosity
V_p	Volume of water without porous media
V_t	Volume of water combined with porous media

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