

A Preliminary Study on Rock Bed Heat Storage from Biomass Combustion for Rice Drying

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Abstract. One of the main constraints of biomass fuel utilization in a small scale rice drying system is the operating difficulties related to the adjustment of combustion/feeding rate. Use of thermal storage may reduce the problem since combustion operation can be accomplished in a much shorter time and then the use of heat can be regulated by simply adjusting the air flow. An integrated biomass furnace-rock bed thermal storage with a storage volume of 540 L was designed and tested. There were four experiments conducted in this study. Charging was performed within 1-2 hours with a combustion rate of 11.5-15.5 kg/h. In discharging process, the mixing of air passing through the rock bed and ambient air were regulated by valves. Without adjusting the valve during the discharging process, air temperature increased up to 80°C, which is not suitable for rice batch drying process. Charging with sufficiently high combustion rate (14 kg/h) within 1 hour continued by adjusting the valve during discharging process below 60°C increased the discharge-charge time ratio (DCTR) up to 5.33 at average air temperature of 49°C and ambient temperature of 33°C. The efficiency of heat discharging was ranged from 34.5 to 45.8%. From the simulation, as much as 156.8-268.8 kg of rice was able to be dried by the discharging conditions.

1. Introduction

The use of biomass fuel in a small-scale drying system has major constraints regarding its operation, especially in regulating the rate of combustion and feeding. Manually combustion rate settings may cause inconvenience for operators by having to set up the feed rate as well as to monitor the combustion process during the drying process. Automatic control can be applied by controlling the motor feeding system, but the use of such a system is quite expensive and often encounters problems of operation.

The use of heat storage in the biomass furnace system can reduce these problems. By applying heat storage system, the operation of combustion can be performed in a much shorter time. Furthermore, during the drying takes place, the heat used is obtained from the heat storage material which in operation is much easier.

Rock is one of the heat storage material that is frequently used for drying. Several studies of rock heat storage using solar collectors for drying have been carried out, for example, the use of rock bed at the bottom of collectors in Jain (2006) [1] and Aboul-Enein et al. (2000) [2] or that separated from collectors in Tambunan et al. (2010) [3]. One of the advantages of rock bed heat storage use is its



capability to be used in high temperature compared to other materials such as water. At 1 atm pressure, water can only store heat with temperatures below 100°C, while rock can be used much higher than that temperature. The main problem of use of rock as a heat storage material is its specific heat capacity much lower than water. If the heat storage use is not at sufficiently high temperature, then the total heat that can be stored per unit volume becomes lower than that of water. Therefore, to obtain the real benefit of rock use, heat storage needs to be done at relatively high temperatures. Thermal storage research on high temperature of rock bed is commonly used to drive turbines in concentrated solar power systems [4-7] (Zenangeh et al., 2012; Allen et al., 2014; Allen et al., 2016; Cascetta et al., 2014). The fluids used in these studies include oil, molten salt, and air. Therefore the use of rocks as the heat storage material is considered to be potential from biomass combustion which is also generated at high temperature.

In batch mode grain drying, the desirable air temperature should be moderate, preferably below 55°C. In addition, the air flow rate for drying should also be set at a certain level to avoid inefficiency of the drying process. For this purpose, the heat originated from storage needs to be mixed with the ambient air in a certain ratio to obtain suitable drying air conditions.

Study on rock bed heat storage using biomass energy sources especially applied for drying was still rare, so we conducted a preliminary study to experimentally investigate the performance of the system. Therefore, an integrated heat rock storage – biomass furnace was designed, built and tested.

2. Materials and methods

2.1. Experimental setup

The design of integrated biomass furnace-rock heat storage with a volume of 540 L is schematically described in figure 1. The walls of furnace and storage chamber were made from steel plate and then insulated by ceramic wool and glass wool. The wall of ducting from the heat storage was also insulated by glass wool. The rock used was crushed basalt rock. The rocks were poured into the storage chamber until the bed height was around 1500 mm or equal to 735 kg. The biomass used was teakwood waste piece. The experiments were conducted in two stages, i.e., charging and discharging processes.

The charging process is started by burning the biomass in the furnace. The blower was then switched on, but at the initial period, the valve connecting the ambient air and the chamber above the bed was completely closed so that the negative pressure above the bed will cause the flue gas to pass through the bed of rocks.

To start the discharging stage, the biomass fuel was removed from the furnace and the valves were adjusted in such a way that mixing of the ambient air and the heated air occurred. At both stages of the process, the temperature measurement was carried out by placing a K type thermocouple inside the rock and the air closed to the measured rock representing the bottom, middle and top regions. In addition, temperature measurements were also carried out at air temperature inside the ducting as well as at the ambient. The temperature changes were recorded during the processes with interval of 1 minute. The charging process was stopped when the air (gas) out had reached 60°C, while the discharging process was stopped when the air temperature had reached less than 10°C above the ambient temperature. Airflow rate was obtained from the measurement of air velocity by using an anemometer in the ducting.

The void fraction was determined by putting the rock bed into a cylindrical chamber, so the volume of the rock bed was 20 L and subsequently was filled by water in such a way that the surface was equal to that of the bed. The water volume filled is denoted by V_{water} , while V_{tot} is the 20 L volume. The void fraction (ε) was calculated by:

$$\varepsilon = \frac{V_{\text{water}}}{V_{\text{tot}}} \quad (1)$$

The true density and the dimension of the rocks involving maximum length, thickness and volume were obtained by measuring 20 samples of rocks. The equivalent diameter was obtained from the measured volume.

2.2. Experimental procedure

Four experiments were carried out in this study with procedures as described in table 1. The biomass fuel feeding was performed manually into the furnace based on the flame condition and the temperature of the furnace. The valves V_1 , V_2 dan V_3 (figure 1) were used to adjust the air flow from ambient air as well as from the storage chamber in order to manually control the combustion process (in the charging stage) as well as the temperature of the air flowing in the duct. The outlet air temperature which is used as the parameter to control the charging as well as the discharging stage was measured inside the duct at the middle position.

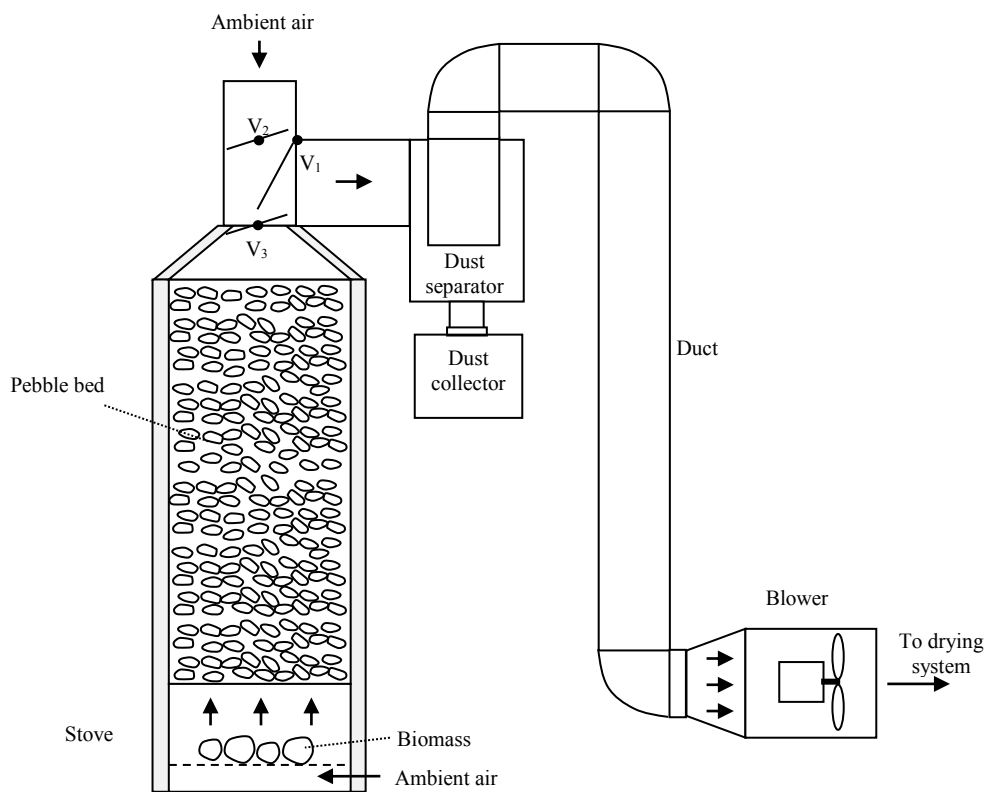


Figure 1. Schematic design of integrated biomass furnace – rock heat storage

2.3. Experimental parameters

The heat used (Q_{disc} , in kJ) to raise the temperature from ambient air (t_i , in $^{\circ}\text{C}$) to outlet air temperature (t_o , in $^{\circ}\text{C}$) during the discharging process was calculated numerically by:

$$Q_{disc} = \int_0^{\theta_{disc}} \dot{m} c_p (t_i - t_o) d\theta \quad (2)$$

where \dot{m} and c_p are the mass flow rate (kg/s) and the specific heat capacity (kJ/kg- $^{\circ}\text{C}$) of flowing air determined at outlet air temperature, respectively.

The overall efficiency (η_{disc}) is the ratio of Q_{disc} to the potential energy of the fuel (i.e heat energy from biomass combustion (Q_b)), which is expressed as:

$$\eta_{disc} = \frac{Q_{disc}}{Q_b} \quad (3)$$

Table 1. Experimental procedures

Procedure		Experiment			
		I	II	III	IV
Valves adjustment		<ul style="list-style-type: none"> Only used V₁. V₂ and V₃ were not installed 	<ul style="list-style-type: none"> Used V₂ and V₃ V₁ was not installed 	<ul style="list-style-type: none"> Used V₂ and V₃ V₁ was not installed 	<ul style="list-style-type: none"> Used V₂ and V₃ V₁ was not installed
Combustion rate		<ul style="list-style-type: none"> Initial period: (± 0.18 kg/min) End period: (± 0.18 kg/min) 	<ul style="list-style-type: none"> Initial period: (± 0.18 kg/min) End period: (± 0.10 kg/min) 	<ul style="list-style-type: none"> Almost constant (± 0.14 kg/min) 	<ul style="list-style-type: none"> Almost constant (± 0.23 kg/min)
Charging			<ul style="list-style-type: none"> Temperature of top region of bed at 120°C. V₂ was adjusted so the outlet air temperature less than 70°C. 	<ul style="list-style-type: none"> Temperature of top region of bed at 120°C. V₂ was adjusted so the outlet air temperature less than 65°C 	<ul style="list-style-type: none"> Charging time was set for 60 minute
Discharging	Outlet air temperature target	<ul style="list-style-type: none"> Initially V₁ was adjusted to reach initial outlet air temperature of 60°C, and subsequently, V₁ was not altered. 	<ul style="list-style-type: none"> Outlet air temperature was kept below 60°C by continuously adjusting V₂ dan V₃ 	<ul style="list-style-type: none"> Outlet air temperature was kept below 60°C by continuously adjusting V₂ dan V₃ 	<ul style="list-style-type: none"> Outlet air temperature was kept below 60°C by continuously adjusting V₂ dan V₃

where Q_b is defined as

$$Q_b = \dot{m}_b h_b \theta_{ch} \quad (4)$$

with \dot{m}_b denotes the average of fuel combustion rate (kg/s), h_b denotes the *lower heating value* of the biomass used (kJ/kg) and θ_{ch} is the charging time (s).

The ratio of discharging-charging time (DCTR) was used as the convenience parameters in thermal storage operation, which is expressed by:

$$DCTR = \frac{\theta_{disc}}{\theta_{ch}} \quad (5)$$

where θ_{disc} is the discharging time (s).

3. Results and discussion

3.1. Physical characteristics of the crushed basalt rock

The physical characteristics of the crushed basalt rock were described in table 2. The length was defined as the maximum length of the piece, while the thickness was measured at the position of half-length. The rock density was 2.63 kg/m^3 and their sizes (length and thickness) varied widely. In general, the pieces have oblong shape with average equivalent diameter of 30 mm. By such the distribution of shape and size, the obtained porosity of the rock bed was 0.47.

Table 2. Physical characteristics of the crushed basalt rock

Parameter	Value
Density (kg/m^3)	2.63
Length (mm)	51 ± 11
Maximum thickness (mm)	28 ± 6
Minimum thickness (mm)	19 ± 4
Porosity (-)	0.47

3.2. Heat storage performance

In experiment I and II, the fuel feeding rate at the first 30 minutes were set to be higher than the rest, while in experiment III and IV the feeding rates were almost constant during the charging state. Table 3 summarizes the experimental parameters in both charging and discharging processes.

The change of bed temperature in bottom region during the charging process (not shown in this paper) from each experiment exhibited different patterns. In experiment I, the temperature of the bottom region increased rapidly up to 350°C and fluctuated at $300\text{--}350^\circ\text{C}$. However in experiment II after the bottom temperature reaches 450°C , the temperature slowly decreased as the feeding rate reduced. The experiment III exhibited continuous increase up to 500°C at the end of charging while in the experiment IV the temperature stable at around 500°C after 35 minutes discharging started due to the higher feeding (and then combustion) rate of fuel. However, change of bed temperature in middle and top region were almost similar for all experiments. In addition, the temperature less fluctuated due to the flue gas that had passed through the high heat capacity of rock bed.

Discharging process was started when the heat supply from furnace had been stopped. The temperature at the bottom region was instantaneously decreased for all experiments. For the middle region, the change was closely related to the condition of end of the charging process. At the earlier period, experiment I and III showed that the middle region temperature still increased while that of experiment II had decreased with respect to time. In experiment II, due to the lower combustion rate in the end period of charging, the middle region temperature had reached its peak before enter to the discharging process. In the experiments I, II and IV the heat transfer from the bottom region to the middle region were still occurred. In the top region the temperature change pattern was similar to that in the middle region.

The air coming out of the bed was mixed with ambient air entering from the chimney inlet so that the temperature could be set by adjusting the valve V_1 (in experiment I) or V_2 and V_3 (in experiments II, III dan IV). In experiment I, the valve V_1 was adjusted only at the initial period of discharging to set the outlet temperature at 60°C . Since the bed temperature at the top region still increased, the outlet temperature increased as well since the valve was not adjusted anymore. The outlet temperature reached 83°C and subsequently decreased when the bed temperature in the top region had reduced.

Such the high temperature is not suitable for rice drying in batch mode. In addition, the discharging time was short, i.e. only 170 min.

Table 3. Performance of furnace-heat storage system

Stage	Parameter	Experiment			
		I	II	III	IV
Charging	Charging time (min)	72	92	115	60
	Total fuel (kg)	11.5	12.5	15.5	14
Discharging	Discharging time (min)	170	282	360	320
	Discharging final temperature (°C)	42.4	38	40.6	41.1
	Average outlet air temperature (°C)	69.4	51.4	52.8	49.6
	Average ambient temperature (°C)	36.0	33.7	34.3	33.7
	Volume flow rate or air (m ³ /s)	0.263	0.245	0.278	0.293

In experiment II, III and IV, the valves V_2 and V_3 were adjusted so the outlet temperature below 60°C. The air volume flow rate used were 0.245, 0.278 and 0.293 m³/s, respectively. By adjusting the valves the average temperature were 51.4, 52.8°C and 49.6°C with discharging time reached 282, 360 and 320 minutes. It is important to note that in this study the discharging time was defined as the time started from the fuel was removed to a condition where the difference between the outlet and the ambient temperature was still higher than 10°C. If the final discharging is defined by using a lower difference of those temperatures, then the discharging time can be sufficiently higher.

3.3. Energy obtained during discharging process

Table 3 shows the energy obtained during discharging process, discharging efficiency and DCTR. The discharging energy of experiment I, II, III and IV were 89.6, 73.4, 111.1 and 89.5 MJ with discharging efficiencies were 45.8, 34.5, 42.2 and 37.6%, respectively. Such the low discharging efficiencies were contributed by combustion process and heat loss from the system. The heat loss from the system involved heat loss through walls during the charging and the discharging process as well as convectively through exhaust gas. The heat loss through exhaust gas was not sufficiently high, however, due to its temperature was kept below 60 or 70°C during the charging process. The highest heat loss was probably the heat penetrating the furnace door since it was made of an uninsulated iron plate.

The discharging efficiency could be influenced by discharging rate and charging method. In experiment I, discharging process was performed in relatively short time, therefore, the heat stored in the rock can be used more efficiently than the others. However, the experiment III, due to its final temperature in the charging period was higher, had higher efficiency than the experiment II. The slightly lower discharging efficiency in Experiment IV might be caused by higher energy loss from the furnace due to its highest combustion rate.

The high rate of fuel combustion in Experiment IV provided sufficient heat charging process in a relatively short charging time, i.e., 60 minutes. By discharging time similar to that of Experiment II

and III, the DCTR of this experiment reached 5.33 while its efficiency was still higher than that of Experiment II. This shows that at a higher combustion rate, charging process was able to be performed effectively. Charging process was able to be carried out sufficiently fast since the bed pores providing high heat transfer rate. The higher combustion rate is still able to be performed to provide higher DCTR, despite a possible reduction of discharging efficiency to occur.

Table 4. Discharging energy and DCTR

Parameters	Experiment			
	I	II	III	IV
Discharging energy (MJ)	89.6	73.4	111.1	89.5
Energy stored in the fuel (MJ)	187	204	263.5	238
η_{disc}	45.8%	34.5%	42.2%	37.6%
DCTR	2.36	3.07	3.13	5.33

3.4. Drying simulation

Experiments II-IV yielded a suitable drying air temperature for rice drying. The determination of the amount of rice able to be dried by those conditions was performed by deep bed rice drying simulation which is developed by Nelwan, et al. 2013 [8]. The simulation results showed that the air having conditions resulted from experiments II, III and IV could be used to dry 156.8, 268.8 and 201.6 kg of rice, respectively, from initial moisture content of 23% w.b. to final moisture content of 14% w.b. By the definition discharging time mentioned before, the final discharging temperature was still in range of 38-41.1°C. Such the condition of air is still to be very potential to be used for drying process, for example the drying air could be used until it decreases up to 35°C, so that the drying load can still be increased.

4. Conclusions

A rock bed heat storage system with heat source from biomass combustion for heating of drying air has been developed in this study. The basalt rock piece was used and they had oblong shape with equivalent diameter of 30 mm and porosity of 0.47. By using 735 kg of rock bed, the charging process could be accomplished within 1-2 hours. Without adjusting the air flow rate in discharging process, from an initial temperature of 60°C, the air drying increased continuously up to 83°C which is not suitable applied for rice drying. By using sufficiently high combustion rate of 14 kg/h in 1-hour charging, the obtained DCTR was 5.33 at outlet and ambient air temperatures of 49°C and 33°C, respectively. However, the high combustion rate could reduce the discharging efficiency. The efficiency of heat discharging for all experiments were ranged from 34.5 to 45.8%. From the simulation, as much as 156.8-268.8 kg of rice was able to be dried by the discharging conditions. The performance improvement could still be performed by lowering the limit of temperature to be used for drying.

Acknowledgement

This research is funded by PTUPT, year 2017. The authors also thank Rustam, Jefrianus and Iqbal who assisted in data collection.

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