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Construction and Testing of Continuous Feed Biomass Thermosyphon Torrefaction Reactor

Nitipong Soponpongpipat*[1] and Sanphasit Chonlaphan

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ABSTRACT

Because of different heat mechanism, the temperature distribution inside a reactor has its own characteristic. This is the limitation to increase the capacity of the reactor. This idea led to modify fixed-bed reactor that has a limitation on non-uniform temperature distribution inside a reactor with increasing heat transfer area by setting thermosyphon tube since fixed-bed reactor has another limitation in capacity and heat loss. Therefore, modifying fixed-bed reactor to operate as semi-batch can fix the limitation and improve thermal efficiency of a reactor as well. In order to study the performance of the reactor for torrefaction process, analyzing the fuel properties of each torrefied biomass batch is necessary. The controlled variables of this research are the temperature of heating chamber, which are 350, 400 and 400°C with an allotted torrefaction time of 35 minutes per batch that is close to research condition of thermosyphon reactor fixed-bed type. Fuel properties analyzed in this research are high heating value (HHV), bulk density, and energy density. This research also recorded the temperature inside the reactor to determine the temperature distribution when operated as a semi-batch reactor. From the results gathered, it was discovered that when the operating reactor reached a steady behavior, the torrefaction process increased to a high level. As seen in energy density ratio, it reached a high level because of the increase of HHV ratio, that is 1.182 - 1.412 for 350 - 450°C. The bulk density ratio is also very low, and the value is close to a herbaceous biomass type that is usually seen in woody samples. These factors cause such energy density ratio in high levels and intensity of such process inside the reactor.

1. INTRODUCTION

Torrefaction temperature and process time are the factors that cause the disintegrating reaction of biomass. This process decreases ratio of oxygen per carbon and hydrogen per carbon close to coal [1]-[4]. Therefore, these are very important factors in designing a machine of a reactor. Let the reactor transfer heat to biomass as designed and keep this condition till the optimum time [5], [6]. The reactor was separated to 2 types depending on the heat transfer mechanism. First is direct heat transfer. Mechanism of heat transfer is convection by fluid or solid thermal carrier through biomass particles. Direct heat transfer was applied for mechanism of reactor, fluidized bed, rotary drum, and microwave. Second is indirect heat transfer. Heat transfer between biomass particle by heat conduction and radiation. Indirect heat transfer was applied for mechanism of reactor, screw conveyer and fixed-bed reactor etc. [7], [2]. Since there are different mechanisms of heat transfer to biomass even with the same torrefaction process condition, the fuel properties can be different [8]-[10]. This means there is no single best reactor that is appropriate for all types of biomasses and all torrefaction conditions [2]. Moving bed and fixed reactor are similar in heat transfer mechanism but different in biomass particle movement. The biomass particles in a fixed bed reactor are not moving. This affected the performance in terms of capacity and heat transfer of the reactor. Moving bed reactor guaranteed to have the best heat transfer performance while having the cheapest operational cost. Direct heat transfer to biomass particles. Production process cost net is 56 Euro/ton. While rotary drum and screw conveyor has a production process that costs 71 and 77 Euro/ton respectively [5], [2]. For this reason, moving bed reactor was modified to a heat transfer mechanism in order to develop a reactor fit to industry scale [2]. In addition, this principle was modified to a lab scale reactor in semi- batch type, for example: SRSB (slot-rectangular spouted bed) and DSRSB (dual-compartment slot-rectangular spouted bed) [8], [11], [12].

Most of construction and modified reactors often begin at a laboratory scale. For studying the reactor behavior and operation process, after improved failing of reactor, this technology will develop to industry scale.

*Department of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University, Nakhon Pathom 73000, Thailand.

[1]Corresponding author;
Tel: +66927345956.
E-mail: Nitipongsopon@gmail.com.

As explained above, moving bed reactor has a good heat transfer at the lowest cost operation. One limitation of moving bed reactor is non-uniform temperature distribution especially in indirect heat transfer type. This makes fuel properties non-uniform too and have a limited capacity of the reactor [13]. The way to solve the problem about non-uniform temperature distribution is to increase the heat transfer area from the reactor to biomass particles. This idea led to modifying the fixed-bed reactor that has limitations about non-uniform temperature distribution inside a reactor by increasing heat transfer area with setting thermosyphon tube. Thermosyphon tube has a good heat transfer and very simple to operate mechanically. Applying thermosyphon tube with the reactor can improve temperature distribution more uniformly. This is the thermosyphon tube's advantage [14]-[16]. Compact bulk arrangement biomass in fixed-bed reactor created water vapor that play a role as an autocatalyst. Reaction increases HHV value [17]. But thermosyphon reactor fixed bed has a limitation in capacity, heat loss in cooling down at completion and heating at the beginning process. With this, thermosyphon reactor fixed-bed type will have less thermal efficiency than continuous and semi-batch type. Therefore, modifying thermosyphon reactor fixed-bed type to semi-batch type can solve its limitation about temperature distribution and heat loss. In addition, it improves reactor capacity and thermal efficiency as well.

As explained above, modifying thermosyphon reactor to semi-batch can solve the limitation but modifying the reactor will change the reactor behavior and process inside it too. Hence, it is very important to understand the torrefaction process and the behavior inside a reactor for the efficiency of operating reactor and development of reactor to industry scale. Reactors that operate as semi-batch has inlet temperature through non-uniform outlet. These can present reactor's behavior. In lab scale reactor, inlet temperature is always lower than the outlet. For example, SRSB (slot-rectangular spouted bed) and DSRSB (dual-compartment slot-rectangular spouted bed) [8], [11], [12]. Torrefaction temperature and time are the most important parameters as explained above. As a result, the reactor's behavior will be affected by its fuel properties. Studying the torrefaction behavior inside a reactor is necessary for developing a reactor. Mean modify thermosyphon reactor to semi-batch needs understanding of torrefaction process and behavior inside a reactor. These would help a reactor operate efficiently and be developed to industry scale.

The explanation of the effects of torrefaction process inside a thermosyphon semi-batch type on fuel properties can be obtained through trial and error only. This can be performed by controlled importance parameter, feed rate, torrefaction temperature, and process time. [5], [2]. Such factors are required since fuel properties can define the performance of the reactor, these led to the research of reactor behavior and fuel properties in each batch after the torrefaction process is complete by controlled heating chamber at 350°C, 400°C, and 450°C. Torrefied biomass was pushed out from the system every 35 minutes. This condition is close to experimental set-up for thermosyphon reactor fixed-bed type [14]. To study the performance of the reactor, the fuel properties that were analyzed in each batch in this research were HHV, bulk density, and energy density. Also, the temperature inside the reactor was recorded in order to determine reactor behavior and temperature distribution. These explained the heat transfer performance of an improved reactor.

2. METHODOLOGY

For the study of the behavior of thermosyphon in semi-batch reactor, since temperature distribution behavior inside a reactor will be affected by temperature and process time, fuel properties have changed based on these behaviors. Therefore, it is very necessary to study fuel properties under torrefaction with a thermosyphon semi-batch reactor. After this, it is also necessary to analyze fuel properties with temperature distribution by recording the temperature inside the reactor with the set thermocouple through the reactor.

2.1 Sample

Sawdust was used in this experiment. It is "mixed wood sawdust" collected from wood furniture industry. Samples were chopped by a hammer mill into pieces then sieved until the sample has a particle size of 1 mm - 5 mm. Samples were dried in an oven at 105°C for 24 hrs. Samples were then kept in a desiccator with a moisture control of 10% (w.b.).

2.2 Experimental Set up

Thermosyphon reactor has a thermosyphon tube set as a part of the reactor wall. Heat is transferred from the burner at the bottom. Heat transfer to biomass particles takes place inside the reactor. Condenser section height is 0.6 m. And evaporator section height is 0.3 m. Dowtherm- A is a working fluid. Reactor fuel is LPG. Operation as semi-batch is done by three machines working together; namely: feeding system machine, thermosyphon reactor, and storage machine.

For the study of torrefaction process of thermosyphon reactor semi-batch type, affected by the temperature and process time on fuel properties, each batch was pushed out from the reactor at the beginning of the operation. This needs analysis of the change of fuel properties after the treatment by torrefaction and record the temperature inside the reactor for the study of temperature distribution. This will present the reactor's thermal characteristics.

First, the biomass was fed to a feeding system machine to fill-up the thermosyphon reactor. The reactor was then warmed up for 90 minutes. The heating chamber was controlled at 350°C, 400°C, and 450°C. Each condition took a solid residence time of 35 minutes per batch. Torrefied biomass was continuously kept in the storage machine at first until the last batch for fuel property analysis. Therefore, this research requires three conditions to operate as semi-batch reactor. Operational condition is shown on Table 1.

Table 1. Experimental conditions.

Case	Biomass	Controlled Temperature	Torrefaction Time
1	sawdust	350	35
2	sawdust	400	35
3	sawdust	450	35

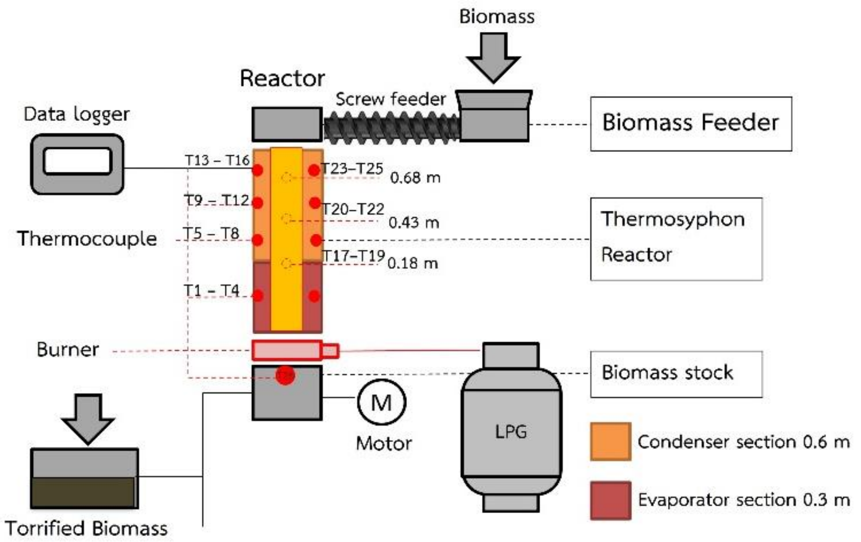

Fig. 1. experimental set up.

2.3 Fuel Properties

Torrefied biomass was pushed out in 35 minutes/batch. In the same length of process time, fuel properties were analyzed in each batch from the beginning. The explanation of torrefaction process and heat transfer performance were obtained by analyzing the fuel properties of each batch. Hence, samples from each batch were analyzed for HHV, bulk density, and energy density following the ASTM standard. 711-724. Fuel properties were co-studied with temperature distribution for the analysis of the reactor's behavior. The trend of temperature distribution and change of fuel properties will explain the torrefaction behavior inside the reactor.

2.3.1 HHV

HHV was analyzed by bomb calorimeter. A sample of 5g for not torrefied and 0.5g for torrefied was loaded to the bomb's head with 10 cm ignition wire on the sample. The testing is in accordance with ASTMD3286-85.

2.3.2 Bulk Density

Bulk density is ratio of weight per volume. This research used a box sized 305 mm x 305 mm x 305 mm and the testing is in accordance with ASTM E-873.

2.3.3 Energy Density

Energy density has a higher heating value compared with volume. Result is from the multiplication of HHV, and bulk density as shown in Equation 1.

$$\text{Energy Density} = \text{HHV} \times \rho_{bulk} \tag{1}$$

When HHV is higher than heating value (MJ/kg) and ρ_{bulk} is bulk density (kg/m^3).

2.4 Temperature Distribution

The reactor's inside temperature and wall temperature were recorded for the study of the reactor's behavior. Reactor wall temperature was set thermocouple 4 levels. Each level was set 4 positions around the reactor. From the bottom, each level is 12 cm, 20 cm, 24 cm, and 24 cm wide for T1 – T4, T5 – T8, T9 – T12, and T13 – T16 respectively. That counts to 16 positions. Inside the reactor has set thermocouple of 3 level. Each level is 18 cm, 25 cm, and 25 cm wide for T17 – T19, T20 – T22, and T23 – T25 respectively. T26 was set in heating chamber and T24 in ambient air as shown in Figure 1.

3. RESULT AND DISCUSSION

The controlled variables are torrefaction temperature and process time. Fuel properties that were studied in this research include HHV, bulk density, and energy density. In addition, this research has recorded temperature distribution inside the reactor for the study of reactor's behavior. Consequently, this study will explain the torrefaction process inside a reactor.

3.1 HHV

From Figure 2, it is found out that HHV slightly increases from the 1st batch to the 4th batch in case of 350°C and 400°C. HHV value is 20.95 MJ/kg – 21.18 MJ/kg and 23.18 MJ/kg – 23.42 MJ/kg respectively until the 5th batch HHV value was closed to the 4th batch. Value difference is 0.23 MJ/kg and 0.24 MJ/kg for case 350°C and 400°C respectively. This trend happened in case 450°C as well. But in this case, HHV value is increased until the 5th batch. The 6th batch is of very close value with the 5th. Value difference is 0.36 MJ/kg.

With the same process time of 35 minutes, the HHV value of each batch slightly increases from the beginning of the operation until the 4th batch and on the 5th batch the value changes just a little bit. This present reactor's behavior reaches a steady state operation (steady behavior). Considering this trend with the temperature distribution data from Figure 3 and Figure 4, the result has shown a significant consistency. Temperature distribution inside the reactor has slightly increased in each batch. Also, the heating rate in each batch is not constant until the reactor reaches a steady behavior. After feeding the biomass, the temperature inside the reactor first decreased then slightly increased until the complete torrefaction time of 35 minutes and torrefied biomass is pushed out to the storage section as shown in Figure 5. The reactor's behavior has shown a profile of temperature distribution that will reach a steady behavior in the 4th batch for 350°C, 400°C and the 5th batch for 450°C.

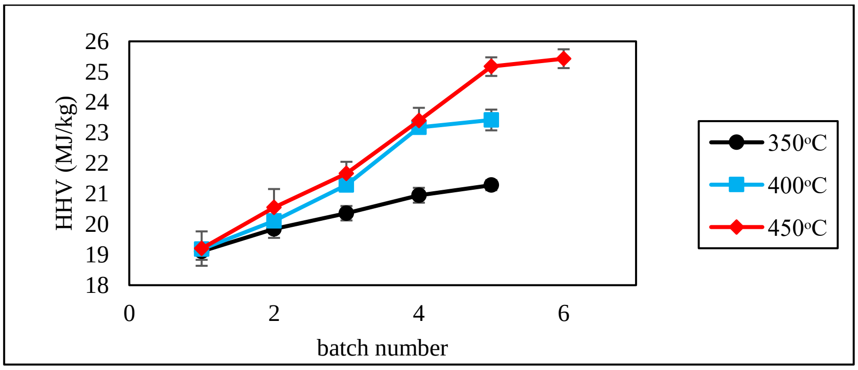

Fig. 2. Higher heating value with batch of biomass.

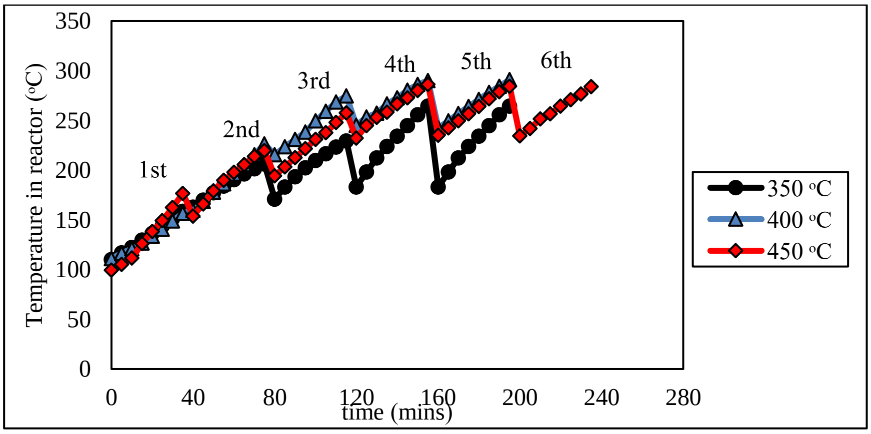

Fig. 3. Average biomass's temperature in each batch.

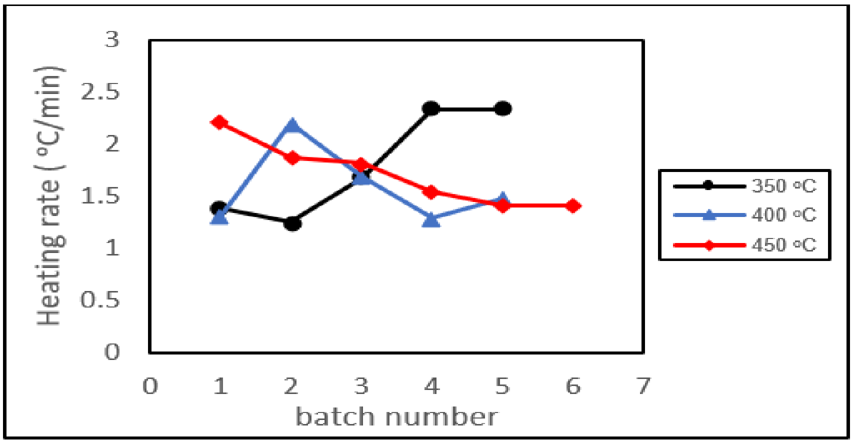

Fig. 4. Heating rate in each batch.

From Figures 3 and 5, each time biomass was fed into the reactor, the average temperature inside the reactor decreases that indicates the reactor's heat loss. Heat loss slightly decreases in every batch and every feeding. Biomass has a characteristic of being resistant to heat conductivity. The reactor's temperature in the bottom of the reactor has the highest temperature because it is close to the heat source. And the height level of 0.43 m and 0.68 m. belong to the lowest temperature because of the heat transfer between the reactor's wall and biomass particles. This causes the average temperature at the beginning to be low. Temperature distribution inside a reactor is shown in Figure 5.

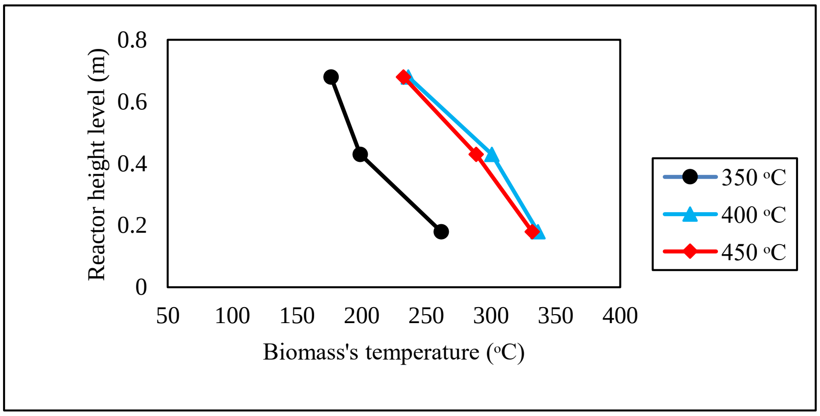

Fig. 5. Biomass's temperature inside reactor.

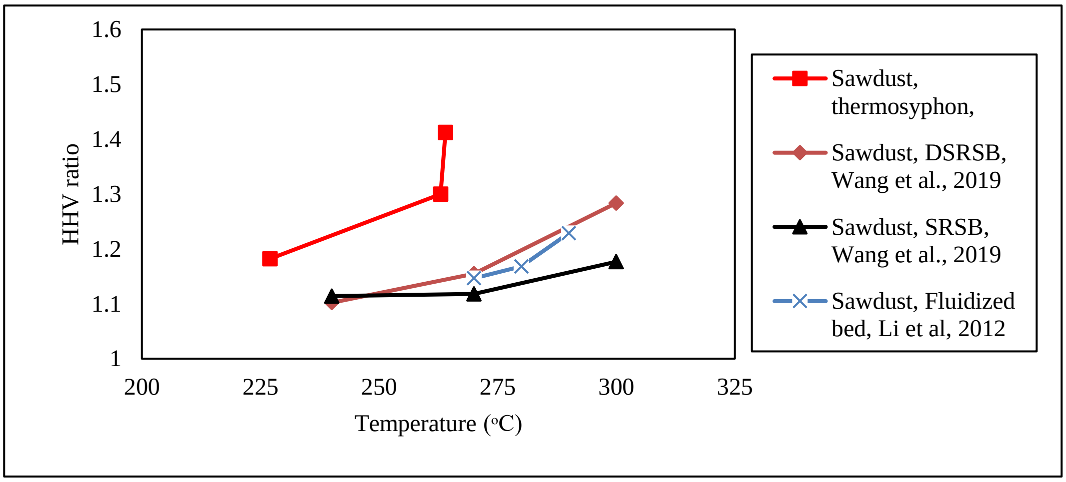

Fig. 6. HHV ratio compared with literature survey data.

From Figure 6, it is showing the comparison of HHV ratio of torrefied sawdust from thermosyphon reactor with torrefied sawdust from the other semi-batch and continuous reactor SRSD, DSRSD, and fluidized bed. [11], [12], [18] In close range, temperature HHV ratio of torrefied biomass is higher than literature survey data. Considering the slope from Figure 6, it has been found that the highest incline slope is torrefied biomass from thermosyphon 0.00622 and then torrefied biomass from fluidized bed 0.00411, DSRSB 0.00303, and SRSB 0.00103 by descending order. This is by compact bulk arrangement of biomass with semi-batch operation. Water vapor produced from the torrefaction process will play a role as autocatalyst because HHV is increased. [17] From Figure 6, it is shown that the torrefaction process inside thermosyphon reactor is in severe level. Considering Figure 2 and Figure 3 has noticed a process inside the reactor that is caused by mass loss during torrefaction process. This can count as a disadvantage but with the severe level of torrefaction process it makes the operation permissible for lower torrefaction temperature in order to save fuel cost.

Both torrefaction temperature and process time are important parameters for fuel properties. When these parameters increase, HHV increases too. [4] Temperature distribution behavior inside the reactor as shown in Figure 3 and Figure 5 is compatible with HHV value in Figure 2. This trend also happened in the data from error bar with standard behavior. Heating rate in each batch also show constant value when the reactor reaches a steady behavior causing HHV to be of constant value when the reactor reaches this state as well. This means that when the average temperature in each batch is increased, HHV in each batch increases too.

3.2 Bulk Density

Each batch biomass's bulk density from the beginning of the operating process is decreased while the reactor's temperature is increased. This is because the torrefaction temperature is an important parameter that affects fuel properties. [4] From Figure 7, bulk density is slightly decreased in each batch: from 1st batch – 3rd batch in case 350°C and 400°C and from 1st batch – 4th batch in case 450°C. This is consistent with the temperature distribution profile in Figure 3. In the same torrefaction time, bulk density in each batch is different. A different value in every case is 153 kg/m^3 and 151 kg/m^3 difference value is 2 kg/m^3,1 .3 % for case 350°C, 149 kg/m^3 and 148 kg/m^3 difference value is 1 kg/m^3, 0.6% for case 400°C, 144 kg/m^3 and 143 kg/m^3 difference value is 1 kg/m^3, 0.69% for case 450°C. This is due to the reason that the temperature distribution has not reached a steady behavior. Then, the temperature inside the reactor is still changing and not stable which then affects the fuel properties.

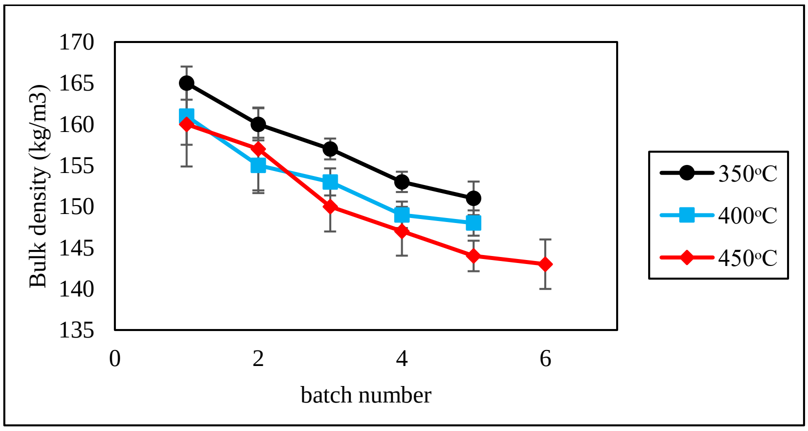

Fig. 7. Bulk density with batch of biomass

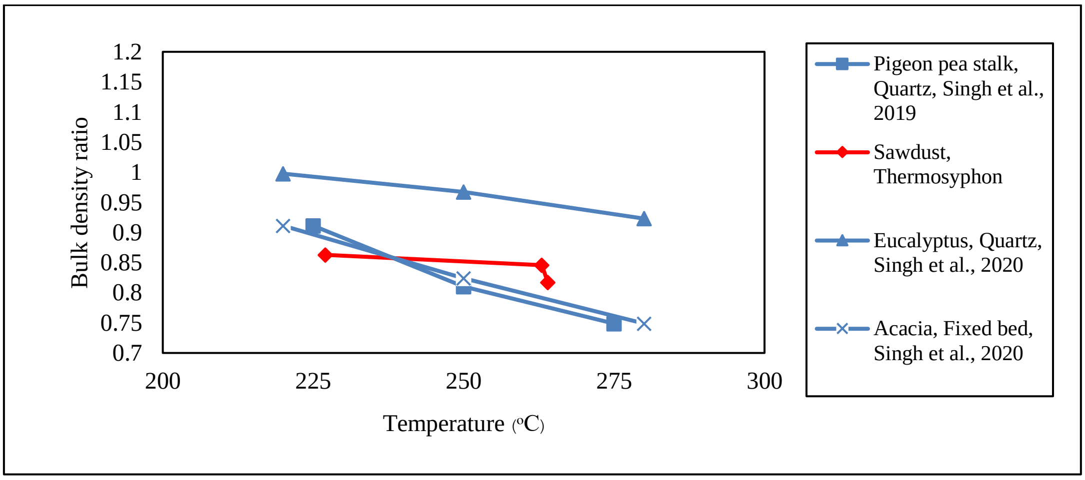

Fig. 8. Bulk density ratio with literature survey data.

Considering the slope of the graph from Figure 8, it is found out that the slope of sawdust and eucalyptus torrefied is coincidentally at -0.00124. This is because they have the same woody biomass type. [19], [20] From Figure 8, it has been found that the bulk density ratio of sawdust torrefied by thermosyphon reactor is close to Acacia and pigeon pea stalk. This has shown that the process inside the reactor is of severe level that led to disintegration. With this reason, bulk density is decreased in large scale.

In the same process time of 35 minutes, bulk density is different in each batch until the 4th batch. The value is close to the 5th batch 153 kg/m^3 and 151 kg/m^3 in case 350°C, 149 kg/m^3 and 148 kg/m^3 in case 400°C 144 kg/m^3 and 143 kg/m^3 in case 450°C. This is as shown in Figure 8.

3.3 Energy Density

The trend of energy density is like HHV. There is direct variation function to torrefaction temperature and process time as shown in Figure 3. Temperature distribution has affected energy density like HHV value. From Figure 9, in the same process time, energy density is slightly increased from the 1st batch. As shown in Figure 2 after the 4th batch, the reactor has reached a steady behavior. Energy density value is stable such as 3.199 GJ/m^3, 3.218 GJ/m^3 in case 350°C, 3.462 GJ/m^3, 3.471 GJ/m^3 in case 400°C, and 3.618 GJ/m^3, 3.611 GJ/m^3 in case 450°C. A difference value is just small, 0.59%, 0.25%, and 0.19% for 350°C, 400°C, and 450°C, respectively.

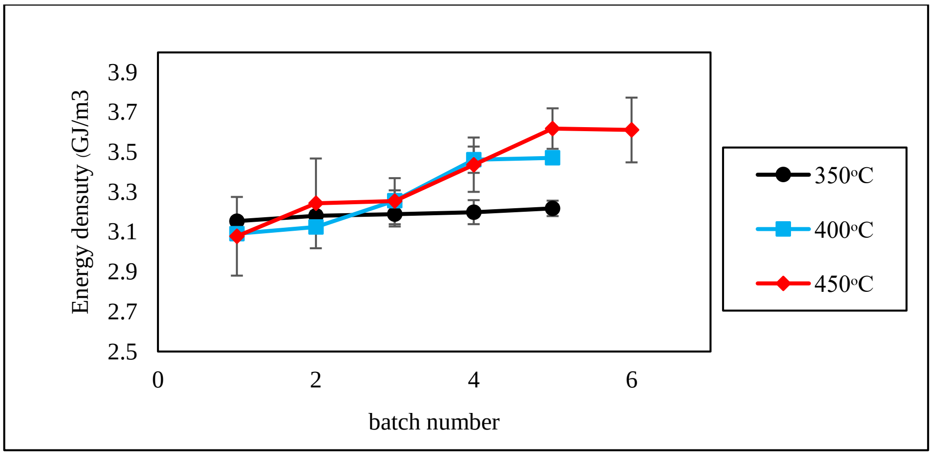

Fig. 9. Energy density with batch of biomass

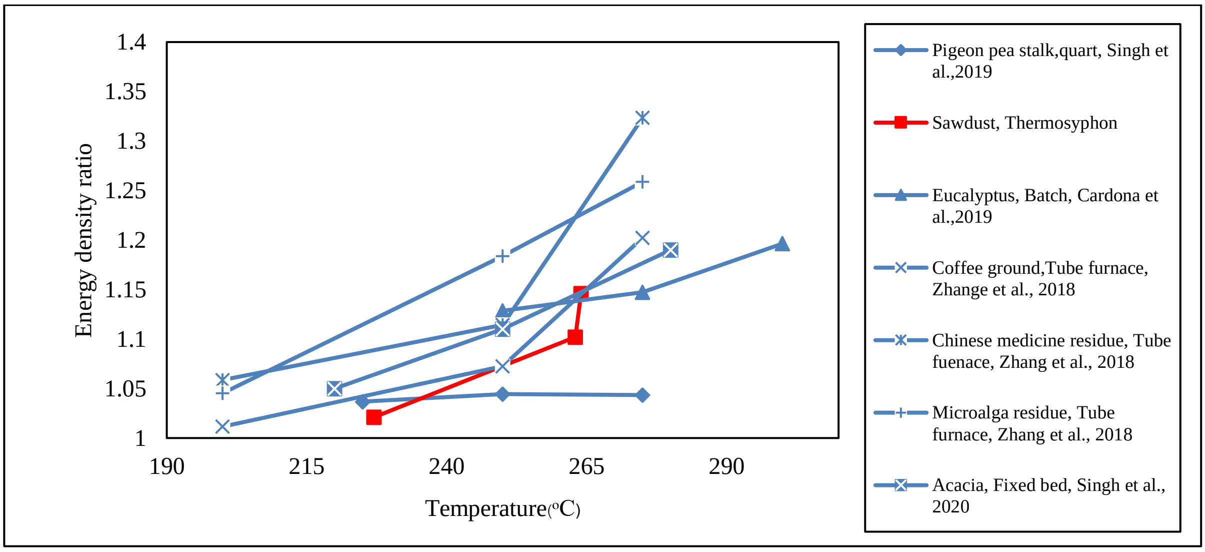

Fig. 10. Energy density ratio with literature survey data

From Figure 10, it has been found that the torrefaction process inside a thermosyphon reactor adheres to the other processes from literature survey data. [19]-[22] Energy density ratio can be as high as noticed from the slope of the graph in Figure 10 due to the increase of HHV, as seen in Figure 2. And bulk density is decreased in large scale from disintegration. Therefore, the increase of energy density in large scale is affected by HHV.

Energy density of sawdust has a similar trend as HHV. This happens when the operation of reactor reaches the steady behavior in the 4th batch and 5th batch for 350°C, 400°C, and 450°C, respectively. From Figure 10, it has been found that energy density has the same trend as the literature survey data and adheres with the data from literature too.

4. CONCLUSION

The purpose of this research is understanding the torrefaction process inside a reactor when operated as semi–batch and how the process affects fuel properties. Torrefaction process is operated by controlled heating chamber in 350°C, 400°C, and 450°C. Biomass was fed every 35 minutes. Temperature inside the reactor was recorded for the analysis of temperature distribution. After the torrefaction process, torrefied biomass was analyzed to fuel properties.

Operating as semi batch can decrease heat loss but still contains some of it when feeding new biomass into the reactor. This is due to the level 0.68 m. of reactor, the lowest temperature area. The temperature is slightly increased from top to bottom of the reactor that is closeted to heat source. After the completion of the torrefaction process, torrefied biomass temperature was close to reactor's wall temperature at that batch. This makes torrefied biomass of each batch have different fuel properties. HHV was increased from the 1st batch through the 4th batch in case 350°C and 400°C. In case 450°C is the 5th batch. HHV ratio of sawdust after torrefaction process with thermosyphon semi-batch reactor is 1.182 – 1.412. The slope of relation between HHV and temperature is 0.00697. Bulk density is decreased in each batch. Slope of relation between bulk density and temperature is -0.00124 that is close to the slope of a eucalyptus because of the similar woody biomass type. Considering bulk density ratio, it has been found that the value is close to Pigeon pea stalk and

Acacia because of the similarity of herbaceous biomass type.

From the result, it has been found that energy density ratio of sawdust torrefied with thermosyphon semi- batch reactor is in high level when compared with torrefied biomass from literature reactor. This is also because of the increase of HHV that is in high level and the bulk density ratio of torrefied sawdust from thermosyphon reactor is very low also. These cause energy density ratio in high level.

When reactor operating machine reaches the steady behavior, the torrefaction process will increase to high level even compared with similar or different type of biomass. This can present how severe torrefaction can be. Such reactions lead torrefaction process inside the reactor to high disintegration. The torrefaction process inside thermosyphon reactor creates water that reacts as a catalyst. These increase HHV and decrease bulk density.

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