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Short Torrefaction Process: A New Alternative Way for Biomass Pellet Upgrading

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ABSTRACT

Ordinary torrefaction process has objectives on the increase of higher heating value and energy density. Because of these expectations, the torrefaction of biomass pellet is facing many limitations. The other interest way to upgrade biomass pellet is short torrefaction which focuses on improvement of hydrophobic property and maintain energy density at the similar level to untreated biomass pellet. This work studied variations of equilibrium moisture content (EMC), durability index, and energy density of cassava rhizome pellet when it was torrefied at short residence times of 0-15 min. The normal residence times of 30 and 60 min were also conducted to identify the suitable residence time for short torrefaction process. The mathematical model was also developed to predict properties of cassava rhizome pellet after torrefaction. It was found that EMC and durability index drastically decreased for short residence times (0-15 min). There was insignificant difference in EMC and durability index for residence times of 30 and 60 minutes. Slight difference in energy density was found for residence time and torrefied temperature range of 0-60 min and 230-270℃, respectively. Therefore, the suitable residence time was dependent on EMC and durability index. The suitable residence time for short torrefaction at torrefied temperature of 230, 250, and 270℃ was 30, 15, and 10 min, respectively. Short torrefaction contributed to improvement of hydrophobic property. However, it was impossible to increase energy density by short torrefaction. In addition, the prediction results obtained from developed model displayed relationship between pellet properties and thermal degradation rate. The average absolute error (AAE) for prediction of EMC and durability index was 11.60 and 0.25%, respectively.

1. INTRODUCTION

Nowadays, biomass pellet is widely utilized both in power production (co-firing with coal) and heat production (domestic and small boiler). With superior storage and transportation properties than biomass chips and other forms of untreated biomass, the production and consumption of biomass pellet has been increasing continuously over the past few years [1]. Although biomass pellet has a higher bulk density and energy density than untreated biomass [2], it still has hydrophilic property and poor resistance to bio-degradation [3], [4]. These drawbacks lead to the need for careful storage and transportation to avoid declination of biomass pellet quality. Torrefaction is a promise process for upgrading biomass pellet's properties. The temperature of this process is in range of 200-300°C which is sufficient to decompose most hemicellulose and some cellulose present in biomass [5], [6], [7]. Product obtained from the process has more hydrophobic property and more resistance to bio-degradation. There are two methods to apply torrefaction in production of torrefied biomass pellet. The first one is torrefaction and then pelletizing, and the second one is pelletizing and then torrefaction [8]. For the first production method the product obtained was called pellet of torrefied biomass which had higher energy density [9] and higher heating value (HHV) [8], [10] but lower moisture content [10], [11] and moisture uptake [9], [12]-[14] compared to untreated biomass pellet. Because of thermal degradation during torrefied period, the natural binder contained in biomass was decreased resulting in high energy consumption for pelletizing [11]. In addition, severe torrefaction caused the requirement of binder such as steam, hot water, and glycerin for pelletizing of torrefied biomass [15]. Although the use of binder resulted in the significantly decrease of energy consumption for production [8], the amount of binder used was excess the values suggested by ISO standard [12]. In terms of economics, overall cost of pellet of torrefied biomass was lower than that of untreated biomass pellet [14]. However, recent work on feasibility study [16] reported a contrast result. It was reported that production of pellet of torrefied biomass

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cannot compete with conventional production of biomass pellet. For the second production method, pelletizing and then torrefaction, the product obtained was called torrefied char of biomass pellet. Its properties consisting of HHV, moisture content, and water resistance were better than untreated biomass pellet. However, torrefied char of biomass pellet had poorer density and durability compared to untreated biomass pellet [9], [17]-[19].

Two main objectives of upgrading of untreated biomass pellet are to decrease the transportation and storage cost. These objectives can be achieved by increasing the energy density and improving the hydrophobic property. Production of both pellet of torrefied biomass and torrefied char of biomass pellet faces many limitations as mentioned above because the production strongly focuses on the increase of HHV and energy density and improvement of hydrophobic property is valued as a by-product. The other interest way to upgrade biomass pellet is to focus on improvement of hydrophobic property and maintain energy density at the similar level to untreated biomass pellet. It can be accomplished by conducting torrefaction of biomass pellet with short residence time namely "short torrefaction". By this production method, thin hydrophobic shell took place on outer surface of biomass pellet resulting in improvement of hydrophobic property. This concept was confirmed by the decrease of equilibrium moisture content (EMC) of Douglas Fir pellet after short torrefaction [10]. The study on bulk density, durability, and fines contents of torrefied pellet with short torrefaction was also reported [20]. However, the data on the variation of EMC, durability, and energy density of biomass pellet after short torrefaction in wide range of torrefied temperature are insufficient to identify that short torrefaction is the promise way to upgrade biomass pellet.

In this work, the variation of equilibrium moisture content, durability index and energy density of torrefied char of cassava rhizome pellet (T-CP) at the short residence time range of 0-15 min was investigated. To specify the suitable residence time for short torrefaction, experiments were also conducted at the normal residence time range of 30-60 min. The simple mathematical model was also developed to predict the properties of the T-CP at various residence times and torrefied temperatures. Finally, identification of the suitable residence time for short torrefaction was discussed.

2. MATERIALS AND METHODS

2.1 Raw Materials

Cassava rhizome (Manihot esculenta species) was used as feedstock for pellet production. Firstly, the cassava rhizome was chopped to reduce its size into 5±2 mm using hammer mill. Later, the chopped cassava rhizome was placed in a hot air oven at 65°C to control the moisture content of chopped cassava rhizome at 8±2 %wb. When the moisture content reached the set point, dried cassava rhizome was placed in desiccators until its temperature reached room temperature. Finally, the prepared cassava rhizome was kept in closed container for pellet production.

2.2 Preparation of Untreated Cassava Rhizome Pellet (U-CP)

To prepare U-CP, water was mixed with prepared cassava rhizome to increase its moisture content to 12-14%wb. Well-mixed cassava rhizome of 10 kg was fed into a rotary flat die pellet mill. The die was rotated at speed of 278 rpm. The mixture was put back into the pellet mill three times to obtain the U-CP with diameter of 6.5 mm. After pelletizing, U-CP was placed at ambient temperature to increase its strength. Finally, U-CP was blown by an air blower to get rid of dust and other contaminants. The clean U-CP was separated and stored with two containers. U-CP in the first container was used as controlled sample for studying the properties of U-CP. The other one was used for preparation of T-CP.

2.3 Preparation of Torrefied Char of U-CP (T-CP)

To prepare T-CP, a laboratory fixed bed cylindrical reactor [21] was used to conduct torrefaction of U-CP. The reactor was heated by a 220V-electrical heater with the heating rate of 20°C/min. Nitrogen was used as purge gas. The nitrogen flow rate was 100×10^{-3} L/min. Torrefied temperature was 230, 250, and 270°C. Although the objective of this work was to investigate the properties of pellet which torrefied at short residence time, the properties of torrefied pellet prepared with long residence time were still necessary for identifying the suitable residence time. Therefore, the residence times were set at 0, 5, 10, 15, 30, and 60 min for each torrefied temperature. It was noted that U-CP was torrefied by indirect heating. Thus, the preheating time of 11.5, 12.5, and 13.5 min was required to reach the torrefied temperature of 230, 250, and 270°C, respectively. For the residence time of 0 min, when the torrefied temperature reached the set point, the electrical heater was immediately stopped. After torrefaction, the reactor was sealed to prevent the torrefied char from outside air and left to cool down until the temperature of T-CP inside the reactor reached room temperature. Then, T-CP was removed from the reactor and kept in airtight plastic containers for further analysis.

2.4 Properties of U-CP and T-CP

The higher heating value (HHV) of both U-CP and T-CP was determined by plain jacket bomb calorimeter. Testing procedure was in accordance with ASTM D5865-07 [23]. Testing procedure for evaluating bulk density was follow ASTM E873-72 [22]. Bulk density (ρ) was calculated form mass of bulk pellets (m) and bulk volume (V) as shown in Equation 1.

$$\rho = \frac{m}{V} \qquad (1)$$

When HHV and bulk density were known, energy density can be determined by Equation 2 [17].

$$ED = HHV \times \rho \qquad (2)$$

To determine equilibrium moisture content (EMC), U-CP and T-CP samples were dried with the temperature of 105±1 °C for 24 h in hot air oven. Later, U-CP and T-CP were left to cool down in desiccator chamber until room temperature was reached. Then, the samples were weighted and recorded as the initial mass (m_i). Later, U-CP and T-CP were placed in a chamber. The air inside the chamber was maintained at 30°C and 90%RH. For every 30 min, digital balance with 0.0001 g readability was used to observe the mass of U-CP and T-CP until there was no variation in weight. At this point, it was recorded as the final mass (m_f). The EMC can be determined by Equation 3 [25].

$$EMC = \left(\frac{m_f - m_i}{m_i}\right) \times 100 \qquad (3)$$

PFI standard [22] suggested the testing procedure for determining the durability index (DI) as follows. The 0.5 kg of pellet sample was recorded as initial pellet mass ($m_{i,pellet}$). It was placed in the test box with the size of 305 x 140 x 305 mm. A metal blade with the length of 230 mm was mouthed at inner wall of the test box. The test box was rotated at 50 rpm for 10 min. After rotating, the mass inside the test box was poured into a 1/8-inch sieve to separate the fines from the pellet sample. The mass of pellet on the sieve was recorded as residual mass (m_r). DI was evaluated by Equation 4.

$$DI = \left(\frac{m_r}{m_{i,pellet}}\right) \times 100 \qquad (4)$$

2.5 Mathematical Model

The prediction of EMC of T-CP based on the one-step kinetic model of biomass decomposition was adapted from previous work [23]. By assumption that T-CP at a given residence time composed of remaining raw biomass (reactant) and torrefied char (product), the prediction was developed by calculating the EMC of both remaining reactant and product. The EMC at observed residence time (EMC_t) can be predicted by Equation 5.

$$EMC_t = \frac{M_O\, exp(-Kt)\, EMC_r + \frac{k_c M_O}{K}(1 - exp(-Kt))EMC_c}{M_t(t)} \qquad (5)$$

Durability index of T-CP at observed residence time (DI_t) can be calculated in the same manner as EMC_t. The DI_t can be obtained by the following equation.

$$DI_t = \frac{M_O\, exp(-Kt)\, DI_r + \frac{k_c M_O}{K}(1 - exp(-Kt))DI_c}{M_t(t)} \qquad (6)$$

Where EMC_t and DI_t represent the EMC and durability index of T-CP at observed residence time (t). EMC_r and DI_r denote the EMC and durability index of U-CP. EMC_c and DI_c were the EMC and durability index of T-CP at the residence time of 60 min. The Value of M_0 was 416.00 g. This value was the mass of U-CP loading into the torrefaction reactor. The rate constants (k_c, k_v, and K) for cassava rhizome were suggested by previous work [23] as following equations.

$$k_c = 0.135\, exp\left(\frac{21777}{RT}\right) \qquad (7)$$

$$k_v = 23460\, exp\left(\frac{77636}{RT}\right) \qquad (8)$$

$$K = k_c + k_v \qquad (9)$$

The values of EMC_c and DI_c at the temperatures of 230, 250, and 270°C and the values of k_c, k_v, and K were shown in Table 1.

Table 1. Values of EMC_c and DI_c of T-CP at the residence time of 60 min and values of kc, kv, and K.

Temperature (°C)	EMC_c (%db.)	DI_c (%)	k_c	k_v	K
230	6.03	99.11	0.000739	0.000203	0.000942
250	5.15	98.38	0.000902	0.000413	0.001315
270	5.01	97.29	0.001085	0.000798	0.001882

3. RESULT AND DISCUSSION

3.1 Equilibrium Moisture Content (EMC) and Water Resistance

The variation of Equilibrium Moisture Content (EMC) of U-CP and T-CP at various residence time was shown in Figure 1 and in Table 2. For the torrefaction temperature of 230°C, the decrease of EMC from 9.85±0.52%db to 6.30± 0.62%db was found when the residence time was increased from 0 to 30 min. There was a slight decrease in EMC when the residence time was longer than 30 min. The lowest EMC of 6.03± 0.23%db was obtained at residence time of 60 min. This value was 0.59 times of EMC of U-CP (10.21±0.56%db). The slight change in EMC after residence time of 30 min indicated that it is not necessary to conduct torrefaction with residence time longer than 30 min. In other words, there was a specific residence time which was suitable to improve EMC of U-CP for each torrefied temperature. The torrefaction with too long residence time resulted in unnecessary heat consumption. The similar trend was also found in case of torrefied temperatures of 250°C and 270°C. For the torrefaction temperature of 250°C, the EMC drastically decreased from 9.05±0.47%db to 5.88±0.60%db when residence time was increased from 0 to 15 min. The insignificant change of EMC can be observed when the residence time was longer than 15 min. Therefore, the suitable residence time to improve EMC of U-CP for this temperature was 15 min. For the torrefaction temperature of 270°C, the vast decrease of EMC from 8.14±0.74%db to 5.32±0.33%db was seen when residence time was increased from 0 to 10 min. The difference in EMC was negligible when residence time was longer than 10 min. Thus, the suitable residence time for torrefied temperature of 270°C was 10 min. The similar trend was reported for terrified char of Douglas Fir pellet as shown in Figure 1 [10]. In addition, prediction results of EMC using developed model were in good agreement with experimental results (Figure 2). The average absolute errors (AAE) of prediction and coefficient of determination (R^2) were 11.60% and 0.82, respectively. The cause of prediction error was decomposition on U-CP during heating period. It was neglected in developed model. The lower EMC of T-CP at residence time of 0 min compared to that of U-CP confirmed that there was decomposition during heating period. Therefore, the more prediction deviation was seen when U-CP was torrefied with higher temperature and longer heating period. Although there was prediction error, the prediction had a similar trend to the experimental results. The developed model indicated that decomposition rate of U-CP strongly affected EMC. Decomposition conducted torrefied char at outer surface of U-CP acting as hydrophobic shield. The decrease mechanism of EMC for T-CP can be described as follows. Water in biomass can be classified into bound water and free water. The bound water was tightly bound to hydroxyl groups of hemicellulose [13]. Movement of bound water can be occurred by diffusion. When moisture content in biomass was higher than fiber saturation point (FSP), free water can be observed [24]. Movement of free water was resulted from capillary forces. When U-CP was exposed to humid air, the water vapor in air penetrated into the outer surface of U-CP by diffusion as bound water. Later, the bound water diffused from outer surface to interior of U-CP resulting in the increase of moisture content. When the moisture content was higher than FSP, free water occurred and flowed to interior of U-CP by capillary effect of micro-void inside U-CP. Previous work explained that hemicellulose was decomposed resulting in removal of most hydroxyl groups during torrefaction [13]. When U-CP was torrefied into T-CP, the water diffusion mechanism from humid air to outer surface was prohibited due to loss of hydroxyl groups. In other words, the outer surface of T-CP played a role as hydrophobic shield preventing interior of T-CP from moisture. Early work [24] revealed that the bound water was the major cause of the increase of moisture content of wood at the beginning state of water uptake (moisture content < FSP). After the moisture content reached FSP, the increase of the moisture content was only resulted from free water. It was clearly seen that it was difficult for mass within T-CP to reach FSP due to the hydrophobic shield of T-CP and the lower EMC of T-CP compared to that of U-CP can be observed. The similar role of hydrophobic surface was also discussed by previous report [17].

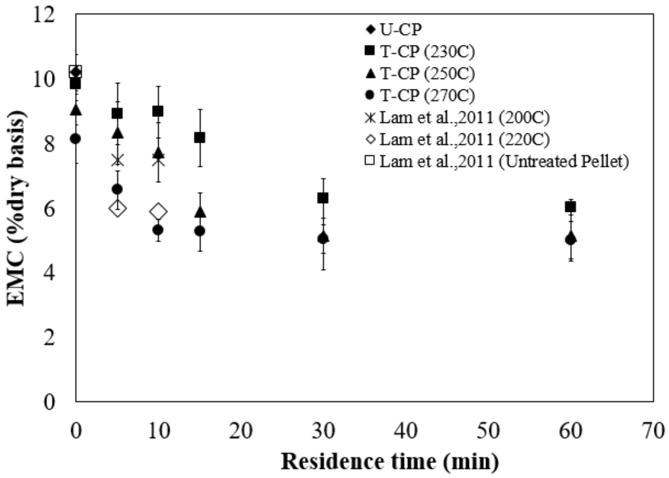
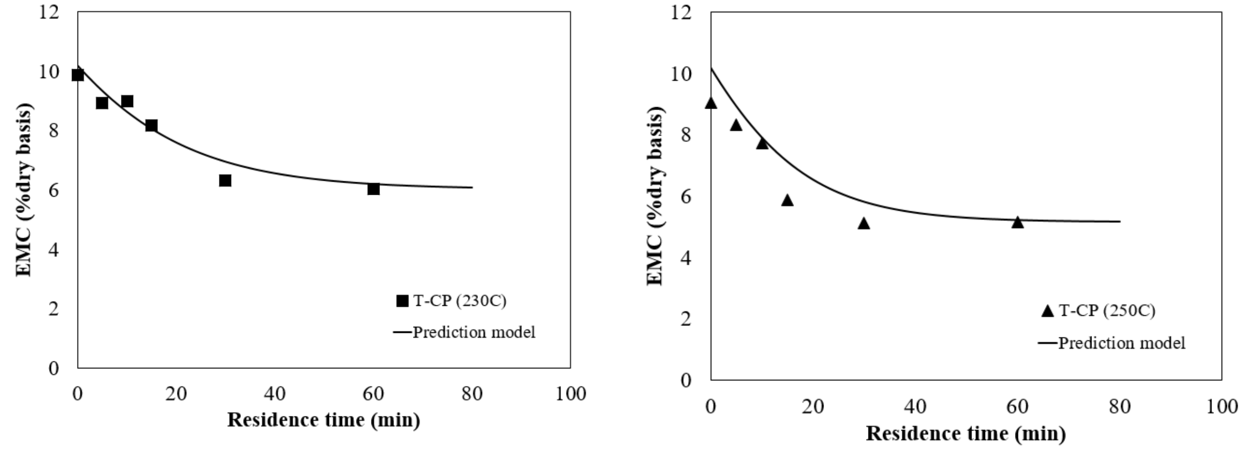


Fig. 1. Equilibrium moisture content (EMC) of U-CP and T-CP at various residence times and torrefied temperatures.

Table 2. The values of EMC of U-CP and T-CP.

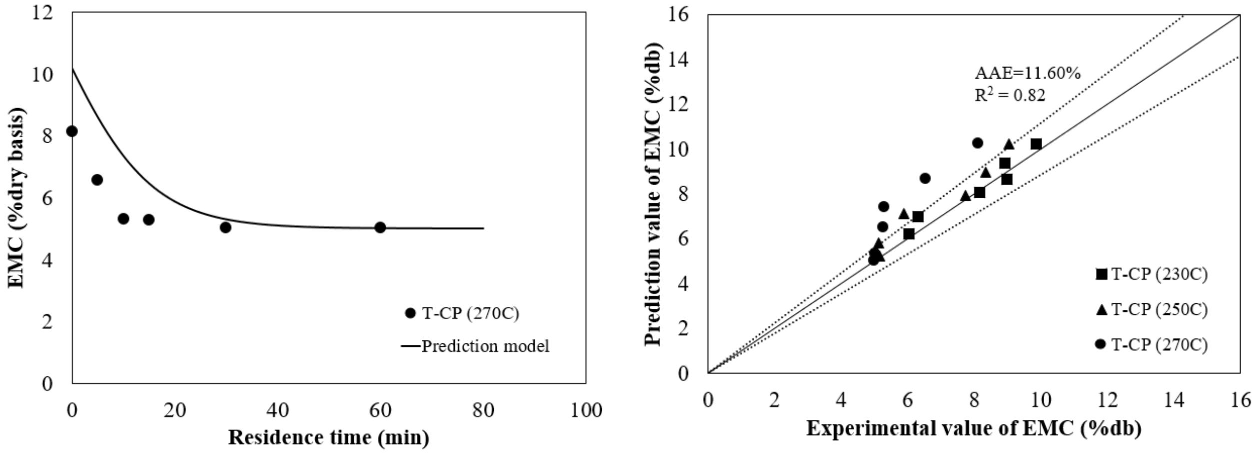
Residence time (min)	U-CP	T-CP (230°C)	T-CP (250°C)	T-CP (270°C)
0	10.21±0.56	9.85±0.52	9.05±0.47	8.14±0.74
5	-	8.92±0.94	8.33±0.97	6.56±0.59
10	-	8.97±0.79	7.72±0.91	5.32±0.33*
15	-	8.17±0.89	5.88±0.60*	5.28±0.60
30	-	6.30± 0.62*	5.13± 1.03	5.03± 0.45
60	-	6.03± 0.23	5.15± 0.79	5.01± 0.57

*Note: The symbol * indicated the suitable residence time to improve EMC of U-CP.*



a. Torrefied temperature of 230°C.

b. Torrefied temperature of 250°C.



c. Torrefied temperature of 270°C.

d. Average absolute error and coefficient of determination (R^2) of prediction.

Fig. 2. Prediction results of equilibrium moisture content (EMC).

In addition, there was temperature gradient along radius of T-CP during torrefaction with short residence time. The highest torrefaction severity took place at the outer surface of T-CP. The experimental results indicated that preparation of sufficient hydrophobicity at outer surface of U-CP to prevent interior from moisture was more interesting method instead of conducting severe torrefaction on the entire mass of U-CP. Therefore, the suitable residence time was a key parameter for achieving this propose. In this work, the suitable residence time was defined as the shortest residence time for each torrefied temperature in which the insignificant variation of EMC can be observed. From Figure 3, the suitable residence time decreased from 30 min to 15 min (50.0%) when the torrefied temperature increased from 230°C to 250°C (8.7%) while the increase from 250°C to 270°C (8.0%) resulted in the decrease from 15 min to 10 min (33.3%). This result indicated that the suitable residence time vastly decreased with the increase of torrefied temperature. Therefore, the torrefaction with high temperature was recommended to decrease the torrefied time and consequently heat consumption for torrefaction can be decreased.

Moreover, investigation on water resistance of U-CP and T-CP at various residence time and torrefied temperature was also conducted by immersing into water. After immersing into water for five (5) days, vast loosening of U-CP was observed. Moderate loosening was seen for all residence times of T-CP torrefied at 230°C, T-CP torrefied at 250°C and residence time shorter than 15 min and T-CP torrefied at 270°C and residence time shorter than 10 min. There was a slight change in shape for T-CP torrefied at 250°C and 270°C with residence time longer than the suitable residence time (Figure 4). Previous work [8] reported the good water resistance of wood pellet torrefied at 260°C for 15 min. These results indicated that torrefaction with the suitable residence time was sufficient to improve water resistance of T-CP.

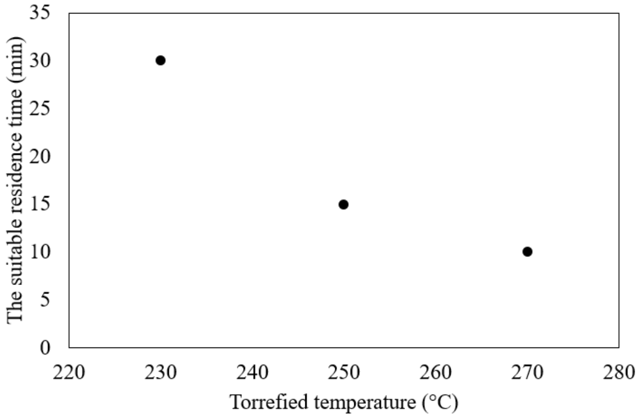


Fig. 3. Relationship between the suitable residence times and torrefied temperatures.

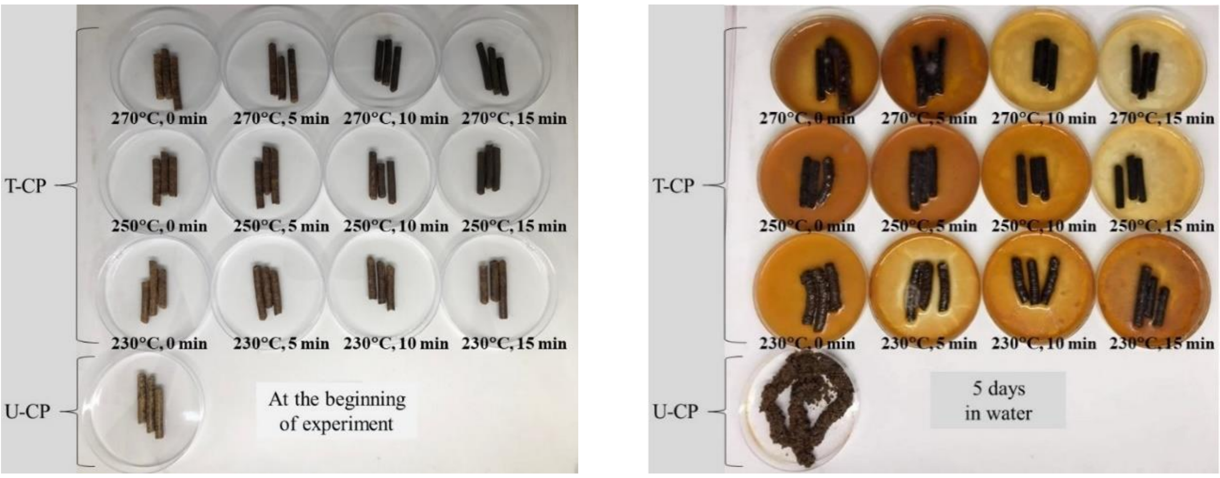


Fig. 4. The loosening of U-CP and T-CP when they were immersed in water.

3.2 Durability Index

Relationship between residence time and durability index of U-CP and T-CP was shown in Figure 5. The durability index of U-CP was 99.44% which was higher than that of T-CP. For torrefied temperature of 230°C, durability index of T-CP was insignificantly different for every value of residence time. For torrefied temperature of 250°C and 270°C, the durability index of T-CP slightly decreased from 99.15% to 98.66% and drastically decreased from 99.07% to 97.33%, respectively, when the residence time was increased from 0 to 15 min. There was insignificant difference of durability index for each torrefied temperature when residence time was longer than 15 min. The prediction results of durability index obtained from established model was shown in Figure 6. A good agreement with experimental data with AAE of 0.25% and R^2 of 0.90 indicated that the durability index was strongly related with the decomposition rate of U-CP. The torrefaction with high temperature contributed to high decomposition rate which led to a drastic decrease of durability index, although the torrefaction was conducted with short residence time. The similar result was also reported by Larsson *et al.* [11] and Ghiasi *et al.* [8]. According to the Pellet Fuel Institute (PFI) standard [22], the acceptable value of durability index was in the range of 95.0%-96.5%. The durability index of T-CP obtained at torrefied temperature of 270°C and the residence time of 10 min (which was the suitable residence time in terms of EMC) was 97.43±0.13%. This value was slightly above an acceptable criterion of PFI. Therefore, it was predicted that there was a certain value of torrefied temperature which resulting in unacceptable durability index. This prediction was confirmed by previous work. The unacceptable durability index of 90.96±0.82% was found at the torrefied temperature of 280°C and the residence time of 30 min [9]. Therefore, the torrefaction with very high temperature should be conducted carefully to avoid unacceptable durability index, even though it was conducted under very short residence time.

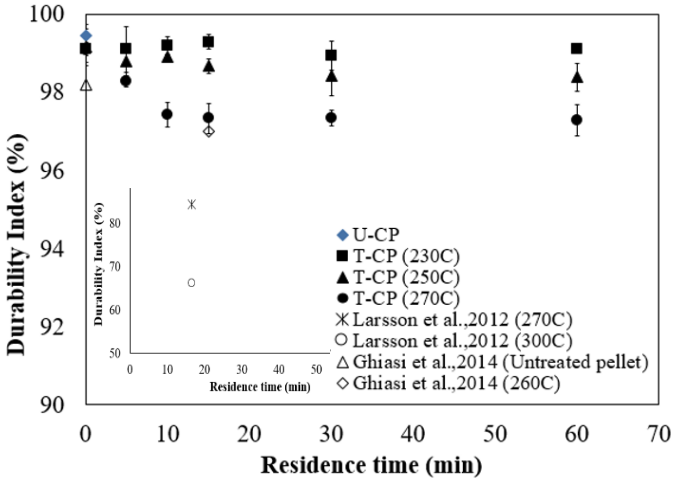
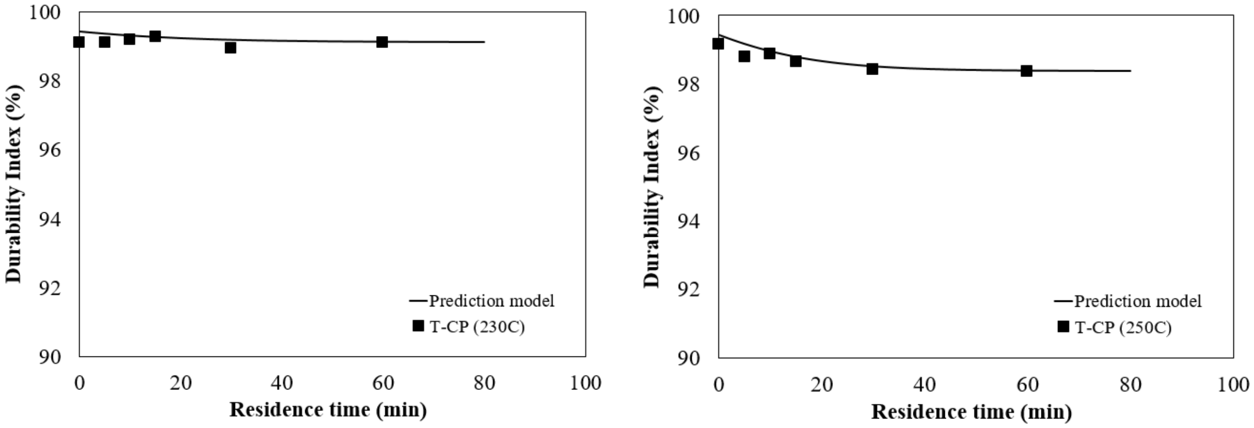
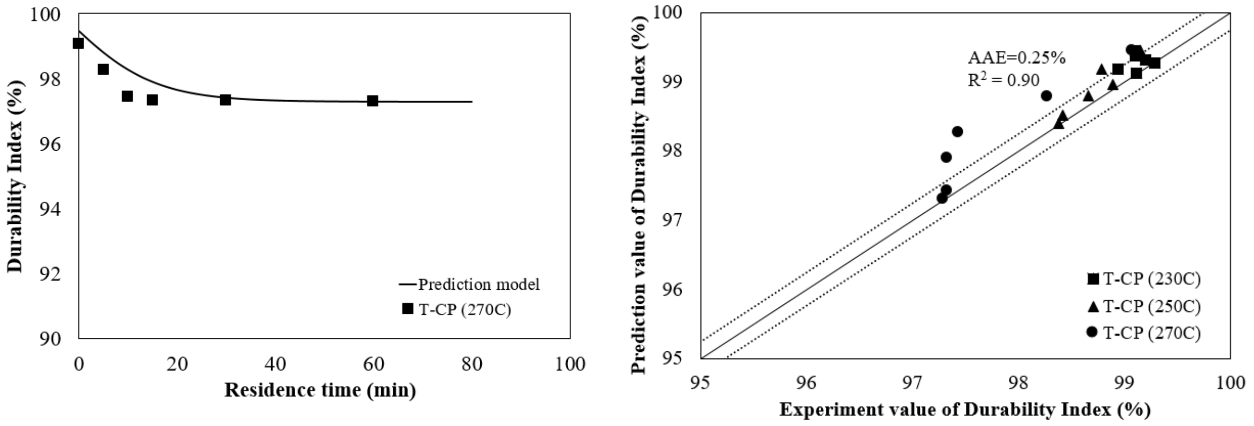


Fig. 5. Durability index of U-CP and T-CP at various residence times and torrefied temperatures.



a. Torrefied temperature of 230°C.

b. Torrefied temperature of 250°C.



c. Torrefied temperature of 270°C.

d. Average absolute error and coefficient of determination (R^2) of prediction.

Fig. 6. Prediction results of durability index.

3.3 Energy Density

The relationship between energy density and residence time is shown in Figure 7 and Table 3. The energy density of U-CP was slightly different from that of T-CP. The insignificant difference in energy density of T-CP was observed for all torrefied temperatures and residence times. The energy density of U-CP and T-CP was in range of 12.70 – 12.92 GJ/m^3. The similar trend was reported [9], [17]. In general, torrefaction resulted in an increase of higher heating value (HHV) and a decrease of bulk density. For T-CP obtained from all torrefied temperature and residence time, the increaseing rate of HHV was close to the decreasing rate of bulk density as shown in Figures 8 and 9. These results led to the insignificant difference in energy density of T-CP obtained from various condition. It was clearly seen that there was no possibility in increasing energy density by pelletising and then torrefaction. In other words, the energy density of T-CP did not affect the suitable residence time for short torrefaction process. It was noted from Figure 7 that the control pellet reported by Peng *et al.* [17] had a different trend from that of T-CP. The energy density of torrefied control pellet dramatically decreased because the decreasing rate of bulk density was higher than the increasing rate of HHV. The control pellet was produced by press machine while other pellets and T-CP were produced by rotary pellet mill. The difference in production machine may result in variation in decomposition rates during torrefaction. Unfortunately, there was insufficient data to confirm this assumption. Therefore, further study on pellet produed by various machine types is nescessary. However, the data of T-CP produced by rotary pellet mill revealed that the energy density was insignificantly changed even though it was torrefied with different condition.

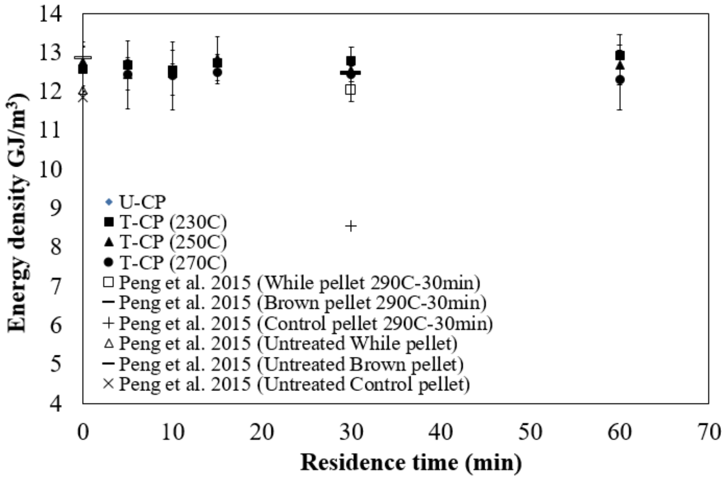


Fig. 7. Relationship between energy density and residence times.

Table 3. Values of energy density (GJ/m^3) of U-CP and T-CP.

Residence time (min)	U-CP	T-CP (230°C)	T-CP (250°C)	T-CP (270°C)
0	12.70±0.56	12.57±0.57	12.76±0.08	12.58±0.58
5	-	12.67±0.14	12.45±0.42	12.43±0.87
10	-	12.56±0.16	12.47±0.57	12.41±0.87
15	-	12.74±0.23	12.83±0.56	12.49±0.30
30	-	12.78±0.12	12.55±0.30	12.44±0.71
60	-	12.92±0.55	12.68±0.50	12.29±0.75

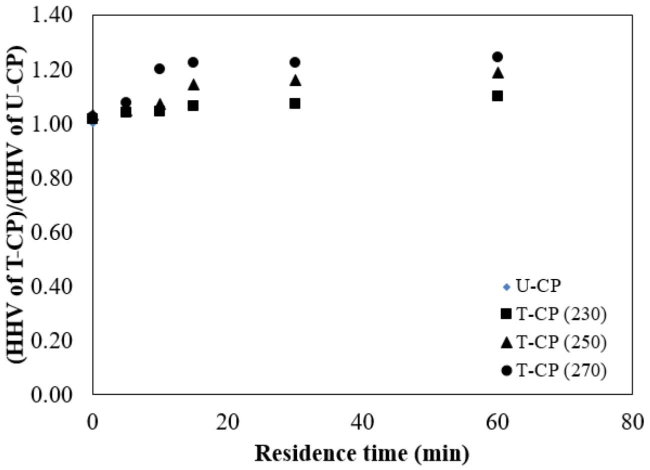


Fig. 8. The HHV ratio at various residence time.

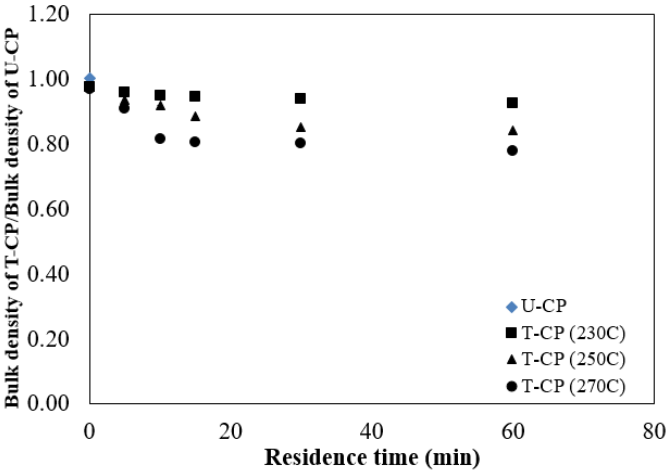


Fig. 9. The bulk density ratio at various residence time.

4. CONCLUSION

The alternative torrefied process for biomass pellet upgrading called short torrefaction was introduced. Instead of conducting torrefaction to increase the energy density, the objectives of this process were to increase water resistance and decrease moisture absorption by converting the outer surface of biomass pellet into the hydrophobic shield. Short torrefaction still resulted in the increase of HHV. However, it was impossible to increase energy density by short torrefaction. Short torrefaction resulted in lower energy consumption compared to that of ordinary torrefaction. The important parameter to achieve the lower energy consumption and good storage properties was the suitable residence time. Two criteria for identification of the suitable residence time were equilibrium moisture content (EMC) and durability index. In terms of EMC, the suitable residence time was defined as the shortest residence time for each torrefied temperature which the insignificant variation of EMC can be observed. For EMC criterion, the suitable residence time tended to decrease with the increase of torrefied temperature. In terms of durability index, too long residence time contributed to unacceptable durability index. Therefore, the suitable residence time was the longest residence time for each torrefied temperature in which the value of durability index can still be accepted. When two criteria were satisfied, the suitable residence time can be identified.

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NOMENCLATURE

ρ	Bulk density	(kg/m^3)
k_c	Rate constant of char product	
k_v	Rate constant of volatile product	
m	Mass of bulk pellets	(kg)
m_f	Final mass of sample	(g)
m_i	Initial mass of sample	(g)
$m_{i,pellet}$	Initial mass of pellet sample	(g)
m_r	Residual mass of pellet sample on sieve	(g)
t	Residence time	(s, min)
ED	Energy density	(GJ/m^3)
EMC	Equilibrium moisture content	(%db.)
EMC_c	Equilibrium moisture content at residence time of 60 min	(%db.)
EMC_r	Equilibrium moisture content of reactant (U-CP)	(%db.)
EMC_t	Equilibrium moisture content at observed residence time	(%db.)
HHV	Higher heating value	(MJ/kg)
K	Summation of rate constant ($K = k_v + k_c$)	
M_0	Initial mass of biomass pellet (U-CP)	(g)
M_t	Mass of biomass pellet during torrefaction at a given residence time	(g)
PDI	Pellet durability index	(%)
PDI_c	Pellet durability index at residence time of 60 min	(%)
PDI_r	Pellet durability index of reactant (U-CP)	(%)
PDI_t	Pellet durability index at observed residence time	(%)
R	Universal gas constant (8.3144 x 10^{-3} kJ/mol-K)	
T	Torrefied temperature	(K)
V	Bulk volume	(m^3)

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