

Thermal mechanism of large biomass particles during torrefaction

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Abstract: Using large biomass particles for torrefaction can decrease the grinding costs and therefore the total operating costs. However, the heat and mass transfer phenomena in larger particles are more pronounced during torrefaction compared to smaller ones. In this study, the effect of temperature gradient and exothermicity generated inside the biomass on the yield and physicochemical properties of biomass torrefied at 260°C and 300°C were studied. Cylindrical eucalyptus wood particles prepared into different dimensions based on aspect ratios (length to diameter ratio or L/D ratio) as L/D = 2, L/D = 3 and L/D = 5 were used. Increasing length (from 60 to 100 mm) with fixed diameter (20 mm) showed negligible effect on the temperature profile and core peak temperature, while a higher thermal shoot was clearly observed when increasing particle diameter (from 20 to 30 mm) with fixed length (10 mm). Higher torrefaction temperature enhanced the energy density of the torrefied products. Increasing particle length (from L/D 3 to L/D 5) lowered the degree of degradation resulting in higher mass and energy yield at 300°C. However, increasing diameter (20 to 30 mm) or reduction in L/D ratio resulted in lower mass and energy yield due to the exacerbated thermal decomposition in thicker particles.

Keywords: Biomass, Torrefaction, Aspect ratio, Core temperature, Mass yield, Energy yield.

1. Introduction

Biomass is considered a benign and sustainable energy source to cope with the rising global need for energy and its negative impact on climate change [1]. However, biomass in native form possess poor grinding and fuel properties for thermochemical conversions. Hence, to upgrade the fuel quality, a mild pyrolysis pretreatment called torrefaction is applied at temperatures between 200 to 300°C [2-4]. Torrefaction leads to drying and disruption of the biomass constituents and subsequently improving the grindability, sphericity, uniformity and energy yield of feedstocks [3, 5-6]. It is a complex process involving external and intraparticle transfer of heat coupled with mass transfer through the convection and diffusion of volatiles [7-8].

Biomass is a poor conductor of heat and, hence, form a considerable temperature gradient when exposed to thermal treatment. It is widely reported that the size, shape, and direction of the biomass microstructural building blocks strongly influence the temperature gradients [8-10]. However, these effects may not be significant for sufficiently very small sized particles where the torrefaction reaction is only kinetically controlled [11]. On the contrary, large (thermally thick) biomass particles such as pellets, logs or chips impose some resistance to thermal propagation [7, 12]. These particles readily develop temperature gradients causing non-uniform chemical reactions inside the biomass especially when subjected to rapid heating [11]. Consequently, the influence of heat and mass transport affect the process conditions and product yield of the torrefied biomass [13]. Relatively large biomass particles tend to exhibit an increase in temperatures at its center above that at the surface [3, 6, 13]. This thermal overshoot is the result of the exothermic decomposition of the biomass constituents in the core of the biomass samples [4]. Thus, the rise and growth rate of the core temperature are critical parameters that can influence the properties of torrefied biomass significantly and aggravate the product homogeneity [8]. During torrefaction, the volatiles are released due to depolymerization processes and travel outward through biomass pores.

However, this devolatilization is limited in large biomass due to transport restrictions, in consequence, the gases deposit on the biomass forming a char-volatile exothermic reaction which is also referred as secondary reactions [14-15]. Therefore, depending on the amount of volatile release, the char-volatile exothermic reactions inside the biomass can raise the core temperature above that at the surface [7]. In addition, the poor thermal conductivity of biomass traps the heat released from the exothermic reaction leading to increase in the core temperature. Peng [10] investigated the effect of torrefaction of biomass size less than 1 mm in a TGA and a tubular fixed bed reactor. The authors reported that the reaction rate was influenced by the particle size, particularly at high temperatures. Wang et al. [12] investigated the torrefaction of sawdust particles of different sizes (0.25-0.5, 0.5-1.0 and 1.0-2.0 mm). The results showed that biomass torrefaction was affected by both particle size and temperature. They observed an increase in weight loss of sawdust with increase in particle size and treatment temperature. Rodrigues and Rousset [16] on the attempt to analyze the fuel quality of large eucalyptus wood chip when treated at 220°C, 250°C and 280°C, reported that the average temperature measured on the biomass surface during the torrefaction process is higher than the core in the heating phase. The opposite was observed during the holding period at 250°C and 280°C indicated as exothermic zone. This suggests that as the treatment temperature increases, the activation energy of the biomass is likely to be reached and devolatilisation is enhanced generating heat with the biomass body.

Basu et al. [7] investigated torrefaction at 250°C for large poplar wood particles (water content of 6.39% wet basis) in a convective bed reactor. They conducted two sets of experiments by varying the diameter (4.75-25.4 mm) in the first set, and the second set using variable length sizes (8-65 mm) and keeping the diameter of all samples at 4.75 mm. The authors found that preheating and drying time was pulled with an increase in diameter size, while the torrefaction time required to attain the desired energy density decreases. Increase in core temperature of the particle was

detected with an increase in diameter while keeping a fixed length. However, the research did not include the thermal behavior at severe conditions such as the range reported by Chen et al. [4] (275–300°C), which might lead to different torrefaction behaviors [17]. Regmi et al. [18] introduced the effect of changes in the length to diameter (L/D) ratio on the center line temperature of hybrid poplar wood torrefaction at 270°C. They observed an increase in core temperature when the L/D ratio decreased. Thus, the decrease in L/D ratio would lead to non-uniform properties within the biomass after torrefaction due to increased exothermal shoot at the core of the particles. They concluded that a better torrefaction of cylindrical particles would be achieved with smaller diameter particles since it lowers the deviation of the core temperature from the surface temperature.

Although there have been considerable advances in developing commercial biomass torrefaction plants, there are still some challenges to improve the quality and efficiency of the process. Among the approaches to improve the process efficiency is to establish the optimal treatment conditions and to reduce the grinding energy demand. However, optimization of the process depends on the biomass type, size, polymeric structures, and treatment conditions (temperature and residence time). Consequently, one approach to achieve this goal is by studying the heat transfer mechanism of biomass undergoing torrefaction. The current study investigated the effect of biomass size on the heat transfer mechanism causing temperature gradient which results in non-uniform chemical reactions and heat generation during torrefaction [11]. Therefore, the primary driver for this research was to understand the temperature profile during torrefaction of large pieces of biomass, and the effect of size change on temperature profile and mass yield of the torrefied biomass.

2. Materials and Methods

2.1. Sample preparation

Eucalyptus wood were machined into workable sizes and smooth-surface cylindrical shapes with approximate dimensions as shown in Table 1. The samples were produced from the same wood log and cut axially along the grain direction to maintain consistency of biomass properties, as the thermal properties of wood vary less in the grain direction [8, 17].

The prepared wood samples were oven dried at 110°C for an overnight to remove residual water content from the biomass. The dry moisture content of the wood was reduced to 7.8%. The

ultimate and proximate analysis of the raw biomass are reported in Table 2.

Table 1. Sample dimensions.

Length (L), mm	Diameter (D), mm	Aspect ratio (L/D)
60	30	2
60	20	3
100	20	5

Table 2. Proximate and ultimate analysis of the raw Eucalyptus sample.

Proximate analysis expressed in % ^{db.}	
Fixed carbon	19.0
Volatile matter	80.9
Ash	0.1
Ultimate analysis expressed in % ^{db.}	
C	50.1
H	6.1
N	0.1
O ^a	43.6

^{db.} Dry basis ^a Obtained by difference

To continuously monitor and record the temperature profile, 1-mm diameter K-type thermocouples were placed at various holes drilled on the biomass body as shown in Figure 1. The holes were created to a maximum diameter of 1.1 mm to reduce the convection resistance that might occur due to the gaseous products, hence, minimizing the measurement error. The thermocouples were imbedded in the particle core (TC2) and at 4/5th the length from the core of the biomass sample (TC3); both locations are along the biomass centerline (R=0) as indicated in Figure 2. Another thermocouple (TC4) is placed at 1 mm below the surface to record the surface temperature profile during the process.

2.2. Reactor setup and procedures

A horizontal tubular reactor heated through a heating coil as shown in Figure 1 was used for the torrefaction experiment. The reactor was equipped with a nitrogen supply system, volatiles cooling section, temperature controller and a data logger to record the temperature profiles. The furnace temperature was regulated and recorded by thermocouple (TC1). Nitrogen gas was used to provide an inert environment for the torrefaction experiment and to sweep out the volatiles produced during the process.

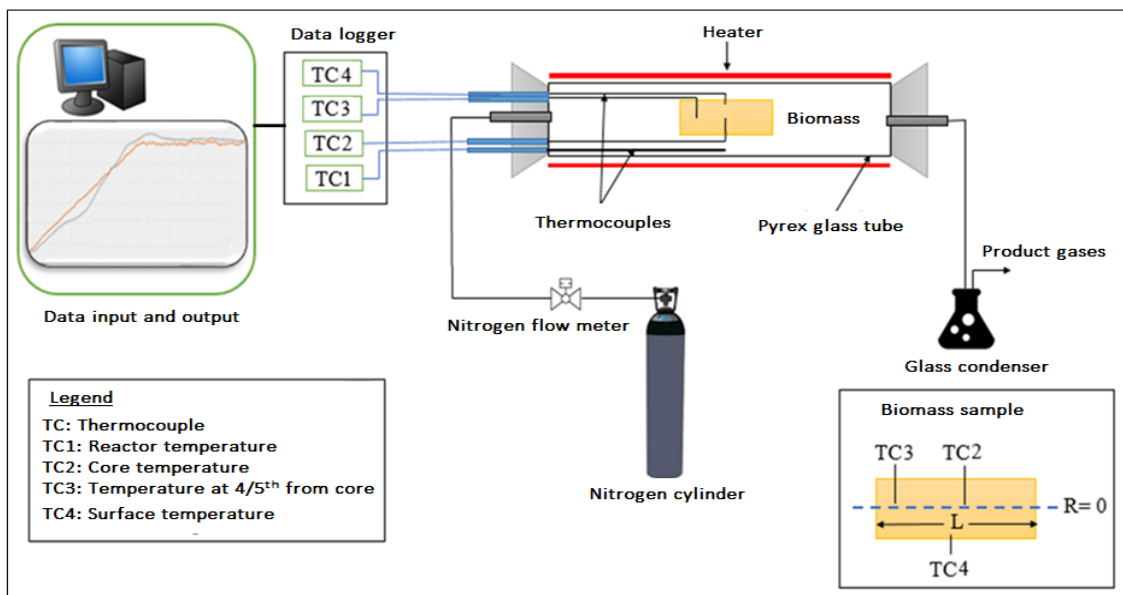


Figure 1. Torrefaction reactor setup.

All experiments were conducted using a 5°C/min heating rate to the temperatures of 260°C and 300°C followed by a 60 min isothermal heating period. These process temperatures depict the regimes for medium and severe torrefaction conditions, respectively [4]. The initial surface temperature of the samples was maintained at 26±1°C prior to starting the process. The real time reactor temperature fluctuations were kept below 3°C from the desired process temperature to avoid additional heating. Finally, with the sample and thermocouples placed inside, the reactor was sealed and purged for 10 min with nitrogen gas at a flowrate of 200 cc/min to displace the oxygen present inside. After an inert environment inside the reactor was achieved, the torrefaction process was started using the same nitrogen flowrate throughout the process. The gases liberated during the process were directed through a glass condenser to be cooled and exit from the process. After the specified torrefaction time the reactor was cooled down to room temperature under nitrogen atmosphere. The mass yield, energy yield and energy density were studied and reported in dry basis using data determined by the proximate analysis according to the following explanations:

Mass yield

The mass yield (MY) of each wood sample was measured before and after the torrefaction experiment by direct sample weighing as follows:

$$MY = \frac{M_T}{M_0} \times 100\% \quad (1)$$

Where: M_T is the mass after torrefaction

M_0 is the mass of raw biomass, expressed in dry basis

Energy density

Energy density is a term to describe the amount of energy released when a unit mass of a torrefaction product is combusted and its products are cooled. Other synonyms for energy density are specific energy, heating value or calorific value [3]. The energy density or heating value in this study was indirectly determined by calculation using the correlation proposed by Sheng and Azevedo [19] based on the weight percentages of the elemental carbon, hydrogen, and oxygen obtained from the elemental analyzer:

$$HHV\left(\frac{MJ}{kg}\right) = -1.3675 + 0.3137 C + 0.7009 H + 0.0318 O \quad (2)$$

Where: C, H, O are the content of carbon, hydrogen, oxygen in biomass, expressed on wt% dry ash free basis

Energy yield

Energy yield (EY) is a fraction of the initial energy in the biomass retained after torrefaction.

$$EY = (MY) \left(\frac{HHV_T}{HHV_0} \right) \quad (3)$$

Where: MY is the mass yield explained in equation (1)

HHV_T is the higher heating value of torrefaction solids

HHV_0 is the higher heating value of raw biomass mass

Enhancement factor

The enhancement factor (EF) represents the HHV ratio between the torrefied biomass and its raw biomass [4, 20]. The value of this factor is greater than unity.

$$EF = \frac{HHV_T}{HHV_0} \quad (4)$$

3. Results and Discussion

3.1. Temperature profile

The temperature profiles of wood samples with an aspect ratio of 2, 3 and 5 were studied to investigate the heat transfer mechanisms during torrefaction. The typical temperature profiles from readings of three thermocouples are illustrated in Figure 2. The profiles show small variation which are attributed to the small inconsistencies in biomass properties when new samples were used for replications. It can be observed from Figure 2 that the temperature at the particle core increased at a specific rate until it is stabilized around the desired torrefaction conditions as programmed (in this case 300°C). The highest temperature was detected at the core of the sample indicating the existence of the thermal shoot. In the same way, the temperature profile at 4/5th the distance from the core (TC3) showed almost similar trend to the core temperature, but eventually drops to a lower temperature range as indicated in Figure 2. A possible explanation to this may be the pressure created at the core which forces the product gases to exit along the axial direction [12, 21], hence cooling that location as more volatiles are released.

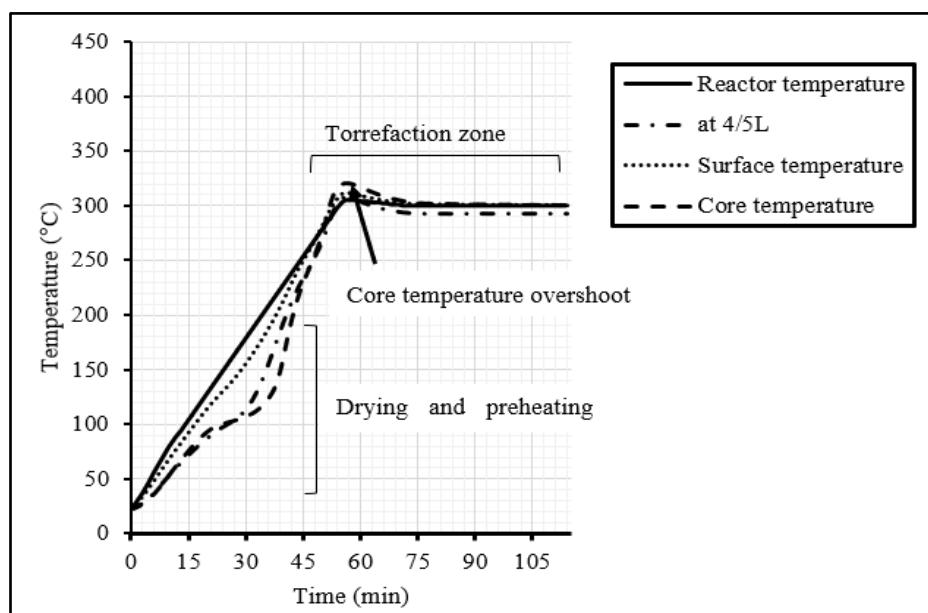


Figure 2. Typical temperature profile of cylindrical wood observed during the experiment.

The initial step during torrefaction/pyrolysis is drying and heating phase in which the biomass loses the moisture content [22]. The process is initiated as heating front progresses from the surface towards toward the undried region inside the wood samples. Studies report that biomass boiling start at the biomass temperature range of 100-135°C [11, 23]. Drying is also influenced by particle size where particles might achieve complete drying simultaneously with the start of pyrolysis at specific locations due to increase in temperature [11, 15, 23]. However, technical investigations explained that particle size has an insignificant effect on mass loss at 200°C, suggesting that only a small amount of chemical degradation takes place and a thermal overshoot of less than 10°C [7, 11]. Thus, the collective time for drying and preheating was considered from the initial temperature of the biomass until the core temperature reach 200°C, after which the torrefaction reaction was considered to proceed until the process ends. It is observed that the time taken to reach from 200°C to the desired torrefaction temperature (both 260°C and 300°C) accounted for less than 8% of the total torrefaction time. The obtained value corroborates the finding of Basu et al. [7] who suggested a value of less than 10% using poplar wood. The time distribution for sample drying and preheating during torrefaction at 260°C and 300°C are demonstrated in Table 3 and Table 4, respectively.

Table 3. Effect of particle aspect ratio on drying and preheating phase and reaction phase time at 260°C, 60 min.

Aspect (L/D) ratio	Time (min) for heating to temperatures of	
	25-200°C	200-260°C
2	46	7
3	40	8
5	40	10

Table 4. Effect of particle aspect ratio on drying and preheating phase and reaction phase time at 300°C, 60 min.

Aspect (L/D) ratio	Time (min) for heating to temperatures of	
	25-200°C	200-300°C
2	46	9
3	44	10
5	43	12

It can be inferred from Table 3 and 4 that the drying and preheating time increased with particle diameter. The preheating time suggests that the rate of heating during the temperature range 25-200°C was faster for small diameter particles (20 mm) than the larger diameter particles (30 mm) of the same length. This is could be due to the typical heat transfer resistance mechanism due to the increase in particle thickness from the biomass surface. However, with the same heating pattern, the generalized time needed to increase from 200°C to the desired torrefaction temperatures (260°C and 300°C) was shorter than that between 25°C and 200°C. This is due to the higher heat demand needed for drying compared to sensible heat required to reach the desired torrefaction temperatures [11]. It is apparent from Tables 3 and 4 that the particles with greater L/D ratio and comparatively smaller diameter required shorter heating time than the case of smaller L/D ratio and larger diameter particles.

Figure 3 (a-f) shows the temperature profile development of the reactor temperature, particles surface and core temperatures during each experiment. These temperature profiles have stages of rising and overtaking each other and eventually stabilizing around the predetermined reaction temperature at the end of the process. Thermal overshooting was detected at the biomass centerline, with the core temperature showing peak temperature compared to the reactor temperature. This observed exothermicity is likely due to the liberation of heat from the polycondensation reactions during thermal degradation of the wood [9, 14]. Volatiles produced during the process would react with each other and with the internal

surface of biomass char forming secondary reactions. The details of mechanism behind secondary reactions will be discussed in section 3.2. Generally, these reactions take place at a low heating rate on thermally thick biomass where the conductive heat transfer is slow [9, 21]. The surface temperature also exhibited a comparatively small thermal shoot. Locating in close proximity of the gaseous environment, heat could be liberated more easily due to less thermal resistance.

The time taken for temperature overshoot to occur was also examined. Small differences among some experimental trails were noted which are mainly caused by the slight variations on moisture contents since moisture enhances heat conductivity [24]. It was observed that the core temperature of particles with L/D ratio of 2 (length and diameter of 60 mm and 30 mm, respectively) torrefied at 260°C overtakes the surface temperature at approximately 55 min from the time the process was commenced. However, the length of time taken by the core temperature to surpass the surface temperature of the particles arranged at a fixed diameter of 20 mm and varied length of 60 and 100 mm (i.e. L/D of 3 and 5) was 51 min and 49 min, respectively. The same trend was also recorded for treatments at 300°C. The core temperature for L/D of 3 exceeded the surface temperature after 51 min from the start of the torrefaction process, whereas the samples with L/D of 5 took a comparatively shorter time (45 min). The reduction in time for all particles with L/D ratio of 5 was probably due to the larger lateral surface area compared to the particles of the same diameter but shorter length (i.e. samples of L/D ratio of 3). It could be then concluded that the transfer of heat was higher triggering rapid drying and preheating of the particles. Moreover, the core temperature transcended the surface temperature at 50 min for biomass L/D ratio of 2. It is further noted that the torrefaction temperature also influenced these trends. This was observed when the core temperature of the biomass with smaller L/D of 2 at 260°C took a relatively longer time (55 min) to surpass the surface temperature compared with particles torrefied at 300°C (50 min).

3.2. Core temperature

The results of the experiments in line with previous studies [7, 11, 21] are in clear support on demonstrating the core thermal shoot as a function of biomass size. As indicated in Figure 3, temperature profiles of the samples showed growth in the temperature curves which are referred as thermal shoots or exothermic overshoots in this discussion. During torrefaction the pyrolysis front progresses inside the wood samples from the surface as mentioned earlier, but due to the symmetrical shape of the wood samples, the heat propagated towards the center and trapped at the biomass centerline. As a result, the temperature at the center increased more owing to the biomass poor thermal conductivity. Furthermore, the core temperature overshoot can also be attributed to the feedstock type [15, 25]. In general, the relatively higher density (370 to 770 kg/m³) of hardwood reduces its permeability and limiting diffusion of devolatilized gases during torrefaction [8]. This process might lead to pressure buildup and contact between the volatiles and char which contributes to the increase in temperature specially when the biomass thickness increases; a case of L/D ratio of 2 in Figure 3 (a and d). The temperature profiles of these samples at the end of the torrefaction zone tend to stabilize at higher temperatures, approximately 12°C and 20°C for the reactor temperatures at 260°C and 300°C, respectively. This phenomenon might be associated to a small thermal or pyrolytic runaway which occur at high temperatures derived by the exothermic shoot [11, 26]. As a result, sufficiently high temperatures result to a simultaneous rapid decompositions and internment of primary vapors and volatiles in the hot biomass matrix allowing to increase the temperature [15, 27-28]. In addition, it also assumed that higher partial pressure linked to drying evaporation and devolatilization in comparatively thicker biomass might be another plausible factor for such occurrences.

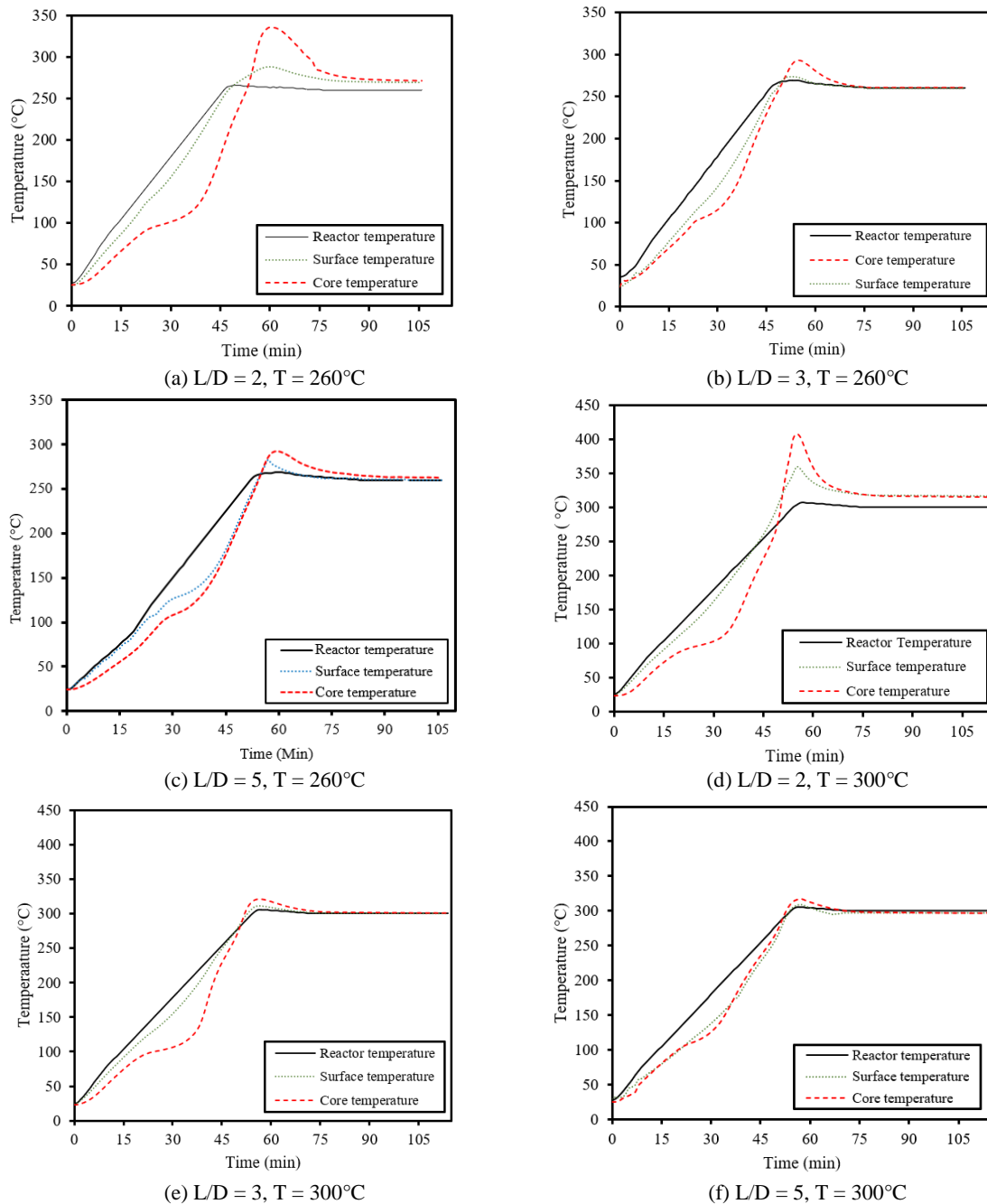


Figure 3. Temperature profiles measured at the core and surface of eucalyptus wood with different L/D ratios and torrefied temperatures with 60 min residence time.

Effect of particle length on core temperature

To investigate the effect of particle length, the diameter of the biomass samples was fixed, and L/D ratios were varied between 3 and 5. The obtained results indicated that the peak core temperature was similar for both the L/D ratios. The maximum core temperatures for the combination of varied lengths 60-100 mm and constant diameter of 20 mm are given in Table 5. It can be observed that there was no change in maximum core temperature if the diameter was kept constant. This indicated that the radial heat transfer is more eminent than axial heat transfer in medium-sized cylindrical biomass [3, 11]. It was expected that an increase in the length of biomass might result into higher volatile combustion, thus, producing more heat [18]. However, increasing the particles length corresponds to increasing its lateral surface area, thereby, enhancing the heat transfer in the radial direction. This decreases the char-volatile reactions hampering the core temperature from increasing too

rapidly. Hence it can be implied that for a fixed diameter, the change in size (volume) does not have a significant effect in maximum core-surface temperature difference.

Effect of particle radius on core temperature

It is indicated in Table 5 that the core temperature rises with increasing diameter of the samples for the given torrefaction conditions. Particles with larger diameter (30 mm) and L/D of 2 experience higher core temperature shoot as compared to the same length (60 mm) samples but with a diameter of 20 mm. Comparison between the core temperature profiles of the different L/D ratios in Figure 4 shows that larger diameter particles exhibit higher core temperature peak. This was possibly created by the increased thermal conduction resistance of the particles due to the increment in diameter, thereby, trapping more heat inside the biomass matrix. Besides, a considerable amount of heat from the char-volatile

reaction in the form of secondary reactions, cracking or re-polymerization might increase the thermal overshoot [8, 28]. Therefore, from this observation it can be concluded that larger diameter particles lead to non-uniform temperature distribution and increased core to surface temperature differences with the particles. Thus, it can be presumed that the selection of particles with smaller diameters are more suitable as they decrease the thermal shoot and, hence, lessen further biomass degradation due to the increased centerline temperature. However, size reduction might intensify the energy consumption for the process and reduces the overall efficiency of the system.

Effect of L/D ratio on core temperature

Obtained results on the peak core temperatures with respect to the particles aspect ratio are listed in Table 5. It was observed that the core temperature as well as the profile changed with changes in particle diameter and length. The results of the core temperature profile shown in Figures 4 (a) and (b) for the aspect ratio of 2, 3 and 5 illustrated that the particles followed an almost similar behavior during the drying and heat up period. It is obvious from the Figures that particles with L/D ratio of 2

experienced a higher exothermal shoot than L/D of 3 and 5 particles which is due to the increased thickness (as diameter increased). Furthermore, the temperature buildup caused by the reverse of heat transfer from radially inwards to radially outwards during torrefaction at 260°C caused a temperature difference up to 48°C between the surface and core for L/D of 2 compared to the L/D ratio of 3 and 5 which both show a shoot of approximately 22°C. However, treatment at 300°C resulted in a core to surface temperature shoot difference of up 58°C for the L/D ratio of 2 samples whereas L/D of 3 and 5 resulted to a shoot of 16 and 19°C, respectively. This thermal shoot facilitates the biomass degradation locally in the centerline. As a result, the centerline conversion might be higher at the core than the particle surface. Another factor which is worth noting for increasing exothermicity in smaller aspect ratio particles which are associated with increased diameter is the increase in permeability of pyrolyzed biomass (char). It is assumed that the increase in pressure in these particles forces more volatiles to be released during pyrolysis. These volatiles then flow towards the hot charred section of the biomass thereby creating heterogenous secondary reactions [8].

Table 5. Peak core temperature during torrefaction at 260°C and 300°C, 60 min residence time.

Length (L), mm	Diameter (D), mm	Aspect ratio (L/D)	Peak core temperature, °C	
			Torrefied at 260°C	Torrefied at 300°C
60	30	2	336	408
			336	408
60	20	3	292	321
			293	321
100	20	5	292	318
			292	318

Noted: Peak core temperatures reported for duplicated experiments

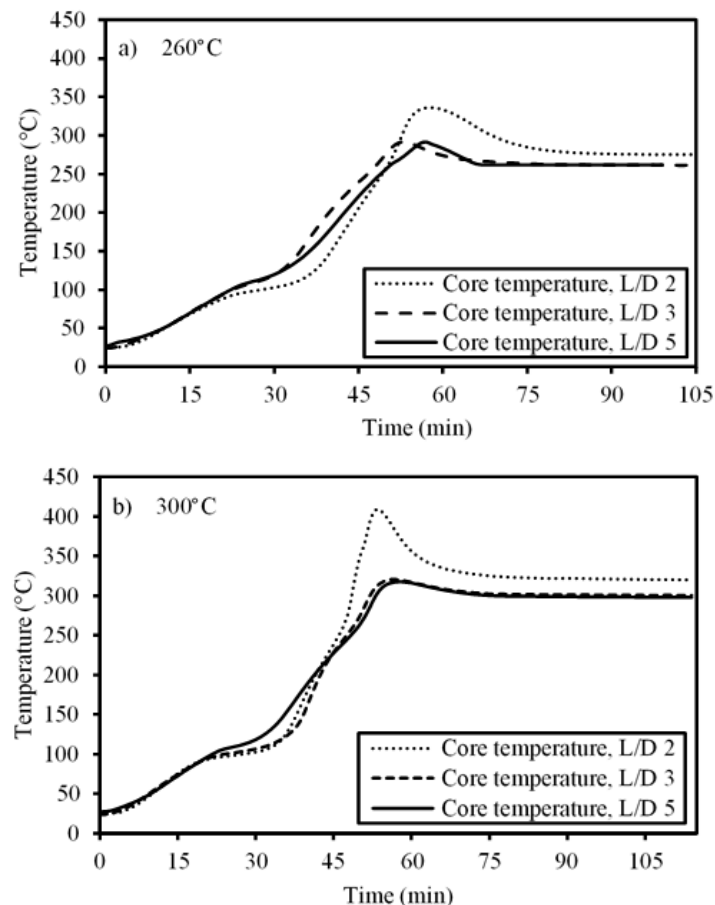


Figure 4. Comparison of core temperature profile for L/D of 2, 3 and 5 torrefied for 60 min at (a) 260°C and (b) 300°C..

Table 6. Characterization of torrefied and raw samples.

Sample	C, %wt	H, %wt	O, %wt	N, %wt	HHV, MJ/kg	Mass yield, %	Energy yield, %	Enhancement factor
Raw	50.1	6.1	43.6	0.1	20.0	100	100	1.00
2-260	59.5	5.6	34.9	0.2	22.3	59.0	65.8	1.12
3-260	53.9	6	40.1	0.2	21.0	76.4	80.3	1.05
5-260	53.1	5.9	40.8	0.3	20.7	76.9	79.6	1.04
2-300	68	4.9	27.2	0.3	24.2	42.1	51.0	1.21
3-300	63.7	5.4	30.9	0.2	23.4	47.5	55.5	1.17
5-300	68.5	5.1	26.4	0.3	24.5	58.8	72.0	1.23

3.3. Mass yield and energy yield

To report the effect of particle aspect ratio with regards to mass and energy densification, the energy density (presented as HHV), mass yield, energy yield, and enhancement factor were investigated and are summarized in Table 6. As previously mentioned, the increase in the process and core temperature thermal shoot would enhance decomposition, which resulted in lower mass and energy yield. However, the energy density and enhancement factor were increased due to the increase in carbon and decrease in hydrogen and oxygen content in the torrefied compared to raw samples.

Effect of particle length on mass and energy yield

Referring to the results shown in Table 6, varying length with fixed diameter ($D = 20$ mm; $L = 60$ mm and 100 mm) did not have any insignificant effect on mass and energy yield when the sample was treated at 260°C. However, when increased to 300°C, the effect of length could be clearly observed. When the length was increased from 60 mm to 100 mm, the mass yield was increased from 47.5% to 58.8% and the energy yield was increased from 55.5% to 72.0%. There was little or no influence of particle length on the heating value (HHV), while more pronouncing effect was observed by varying torrefaction temperature. The HHV was increased from 20.7-22.3 MJ/kg to 23.4-24.5 MJ/kg when the temperature was increased from 260°C to 300°C. The same trend was observed for the enhancement factor (EF), which was more influenced by temperature. The EF, which represents the energy density, was increased by 4-23%.

This phenomenon is explained by the moisture and volatile release from the outer surface of the biomass through mass transfer during torrefaction. Moreover, the wood structure which is made up of many lumina or pores (diameter of 20-30 μ m) that are arranged axially along the growth direction highly influences the devolatilization of gases from the particles [29]. This makes the wood permeability much higher along the growth direction than in the radial and tangential directions [17-18]. Thus, majority of the volatiles produced by heating the biomass travel through these pores, while few vapors leave through the radial or tangential direction as the pits between the cells expand during the process [21]. Hence, it could conceivably be postulated that more volatiles might be released through the two ends on the axial direction of the shorter length cylindrical particles while the longer particles impose resistance to the escape of the gaseous products, allowing for some of the gaseous products to be retained in the biomass.

Effect of particle diameter on mass and energy yield

Varying particle diameter had a significant effect on the thermal overshoot (as shown in Figure 3) as well as mass and energy yield at both treatment temperatures. At 260°C, the mass yield dropped from 76.4% to 59.0%, and the energy yield dropped from 80.3% to 65.8%, when the diameter increased from 20 mm to 30 mm with fixed length (60 mm). The same trend was also observed at 300°C.

The effect of particle diameter may be related to the high thermal decompositions as a result of heat generated by the exothermic secondary reaction and the resistance to thermal conductivity at the biomass center. As already presented in Table 5, the biomass core temperature increased from 321°C to 408°C when increasing the diameter from 20 mm to 30 mm.

Effect of aspect ratio on mass yield, energy yield and energy density

When considering the aspect ratio, the mass yield and energy yield increased with increasing L/D ratio and vice versa for both temperature conditions. The particles with the lowest aspect ratio (larger diameter) have lower mass and energy yield and vice versa. Particle length has an important influence on the final mass yield, due to the more significant mass transfer resistance compared to heat transfer resistance.

3.4. Observed physical changes

The change in the color of the biomass undergoing torrefaction is an indicator of process severity. The color of biomass changes due to the losses of the free moisture from the biomass bound moisture, and light volatile gases at different stages of torrefaction [30]. The biomass color is also affected by the increase in treatment time and temperature from brownish to dark. This is caused mainly due to hydrolysis and oxidation reactions inside the biomass [11]. Moreover, the type of the raw biomass feedstock influences the color of torrefied biomass [25].

Figure 5 indicates the color variation of an axially dissected biomass sample caused by the torrefaction severity that occurred due to the core temperature shoot. This color variation was observed using an optical microscope (Dino-Lite AM4515T8) with a magnification of 45x and resolution of 1280x1024 to capture the color gradient on the sample matrix. It is observed that the color of the biomass body tends to be darker at the core of the biomass being an evidence of a higher exothermic reaction and more severe torrefaction, i.e. reaching to 336°C when torrefying at 260°C (referred to Table 5).

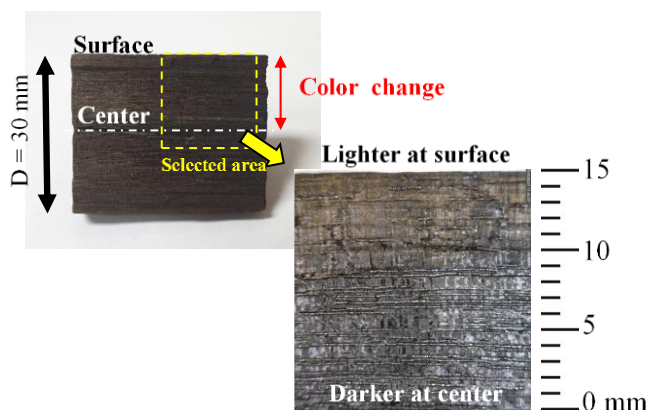


Figure 5. Color variation of an axially dissected section of a 60 mm long and 30 mm diameter ($L/D = 2$) eucalyptus wood torrefied at 260°C and 60 min residence time.

4. Conclusions

The present work investigated the effect of particle size during torrefaction based on its aspect ratio with the focus on large particles. The thermal mechanism, mass yield, energy yield, and energy density of the torrefied particles were found to be strongly dependent on the particle dimensions and torrefaction temperature. Thus, the following observations were drawn accordingly:

- The increase in the L/D ratio when particle length increased decreases the peak temperature shoot at the centerline of the biomass. As a result, the mass yield and energy yield increased with the increase in the particle length and L/D ratio.

- Mass yield and energy yield were reduced as the diameter of the particles increased. More degradation was mostly due to the development of a higher core exothermal overshoot. The highest mass and energy yield were obtained at 260°C and particle L/D ratio of 5. Thicker diameter particles showed higher decomposition which increased the elemental carbon leading to a rise in the energy density (represented by HHV) and higher enhancement factor obtained for particles of $L/D = 2$ than particles of $L/D = 3$ of the same length.

- Majority of the treatment time was spent on drying and preheating biomass to reach the desired reaction temperature.

As evidenced in this research, heat transfer exhibited an important role controlling torrefaction reaction. Understanding of heat transfer not only will assist in the selection of best treatment condition, but also troubleshooting for possible thermal runways which may occur during torrefaction/thermochemical conversion of thermally thick particles. Recommendations for future work include simultaneous investigation of mass loss dynamics, pressure and temperature buildup for the better insights of reaction controlling factors and computer simulation which will complement the understanding to visualize the intra-particle heat transfer behavior.

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