Temperature Evolution and Heating Rates of Biomass undergoing Ablative Pyrolysis

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ABSTRACT

The ablative reactor may be employed to enable fast pyrolysis to produce bio-oil from relatively large-sized biomass samples. Ablation mainly involves direct compressive force and conductive heat transfer between a hot surface and the biomass materials. Temperature evolution and heating rates are important operating factors in the biomass thermal conversion process. In this work, experimental and analytical investigations were carried out for different vertical dimensions of the biomass samples (2-20mm) and hot plate temperatures (400-550°C). It was shown that the thermal characteristics of the biomass were mainly affected by the transient conditions. It was observed that volatile release occurred during the transient heat transfer periods. It was found that at the maximum hot plate temperature of 550°C, the highest heating rate that could be achieved by ablation was more than 600°C/min.

Keywords-ablation; agricultural residues; clean energy; heat conduction; thermal conversion

I. INTRODUCTION

Biomass is a major source of alternative energy [1, 2]. Utilization of biomass is normally conducted via thermal routes such as combustion, gasification and, slow pyrolysis [3, 4]. Rapid decomposition of biomass can occur at moderate to high heating rates. Fast pyrolysis is a thermochemical process to convert lignocellulosic biomass materials into liquid products. In this reaction route, biomass temperature is raised to 400–600°C in non-oxidizing atmosphere at very fast heating rates (>10–200°C/s) and short reaction times (typically < 2s), releasing volatile gases that can be rapidly condensed into organic liquids or bio-oil [5].

There have been many fast pyrolysis reactors studied including fluidized bed, free-fall, auger, and ablative reactors. Most reactor types require the biomass materials to be grinded into very small sizes of about 1.0mm or less whose cost represents a significant portion of the total processing cost. Ablative pyrolyzer is a type of moderately fast pyrolysis reactor where raw materials are directly subjected to a hot plate. Thermal erosion or melting of the biomass occurs at a contact layer as it is directly pressed against a hot solid surface. This enables high rates of conductive heat transfer, making the process fast, cheap, and highly efficient. The ablative reactor is able to utilize large pieces of wood [6]. Nonetheless, ablation is surface area controlled, hence, upscaling could be a tough challenge. Several ablative pyrolysis systems have been developed and studied in the past 40 years. The first pioneering work on ablative pyrolysis was conducted in [7]. It was shown that woody biomass could be thermally decomposed by ablation, producing a vaporizing layer of degrading solid. Subsequent experiments on ablative heat transfer were carried out with focus on wood pyrolysis in [8, 9]. Authors in [10] developed an ablative pyrolysis reactor with multiple blades

and reported bio-oil yield of up to 68% w/w. Recently, an ablative reactor for pyrolysis of thick woodchips was developed, achieving bio-oil yield of about 60%. Authors in [11, 12] employed an ablative pyrolyzer to produce bio-oils from various agricultural residues under atmospheric and vacuum conditions. It is clear that temperature characteristic, heating rate, and heat transfer between organic materials and heat sources are considered very important for pyrolysis product distribution. In ablative pyrolysis, it is known that there are steep temperature gradients occurring on the thick biomass surface. This impression could be speculative since there was no or very little data to back up the claim. So far, a modest amount of experimental results regarding the biomass heating characteristics during ablation heat transfer is available in the existing literature.

Therefore, in this work, ablation of thick biomass samples was carried out on a hot plate. Heating rates and temperature profiles at different depths of the biomass samples were measured, evaluated and presented, along with the simplified analytical heat conduction results. Information generated from this work will be useful in adopting the ablative pyrolysis technique to produce organic liquids or bio-oil from biomass.

II. MATERIALS AND METHODS

A. Thermal Ablation Experiments

The feedstock used in this study was hemp hurds (Cannabis sativa L.) collected from Chiang Mai's countryside, Thailand. This plant is a stout and aromatic herb. Its stalk is slender and hollow. It was used in this work to represent an example of agricultural residue available locally. Its physical density was about 85kg/m^3. Dirt and other impurities in the feedstock were removed by washing with water, and the feedstock was then naturally dried in sunlight. The moisture content was determined to be 9-10% w/w. The dried samples were cylindrical shaped with about 2mm diameter. Afterwards, they were cut into 40mm long pieces which were stored for later experiments. Figure 1 illustrates the experimental setup. The thermal decomposition of hemp samples was carried out at the hot plate temperatures of 400, 450, and 550°C at 4 different depths of 2, 5, 10, and 20mm inside the biomass samples from the hot plate surface. The hot plate was heated by a cooking gas flame whose temperature was monitored and controlled via an electronic control system actuating the amount of fuel gas flow. The exterior of the reactor chamber except the bottom was fully insulated to minimize heat losses. Biomass temperatures were measured using a type K thermocouple connected to a data logger at 500ms sampling rate. Nitrogen was used at a flow rate of 500mL/min to purge releasing volatiles. Each test case was repeated for at least 3 times.

B. Simplified Heat Conduction Modeling

A simple analytical study was performed for the heat transfer between the hot plate and the cylindrical shaped biomass sample. Conduction is considered as the main heat transfer mode and can be expressed as:

$$\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_g=c_p\rho\frac{\partial T}{\partial t} \quad (1)$$

where Q_g is heat generation inside the particle.

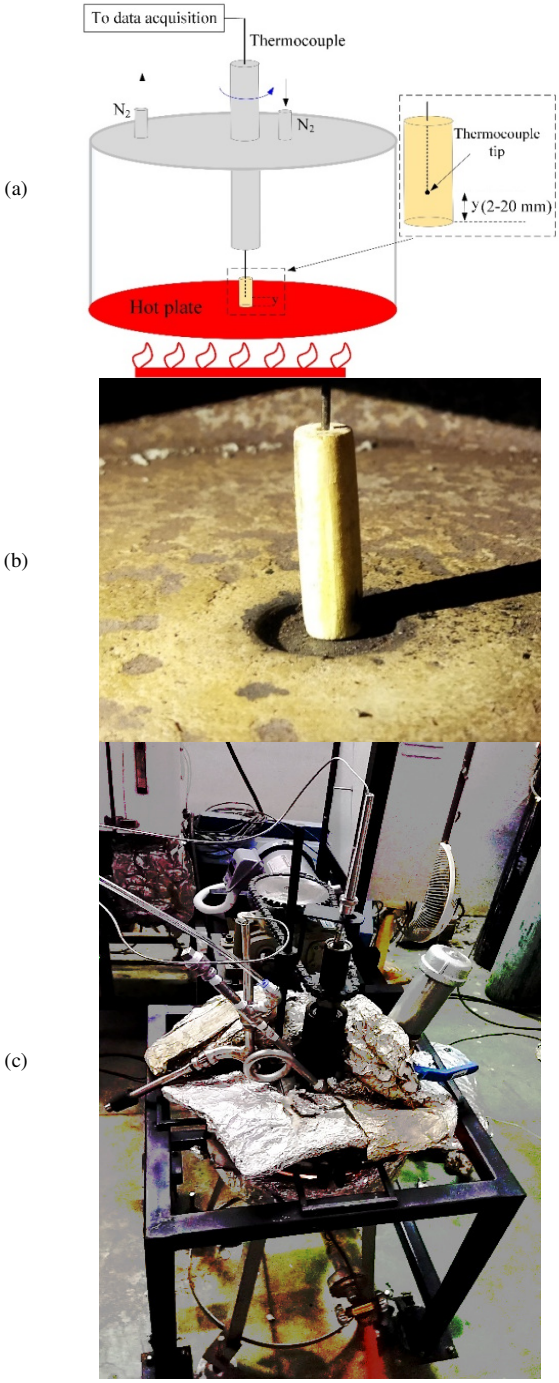

Fig. 1. (a) Schematical diagram, (b) a pictures of biomass on the hot plate, and (c) the experimental setup of the ablative reactor.

We assume that heat is transferred only in one dimension (z-axis) and the system has no heat generation inside the particle. Thus, the expression of conductive heat transfer is equal to the internal energy transfer within the sample body:

$$-kA\frac{dT}{dz}=\dot{m}cp\frac{dT}{dt} \quad (2)$$

Therefore, the temperature evolution could be expressed by:

$$T(t) = T_1 - e^{-\left[\frac{kA}{\rho C_p vz}\right]t} \quad (3)$$

where $T(t)$ is the biomass temperature, T_1 is the hot plate temperature, k is the thermal conductivity of the biomass sample, A is the area of biomass surface in contact to the hot plate, ρc_p is the heat capacity of the biomass sample, v is the volume of the biomass sample, z is the depth, and t is the time.

III. RESULTS AND DISCUSSION

Figure 2 illustrates the temperature evolution and heating rates in the biomass sample at various vertical locations from the surface contact and temperatures of the hot surface. Overall, the temperature of the biomass body appeared to approach the hot surface temperature exponentially. It changed rapidly at the beginning, and after that it slowed down and stayed stable, like the result of the conduction model [13]. There were two main temperature regions: firstly, the transient or unsteady state occurred in the starting period and subsequently, the constant temperature region or steady state.

The starting time of the steady state was affected by the dimension of the biomass sample. For instance, at 450°C, and the distances between the sample and the hot plate of 2, 5, and 10mm, the steady state was reached within about 170s, while at 20mm, it took around 200s. Small sized biomass was likely to reach the steady state quicker than the bigger samples. Similarly, at the condition described by 450°C, 20mm, the steady state was reached in 160s. On the contrary, at the higher temperature of 550°C, the time to reach the steady state was not obviously affected by the biomass particle dimension. Furthermore, the short depth can approach the hot plate temperature easily. For high heat transfer, smaller sized samples are desired as anticipated. However, in practice, the size of biomass may not be very small because of its processing cost [6]. A reasonable size of the biomass samples should be carefully considered for practical use.

Regarding the hot plate temperature, it had significant effect on conductive heat transfer. Low temperature setting would take longer time to reach the steady state than high temperature setting. As shown in Figure 2, for a distance of 20mm at 400°C, it took 160s to reach the steady state while at 450 and 500°C, it took 140 and 120s, respectively. Similarly, for a fixed depth of 20mm, the time it took to reach steady state was 200s at 400°C, but only 120s at 500°C. The temperature and time data can be used to derive the corresponding heating rates. The factor is useful in determining if slow or fast pyrolysis occurs [14]. Overall, the heating rates were found to fluctuate radically during the transient period, before reaching zero heating rate at the steady state. For instance, at 400°C and 10mm distance, the heating rate (purple lined spots) approached zero in 180min as the temperature (green line) became constant.

The smaller sized biomass samples appeared to experience higher heating rates than the bigger samples, as expected. This was due to the fact that smaller sized samples have lower heat resistance [15], hence, greater heat transfer in the initial stage than the larger sized samples. For example, the heating rates at the time of 20s and hot plate temperature of 450°C were approximately 5.0, 4.3, and 3.6°C/s for the biomass samples with depths of 2, 5, and 20mm, respectively. At 140s, the biomass samples with depth of 2 and 5mm had the heating rates reaching zero, while the sample with depth of 20mm exhibited a heating rate of about 2°C/s. In addition, it was observed that the release of volatiles from the biomass decomposition occurred mainly during the transient period and it appeared to stop when the steady state was reached [16]. This observation could be useful in designing and operating the ablative pyrolysis system to obtain the fast release of volatiles. At the highest temperature setting and relatively small sized biomass samples of 2 and 5mm, the maximum heating rates obtained were about 11°C/s or 660°C/min at 20 and 50s, respectively. Meanwhile, at the sample depth of 10mm for the same maximum hot plate temperature setting, the heating rate of nearly 10°C/s or 600°C/min was achieved. All the above are considered as fast pyrolysis [14].

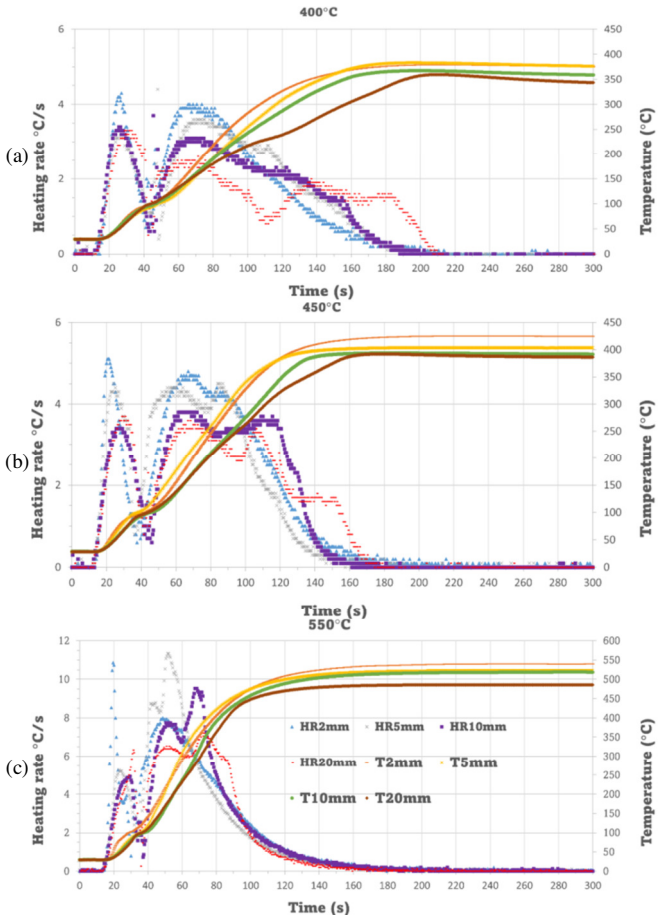

Fig. 2. Temperature profiles and heating rates at different pyrolysis temperatures and depths inside the biomass macroparticles.

In this work, a simplified heat conduction analysis was also performed to predict the temperature evolution during the heat transfer between the hot plate and the biomass sample. The results are shown in Figure 3. The temperature profiles show the two regions of transient and steady states. Different biomass sizes spend different time to reach the steady state. The higher depths or bigger biomass samples take longer time

than smaller counterparts in the transient period. For instance, the biomass with 2mm depth reaches the steady state within 100s while the one with 10mm depth takes about 300s to become steady. Volatiles from biomass thermal degradation are released in the transient period. For practical applications, it may imply that larger sized particles undergo longer transient period which could release more volatiles for higher bio-oil yield. Nonetheless, it should be noted that even though the analytical results showed similar patterns of temperature evolution, their values are markedly different. This may be caused by the fact that the biomass properties (density, thermal conductivity, and heat capacity) used in the analytical study differ from the real values [17]. Furthermore, ablative heat transfer in thick biomass samples may not be simply approximated by a one-dimensional, transient heat conduction model. A more complicated heat transfer model should be adopted in future investigation.

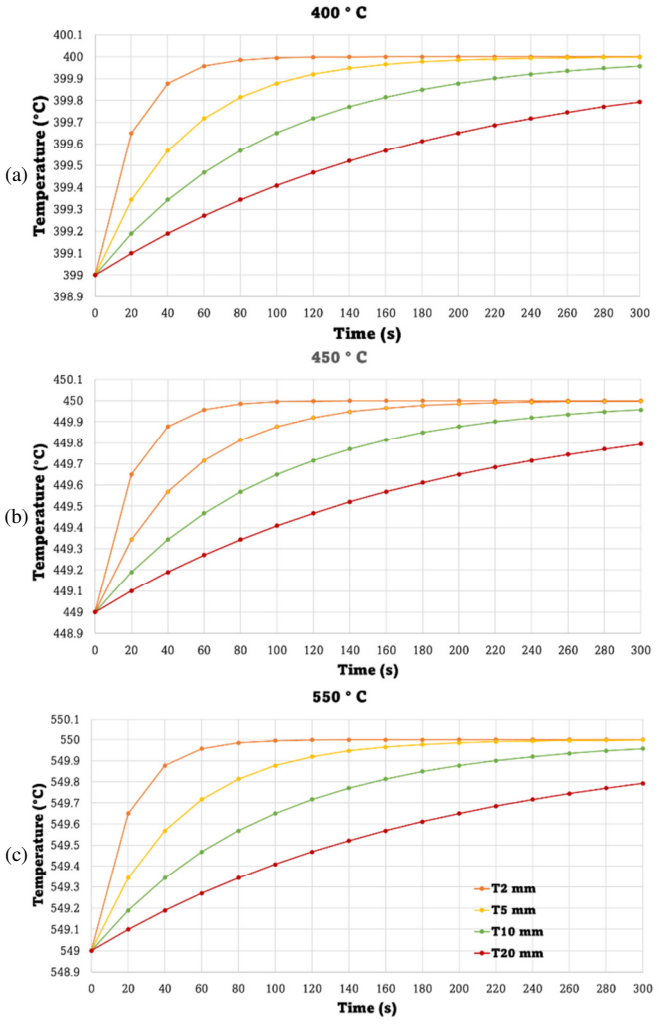

Fig. 3. Simulated temperature profiles at different pyrolysis temperatures and depths inside the biomass macroparticles.

Table I shows a comparison, between this work and those available in the literature, of reactor temperature and realized heating rates for various biomass types and shapes when undergoing ablative pyrolysis. It can be seen that while the reactor temperatures were in similar magnitude (365 to 800°C), our work appeared to show higher maximum heating rates, up to 660°C/min, compared to 174 and 20°C/min reported in [13] and [6], respectively. This was possibly due to the fact that the biomass size used in this work was the smallest among the compared works. It is also likely that their temperature gradients were not measured directly, but estimated from temperature measurement at points some distance further from the surface than the location done in this work.

TABLE I. COMPARISON OF BIOMASS TYPE AND SHAPE, AND THERMAL CHARACTERISTICS OF ABLATIVE PYROLYSIS BETWEEN THIS WORK AND OTHERS

Biomass material (shape)	Heating rate (°C/min)	Reactor temperature (°C)	Dimensions (diam. × length) (mm)	Ref.
Pine wood (chip/rod)	7 – 20	500	2×2 – 35×200	[6]
Beechwood (rod)	n/a	400 – 800	2 – 10 (dia.)	[8]
Pine wood (cubic)	n/a	400 – 600	4.75 – 6.25	[10]
Hard wood (sphere)	50 – 174	365 – 606	n/a	[13]
Hemp residue (rod)	30 – 660	400 – 550	1×2 – 1×20	This work

n/a: not available

IV. CONCLUSION

Temperature profile and heating rate are essential factors defining the biomass pyrolysis type of slow and fast pyrolysis. In this work, measurements and simplified analytical studies of biomass heating characteristics for different biomass dimensions and hot plate temperature were carried out. From the findings, it was shown that there were two temperature intervals of transient and steady states identified during the biomass thermal decomposition. The small size and high hot plate temperature enabled the biomass sample to reach the steady state within a very short time. Releasing of volatiles occurred mainly during the transient period. At the highest hot plate temperature of 550°C, the biomass underwent the maximum heating rate around 11°C/s or 660° C/min, in the fast pyrolysis range. This information is useful for utilizing the ablation technique for pyrolysis reactor design.

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