

Prediction model of higher heating value of torrefied biomass based on the kinetics of biomass decomposition



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ABSTRACT

This work presented the Higher Heating Value (HHV) prediction model of torrefied biomass based on the kinetics of biomass decomposition. The prediction values were compared with experimental data of torrefied cassava rhizome (*Manihot esculenta* species). Moreover, the model developed in this work was used to explain the effect of torrefaction temperature and residence time on the heating value of the torrefied biomass. The results show that the HHV prediction model gave an over prediction value compared to the HHV obtained by the bomb calorimeter. The average absolute error of the HHV prediction model was 7.03%. At the beginning of torrefaction, the HHV of the torrefied biomass rapidly increased when residence time increased. When a certain residence time was reached, the HHV tended to asymptote to a constant value, i.e. HHV at termination point of thermal degradation reaction (HHV_c). The value of HHV_c strongly depended on the torrefaction temperature. Increasing of HHV_c and decreasing of residue mass (M_t) resulted in increasing of HHV of torrefied biomass. The model developed in this work gave a clear view of the change of HHV at various conditions of torrefaction temperature and time. This understanding leads to production planning with an efficient use of energy in torrefaction process.

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1. Introduction

The torrefaction process is a thermal decomposition of biomass carried out at a temperature range of 200–300 °C under an inert atmosphere. In this process, the composition of biomass such as hemicelluloses, lignin, and cellulose degrades into volatile matter, tar, and char. Many studies have been carried out on decomposition kinetics and kinetic models. One-step [1–4] and two-step [5–7] kinetic models were established for mass loss prediction. In other aspects, many studies reported that the torrefaction process results in an improvement in biomass properties, especially heating value [8]. The heating value is presented in the form of Higher Heating Value (HHV), Lower Heating Value (LHV), and Net Heating Value (NHV), based on dry basis, dry ash-free basis, and as received. For raw biomass, a lot of research has established a model for HHV prediction. The model for the heating value prediction of agriculture residue was established by Yin [9]. Tillman [10] presented a correlation for the prediction of HHV using the percentage of carbon content in biomass. His correlation gave 5% error compared to the experimental data. Demirbas [11] developed a correlation for the prediction of HHV using the weight percentage of C, H, O, and N with 2.2% of mean difference error. Sheng and Azevedo [12] presented a correlation for HHV prediction of biomass in terms of C, H, O, and ash with an accuracy higher than 90% compared to the experimental data. The percentage of volatile matter, moisture, ash, and fix carbon, which can be obtained from proximate analysis, was also used to predict HHV [13–15]. Prediction of HHV using the combination of proximate and elemental analysis data in form of C, H, O, N, S, ash content and H/C ratio was presented by Parikh et al. [16] with ±5% of error. In addition, the content of biomass including ash, cellulose, hemicelluloses, and lignin were used by Jimenez and Gonzalez [17] for the prediction of HHV with an error lower than 10%. The correlation for NHV prediction using proximate analysis data was established by Erol et al. [18].

For torrefied biomass, Almeida et al. [19] developed an HHV model using mass loss of biomass by curve fitting technique. It was found that the heating value has a linear relationship with the mass loss of biomass with a coefficient of determination (R^2) of 0.98. Bridgeman

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et al. [20] and Ibrahim et al. [21] conducted HHV prediction of torrefied biomass using a correlation derived by Friedl et al. [22]. Medic et al. [23] predicted the HHV of raw biomass and torrefied biomass by means of the correlation of Sheng and Azevedo [12]. Chen et al. [24] applied the correlation of Parikh et al. [16] for the HHV prediction of torrefied biomass with lower than 5.3% of relative error.

Chen et al. [25] predicted the higher heating value of torrefied biomass which was performed under oxidative and non-oxidative states using the correlation of Channiwala and Parikh, and Yin. The prediction results showed the relative error lower than 10% comparing with experiment.

As can be seen above, there are very few studies which developed models for predicting the heating value of torrefied biomass. Moreover, those models cannot explain the relationship between the heating value and the decomposition kinetics of biomass. This work, thus, developed an HHV prediction model based on the kinetics of biomass decomposition. The prediction values were compared with experimental data of torrefied cassava rhizome. In addition, the model developed in this work was used to evaluate the effect of torrefaction temperature and residence time on the heating value of the torrefied biomass.

2. Method

2.1. Material

The cassava rhizome (*Manihot esculenta* species) used as feedstock in this work was non-woody biomass which has a relatively short live comparing with wood, and mostly planted in tropical climate zone. It was ground using hammer mill to provide a particle size less than 1 mm. Then, the particle size distribution of ground sample was determined by sieve analysis according to ASTM E11 (1989) standard. The particle size distribution was shown in Fig. 1. The biomass samples were dried in the hot air oven (Red line by BINDER, RE 53) at temperature of 105 °C for 24 h. After that it was placed to cool down in the desiccators. The weight of samples after drying process was measured by digital balance with 0.01 g readability. The moisture content of the samples was controlled at $9 \pm 1\%$. The prepared sample was separated into three parts. The first part (10 g) was used to investigate the kinetic parameters using thermal gravity analysis. The second part (40 g) was treated in a cylindrical reactor to observe the weight loss curve and prepare the torrefied sample for fuel analysis including heating value, proximate, and elemental analysis. The third part (40 g) was used to verify the existence of the termination point of degradation reaction at a certain temperature. The torrefied biomass at the termination point of degradation will also be used to determine its higher heating value.

2.2. Cylindrical reactor

The reactor was made from a stainless steel cylinder with an internal diameter of 3.5 cm, length of 15 cm, and wall thickness of 2.5 mm. Nitrogen was purged through the cylinder reactor to establish an inert atmosphere. The volumetric flow rate of nitrogen was controlled by a rotameter with an accuracy of $\pm 2\%$ Full Scale. The reactor was heated with 3 kW electrical heaters. The temperature was controlled by a digital temperature controller (SHIMAX MAC3 Series). Five thermocouples were installed in the reactor along the longitudinal axis of the reactor. The temperature distribution inside the reactor was observed and recorded by a temperature data logger (GRAPHTEC midi LOGGER GL220) with an accuracy of ± 1 °C. To investigate weight loss of torrefied biomass, the reactor was placed on the rig lying on digital balance with 0.01 g readability as shown in Fig. 2a. The weight loss of torrefied biomass can be monitored by subtracting the present weight from the initial weight.

2.3. Torrefaction procedure

Fig. 2a shows the experimental setup. The second part of the cassava rhizome sample (40 g) was placed into the reactor. Then, it was heated using an electrical heater with a heating rate of 20 °C min^{-1} until it reached at the desired torrefaction temperature. A nitrogen flow rate of 100 mL min^{-1} was purged through the reactor to remove oxygen and the volatile matter to keep an inert atmosphere inside the reactor. The weight of the sample was continuously recorded until the torrefaction process was accomplished. Then, the torrefied sample was kept in air tight plastic bags and stored in desiccators for fuel analysis. The torrefaction temperatures were varied at 220, 260, and 280 °C

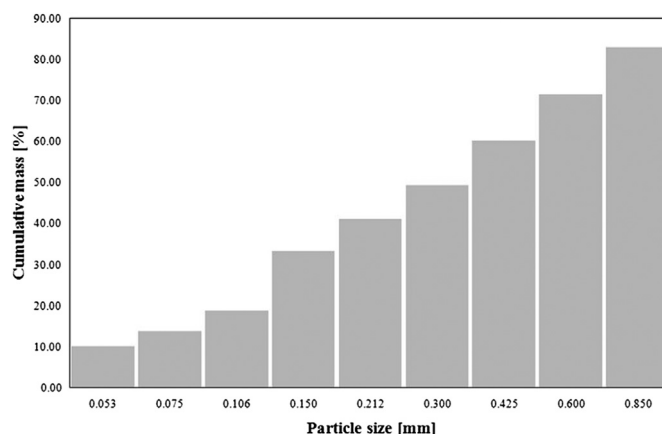


Fig. 1. Distribution of particle size in sieve analysis.

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