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Thermal Upgrading of Biomass as a Fuel by Torrefaction

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Abstract. Direct use of agricultural and wood residues as fuel is usually difficult, because they have poor energy characteristics. Torrefaction appears to be an attractive option of upgrading biomass to a product which retains about 90% of its energy. Torrefaction is a pyrolysis process with low heating rate and temperature lower than 300^{0}C. The important advantages of torrefied biomass include high energy yield and hydrophobicity so that it does not regain moisture during storage, less smoke when burnt, and non fermentable nature. This study reviews and examines the torrefaction process as an alternative treatment to biomass residues, contributing to advance the competitiveness of biomass residues as an energy resource. The aim is to give a good insight into the torrefaction process. During torrefaction process, biomass undergoes changes in physical and chemical properties. The yield of solid product decreases with the temperature and the residence time. The content of carbon in the solid product increases at higher temperature of the torrefaction and longer reaction time while the content of hydrogen and oxygen decrease, increasing the calorific value of the torrefied biomass. The content of CH_4, H_2, C_xH_y, and CO in the product gases increases when the temperature is increased while the content of CO_2 decreases. It is determined from analysis of data that the temperature of torrefaction has greater influence on the torrefied products than reaction time. For this reason, a temperature range higher than 250^{0}C with reaction times around 1 hour is recommended for torrefaction. However, at same operating conditions, mass and energy yields will vary for different biomass, as the polymeric composition and reactivity may differ. Consequently, each biomass will have its own set of operating conditions to achieve the same product quality. For a good design and operation of a biomass torrefaction plant, further understanding for optimisation of the process is required. An important research parameter is the type of biomass, the composition of which determines its behaviour in the torrefaction process. It is suggested that future work should focus on biomass in Thailand for optimum torrefaction conditions, as well as investigations of the combustion behaviour of these fuels.

Keywords: Biomass, Thermal Process, Torrefaction

1. Introduction

Direct use of agricultural and wood residues as fuel is usually difficult, because they have poor energy characteristics, e.g. low heating value, high moisture content, hygroscopic nature, low density and polymorphism, causing high costs during transportation, handling and storage. When aiming to improve the fuel properties of those, there is a need to eliminate the biomass constituents that are not combustible such as water, extractive, minerals, etc. Among the most used processes are the thermal ones, such as pyrolysis, carbonization, and torrefaction. Through these processes products which can be used directly for energy or as a chemical feedstock are obtained. These processes consist of the thermal degradation of biomass with absence of oxygen, from these three products are commonly obtained: gas, liquid and solid in proportions that depend on the method employed and operation parameters.

Torrefaction appears to be an attractive option of upgrading biomass to a product which retains about 90% of its energy. The torrefaction objective is to improve the energy properties of biomass. Torrefaction is a thermal degradation process with low heating rate and temperature lower than 3000C. The important advantages of torrefied biomass include high energy yield and hydrophobicity so that it does not regain moisture during storage, less smoke when burnt, and non fermentable nature. This study reviews and examines the torrefaction process as an alternative treatment to biomass residues, contributing to advance the competitiveness of biomass residues as an energy resource. The aim is to give a good insight into the torrefaction process.

2. Torrefaction Principles

Torrefaction is a thermo-chemical treatment method that is earmarked by an operating temperature ranging from 200°C to 300°C. It is carried out at near atmospheric pressure in the absence of oxygen and characterised by low particle heating rates (<50°C/min). The biomass partly decomposes during the process giving off water and various types of volatiles, which results in a loss of mass and chemical energy to the gas phase. There are two different mechanisms occurred during the process, firstly during drying when moisture evaporates and secondly during decomposition of biomass.

In the initial heating stage, biomass moisture content evaporation is very slow; nonetheless, the biomass temperature increases. In the pre-drying stage, moisture content decreases dramatically while the biomass temperature stays constant. Following this stage, post-drying and intermediate heating occurs. The temperature increases up to 200°C and the physically bounded water is released. Above 200°C torrefaction reaction occurs and devolatilisation takes part in this stage caused mass lose.

In this condition (200°C-300°C), it is believed that moisture in biomass is vapourised and most of volatiles released are from hemicellulose degradation, since hemicelluloses is most reactive in this temperature range and subjected to extensive devolatilisation and carbonisation. Meanwhile, other components; cellulose and lignin, are subjected to limited devolatilisation and carbonisation. This results in product which characterises between charcoal and the original raw biomass.

3. Characteristics of the Torrefied Biomass

Characteristic of the torrefied biomass is different from original biomass and strongly is dependent on torrefaction temperature, reaction time, and biomass type. During the torrefaction process, not only mass of biomass is lost but also energy content in biomass which is in released volatile. But more mass than energy is lost to the gas phase. This phenomenon results in higher calorific value of torrefied biomass.

The moisture uptake of torrefied biomass is very limited due to the dehydration reactions that take place during the torrefaction reaction. These reactions prevent the bonding of biomass hydrogen with water. Hence, the moisture content is much less compared to the content of moisture of the raw biomass.

Another change in the biomass occurs is the tenacious nature. It becomes more fragile as it loses its mechanical strength. As a result, torrefied biomass size reduction becomes easier. Loss of the tenacious nature of the biomass is mainly coupled to the breakdown of hemicellulose matrix, which bonds the cellulose fibres in biomass, and decrease the length of these fibres via depolymerisation process.

In addition, the biomass is also subjected to chemical transformations with little mass loss. In these rearrangement reactions unsaturated structures are formed which are non-polar. It is likely that this property is also the main reason that torrefied biomass is practically preserved so that biological degradation does not occur anymore.

3.1. Mass yield of torrefied biomass

The different types of biomass influence the product distribution (solid, liquid and gas phases) of during torrefaction process. Percentage of residue torrefied mass (solid yield) to original mass of raw biomass is shown in Fig. 1. It can be seen that when the temperature increases, the yield of the solid torrefied product decreases. The effect of the temperature on the solid product is more pronounced at torrefaction temperature above ~250°C. An increase of the reaction time at the torrefied temperature results in a decrease of the yield of solid torrefied biomass (Fig. 2).

The elemental analysis of the raw biomass and the torrefied biomass show that the content of carbon increases, when torrefaction temperature and reaction time of the torrefaction process are increased while the contents of hydrogen and oxygen decrease (Fig. 3-6). This can be inferred that, in torrefaction process, biomass loses relatively more oxygen and hydrogen contents compared to carbon contents. Consequently, H/C and O/C atomic ratios decrease with the temperature. A plot of the molecular ratios of carbon, hydrogen and oxygen on the Van Krevelen diagram, Fig. 7, shows that the change in elementary composition of torrefied biomass moves it towards lignite. The exception is nitrogen content which remained almost constant. Losses in hydrogen and oxygen are due to the formation of water, carbon monoxide and carbon dioxide.

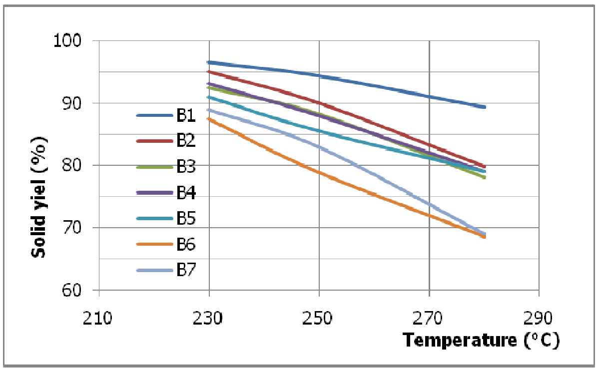

Fig. 1 Effect of torrefaction temperature on mass yield of various torrefied biomass at reaction time of 1 hr.

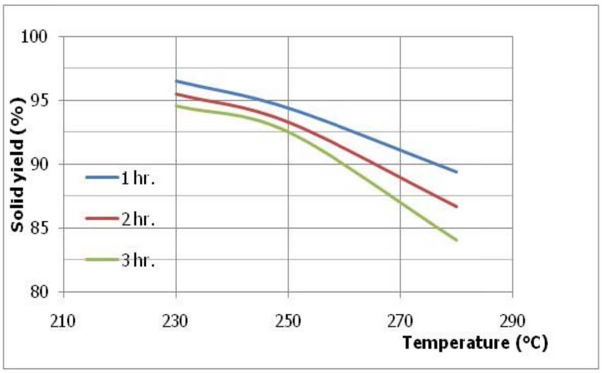

Fig. 2 Effect of torrefaction temperature on mass yield of torrefied biomass at various reaction time.

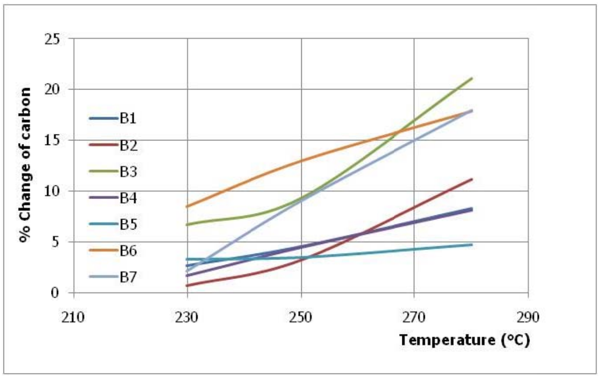

Fig. 3 Change in carbon content of various torrefied biomasses as a result of torrefaction temperature.

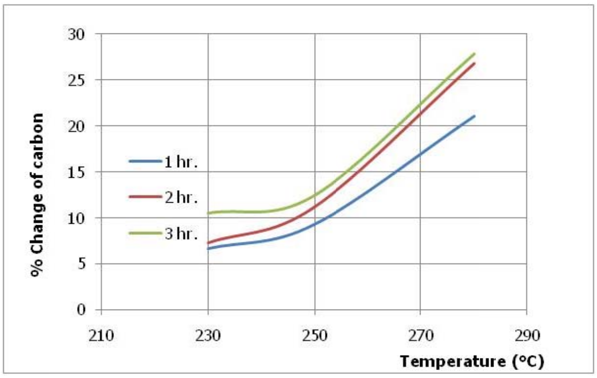

Fig. 4 Change in carbon content of torrefied biomass as a result of torrefaction temperature at different reaction time.

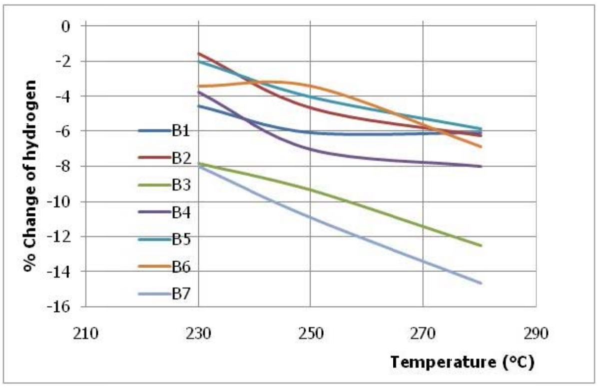

Fig. 5 Change in hydrogen content of various torrefied biomasss as a result of torrefaction temperature.

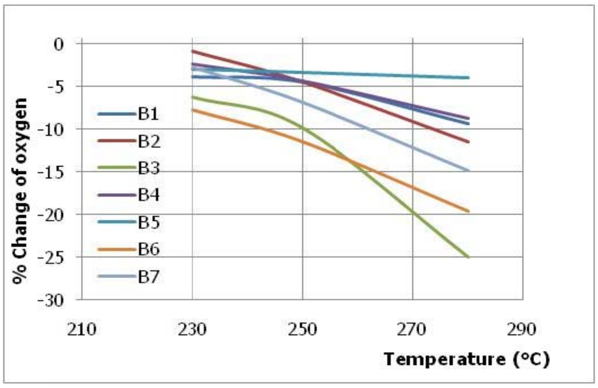

Fig. 6 Change in oxygen content of various torrefied biomasses as a result of torrefaction temperature.

Mass lost of torrefied biomass during devolatilisation process as gaseous phases are detected and mainly composed of carbon dioxide, carbon monoxide and methane. The remaining products comprises of water and condensable organics. Higher torrefaction temperature favours the production of carbon monoxide and methane while carbon dioxide content in the gaseous mixture decreases. Longer reaction time produces the same effect on the composition of the gaseous product as a higher torrefaction temperature.

3.2. Calorific values of torrefied biomass

One drawback of using biomass as a fuel is that low calorific value of raw biomass. For torrefaction process, the calorific value of the torrefied biomass increases with the temperature and at longer reaction time (Fig. 8) due to increase in carbon content and decrease in oxygen content. It can be observed that there is more increase in calorific value of torrefied biomass at torrefaction temperature greater than ~250°C which is coincident to increase of carbon content (Fig. 4).

3.3. Mass yield versus energy yield

Mass yield and energy yield are remained mass, in solid phase, and energy content of torrefied biomass compared to raw biomass. The results of the energy and mass yield of different torrefied biomass at torrefaction temperatures of 250°C are shown in Fig. 9. It can be seen that, for all products of torrefied biomass, the energy yield is greater than the mass yield and becomes more marked for higher torrefied temperature, as shown in Fig. 10. This phenomenon affects to increase in calorific value of torrefied biomass as mentioned above. At torrefaction temperature higher than 250°C, the mass lost is more pronounced than energy lost. This is believed to result in markedly increasing of calorific value of torrefied biomass at torrefaction temperature greater than 250°C.

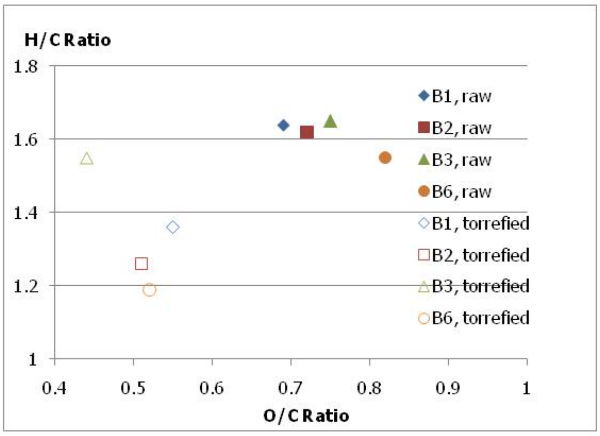

Fig. 7 Van Krevelen diagram

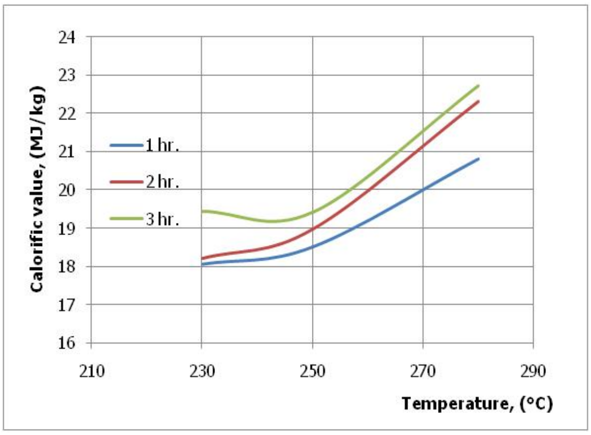

Fig. 8 Effect of torrefaction temperature on calorific value of torrefied biomass.

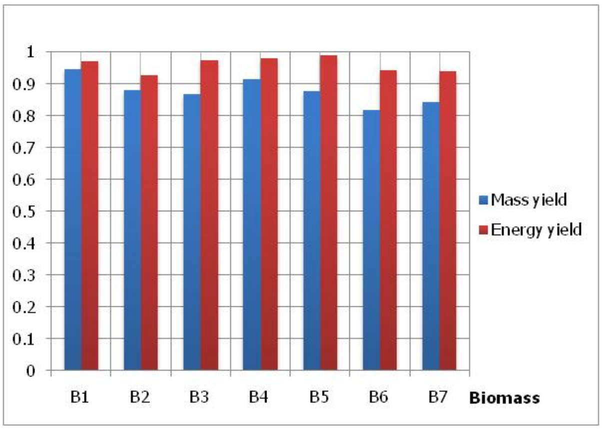

Fig. 9 Mass yield and energy yield of different torrefied biomass

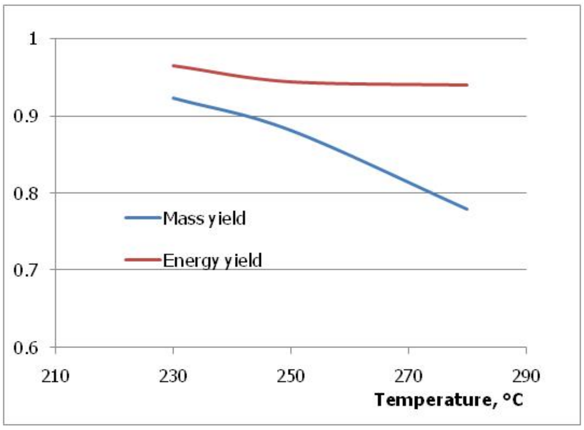

Fig. 10 Effect of torrefaction temperature on mass yield and energy yield of torrefied biomass

3.4. Degree of torrefaction

One benefit of torrefaction process is the increase in energy content per unit of mass yield of torrefied biomass. Even there is energy lost during the torrefaction process but lessen than mass lost resulting in increasing energy intensity. One indicator to identify or illustrate the relative energy gain in torrefied biomass is called "degree of torrefaction". The degree of torrefaction is assessed as a ratio between the calorific value of the torrefied biomass and the calorific value of the raw biomass. If the degree of torrefaction is greater than unity, it means that there is relative energy gain per unit mass when subjected to torrefaction process. The greater the degree of torrefaction over one, the higher relative energy gain per unit mass. The results show that the degree of torrefaction is greater than unity due to the increase of calorific value of torrefied biomass which is increased with the temperature. This can be explained by the fact that percentage of mass loss is greater than percentage of energy loss.

4. Conclusion and Recommendations

Biomass can be upgraded and used as a fuel by torrefaction process. The product, usually called torrefied biomass, is more suitable than raw biomass in term of; calorific value and physical and chemical properties. Torrefied biomass can be produced from different types of biomass while yielding similar product properties. The main reason for this is that about all biomass are built from the same polymers (lignocellulose). The chemical changes of these polymers during torrefaction process are practically similar resulting in the same property changes. It is determined from analysis of data that the temperature of torrefaction has greater influence on the torrefied products than reaction time. For this reason, a temperature range of 250^0C to 300^0C with reaction times around 1 hour is recommended for torrefaction process. However, at same operating conditions, mass and energy yields will vary for different biomass, as the polymeric composition and reactivity may differ. Consequently, each biomass will have its own set of operating conditions to achieve the same product quality.

For a good design and operation of a biomass torrefaction plant, further understanding for optimisation of the process is required. An important research parameter is the type of biomass, the composition of which determines its behaviour in the torrefaction process. It is suggested that future work should focus on biomass in Thailand for optimum torrefaction conditions, as well as investigations of the combustion behaviour of these fuels.

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