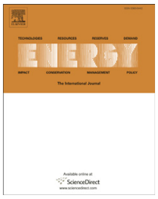
Energy 74 (2014) 181–189

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Energetic and exergetic evaluation of residual biomass in a torrefaction process

D.A. Granados*, H.I. Velásquez, F. Chejne

Universidad Nacional de Colombia sede Medellín, Facultad de Minas, Colombia

ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form
12 May 2014
Accepted 13 May 2014
Available online 11 June 2014

Keywords:
Torrefaction
Energy balances
Residual biomass
Exergy balances
Energy yield
HHV (High Heating Value)

ABSTRACT

A torrefaction process in a TGA (Termo-gravimeter analyzer) for six different types of residual biomass (sugarcane bagasse, banana rachis, rice husk, palm oil fiber, sawdust and coffee waste) was developed in this paper. These six materials were evaluated before and after the torrefaction process through HHV (High Heating Value) and energetic and exergetic balances in order to find a promising solid fuel biomass in a torrefaction process. Torrefaction is a thermal process performed in an inert atmosphere at temperatures between 200 and 300 °C, with residence times lower than 60 min and heating rates lower than 20 °C/min. Its aim is to improve biomass as a solid fuel. In this processing, the lignocellulosic components are degraded (hemicellulose and cellulose are more degraded than lignin), having as result a biomass with a predominant amount of lignin. In this work, the torrefaction process was carried out at a temperature of 250 °C in an inert atmosphere with 10 °C/min of heating rate and a residence time of 30 min. As a result, it was found that the biggest and lowest increases in HHV for torrefied biomass were14.5% and 5.2% for sawdust and palm oil fiber, respectively. Sawdust was found to have the best performance in the torrefaction process evaluated from the energy yield parameter but rice husk was the best biomass in the energetic balances of the process. Energy and exergy balances show that palm oil fiber and banana rachis are the least efficient biomass in the torrefaction process.

1. Introduction

Biomass is a promising source of solid fuels that compete with fossil fuels like oil and coal because of its low emission of greenhouse gases and its acceptable performance in thermal processes. Despite the benefits of using biomass in thermal processes, its implementation has a major limitation for projects involving high biomass flows. High humidity and low biomass density reduces the feasibility of the projects as the projects' size increases. This is due to the high cost associated with the transport of large amounts of biomass. It is for this reason that only small and medium scale projects may become the only option for obtaining economic benefits from the transformation of thermal biomass.

The torrefaction process is carried out in inert atmospheres or low amounts of oxygen at temperatures in the range of 200–300 °C and low heating rates (<20 °C/min) [1]. During the torrefaction process a mass loss of up to 40% and an energy loss between 5 and 10% are registered for the biomass and a HHV (High Heating Value) is generated [2–4]. Different authors in the literature have experimentally evaluated the performance of biomass when it is subjected to a torrefaction process with variations in operating parameters [5,6], have evaluated the kinetics to suggest reaction mechanisms [7], and have evaluated the torrefied biomass in a combustion process [8–10], gasification [10–12]and crushing [13–15] to improve the process or the performance of the biomass. In addition to the above experimental studies, other approaches such as developing process models [16,17], mass and energy balances that provide information on process feasibility [18–20] and some cost analysis can be found in the literature [21,22].

Bourgois et al. [5] examined the effect of a thermal process at 260 °C in an inert atmosphere on a pine biomass. Residence times were varied between 15 min and 4 h. The gases generated in the process were examined by chromatography, finding the dominant presence of non-condensable components such as CO, CO_2, O_2 and N_2. The authors concluded that CO generation is instantaneous, so that CO_2 generation is not a product of CO combustion. The torrefied solid was analyzed by monitoring its weight during torrefaction and by ultimate and proximate analysis. In these tests it was found that when the residence time varies between 15 min and 4 h, the mass (20–50%), the amount of hydrogen (0.2–19%) and the

---

* Corresponding author.
E-mail addresses: dagranad@unal.edu.co, dagranad@gmail.com (D.A. Granados), fchejne@unal.edu.co (F. Chejne).

http://dx.doi.org/10.1016/j.energy.2014.05.046

amount of oxygen of the biomass (5–40%) decrease. In contrast, the amount of carbon in the torrefied material (4–33%) and lignin (30–200%) increase when the residence time increases. In general, the torrefaction process produces an increase in the biomass HHV of up to 44% and improves hydrophobic characteristics that directly impact the lifetime of the material. These tests were performed only at a process temperature, and the heating rate of the biomass or the particle size used is not mentioned in the article, leaving unrevealed much of the behavior of the material when the temperature and other parameters, such as the fraction of oxygen in the process, are modified. These tests were not conducted under experimental design so they only evaluated the impact of a parameter in the process and, therefore, the effect of the other variables in the results cannot be concluded with certainty.

In a later work, Bourgois et al. [6] performed experimental tests similar to those of previous work [5], with the same operating parameters unspecified such as particle size and heating rates and with the difference that the residence time was kept constant and the temperature varied in the range of 240–290 °C. The trends found in the behavior of parameters, such as mass loss, oxygen, hydrogen and lignin, were very similar to those found in previous work. It is noteworthy that the same shortcomings noted in previous work were evidenced again.

Pentananunt et al. [2] evaluated the final characteristics of the torrefied biomass such as proximate and ultimate analysis, and density, but with an additional component corresponding to the performance analysis of the material roasted in a combustion process. In the torrefaction tests, the temperature and residence times were varied from 250 to 270 °C and 2–3 h, respectively. This study found similar results to those found in the works of Bourgois et al. [5,6], in terms of the reduction of hydrogen and oxygen, and increased carbon when the process temperature and the residence time increase. In the combustion tests conducted with torrefied wood and charcoal, the findings were that torrefied biomass shows better performance because it generates less dense smoke, less soot and higher speeds in combustion than virgin biomass. The study does not mention the type of wood used for the torrefaction process.

W-H Chen et al. [23,24] evaluated the torrefaction process in a TGA (Termo-gravimeter analyzer) with four kinds of biomasses with the aim to study the behavior of lignocellulosic structure after thermal process. In this work it was found that hemicellulose is almost completely decomposed, but cellulose and lignin are partially decomposed. They also studied the kinetics of cellulose, hemicelluloses and lignin for different temperatures in an isothermal torrefaction process [23]. They found the kinetic parameter for different ranges of temperature and proposed a reaction order for each reaction in the components. Additionally, they propose a model to predict biomass decomposition from the decomposition of each component. This model has been controverted by different authors because neither synergic effects nor the catalytic effect of ash are considered.

Fisher et al. [10] performed torrefaction tests with willow wood with sizes ranging between 5.6 and 9.5 mm in order to evaluate its performance during the combustion and gasification process. The torrefaction is carried out with heating rates of 5 °C/min from room temperature to 150 °C and maintained there for 45 min. Subsequently, the heating continues with the same heating rate until reaching the process temperature which varies between 270 and 290 °C and it is maintained at this temperature for between 38 and 41 min. Differences in reactivity during the combustion and gasification between torrefied biomass and virgin biomass have been found. The difference in reactivities between these biomasses with longer residence times and higher processing temperatures was evident.

S-W Park et al. [25] evaluated the performance of a torrefied biomass with different operational conditions in a torrefaction process, and in a co-combustion process with coal. In this work low-temperature and several torrefaction processes were developed and blended later with coal for co-combustion tests. The biomass with several torrefaction processes was more reactive than the low-torrefied biomass. This behavior is due to the complete decomposition of some components like hemicelluloses and cellulose in the pre-treatment process because, during combustion process, some shoulders are seen for low-temperature torrefied biomass due to the components that were not decomposed in the torrefaction process.

Repellin et al. [14] evaluated the performance of torrefied biomass in terms of energy consumption in a shredding process. The torrefaction process was carried out with biomass pellets, varying residence time (5–60 min) and process temperatures (180–260 °C), and subsequently crushing the pellets in a ball mill to a particle size of less than 200 μm. Once this particle size was reached, the energy consumed in the grinding process was measured and compared with other virgin and torrefied biomasses with different operating conditions. It was found that with biomass torrefied at higher temperatures significant reductions (93%) in energy consumption can be obtained.

Some authors have addressed the issue of biomass torrefaction by performing mass, energy and exergy balances, trying to add its energy and exergy viability to the obvious benefits of the process.

Prins et al. [18] evaluated the torrefaction process bound to a gasification process. To carry out the analysis of torrefied biomass performance under different operating conditions, different configurations were evaluated combining the torrefaction processes and gasification. One of the tested combinations considers the use of volatiles produced in the torrefaction as an energy part of the gasification. After an exergetic analysis of the different configurations, the authors concluded that when a torrefaction pretreatment is linked to the gasification process, where part of the energy of the process is provided by the exhaust gases and volatiles from the gasification process and torrefaction, respectively, it is possible to improve the performance of the biomass in the gasification process as well as the overall efficiency of the process. These analyses were conducted theoretically and, therefore, the authors suggest experimental verification.

Yan et al. [20] performed mass and energy balances for biomass torrefaction process under two different operating conditions and the same residence time. The torrefied biomass (pine) showed the trends highlighted by different authors in their experimental work when the temperatures increase. In these balances, the heats of reaction in each solid biomass were calculated and the authors concluded that these were totally independent from process temperatures.

Models have been developed trying to describe the torrefaction process. Ratte et al. [17] developed one of the most complete models found so far in the literature for biomass torrefaction process. This model considered two phases inside the reactor: a phase composed by biomass particles and a continuous phase composed of 11 species for the gas entering the reactor and generated in the process. The modeling process is for a continuous process and eight reactions were considered during the torrefaction process. Although the validations performed with experimental data have acceptable agreement with the results of the model, some simplifications in the simulations limited the accuracy of the results and forced the authors to improve them to increase the model's performance. One of the phenomena that occurs during the torrefaction process and which is not considered in the model is the condensation of condensable volatiles or tar generated in the process.

This work was focused on finding a potentially promising solid fuel from residual biomasses when they are treated thermally in a torrefaction process in TGA. For this purpose, the residual