Energy Conversion and Management 90 (2015) 446–457

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A simulation study on the torrefied biomass gasification

Dhruv Tapasvi [a,*], Rajesh S. Kempegowda [b], Khanh-Quang Tran [a], Øyvind Skreiberg [b], Morten Grønli [a]

[a] Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway
[b] SINTEF Energy Research, NO-7465 Trondheim, Norway

ARTICLE INFO

Article history:
Received 1 August 2014
Accepted 16 November 2014
Available online 6 December 2014

Keywords:
Biomass
Gasification
Torrefaction
Energy efficiency
Exergy efficiency

ABSTRACT

Many studies have evaluated biomass behavior in a gasification process. Similar studies with torrefied biomass are needed to evaluate the improvements in biomass properties with torrefaction. This forms the basis of this study. A two-stage biomass gasification model is presented by using Aspen Plus as the simulation and modeling tool. The model included the minimization of the Gibbs free energy of the produced gas to achieve chemical equilibrium in the process, constrained by mass and energy balances for the system. Air and steam were used as the oxidizing agent in the process that uses both untreated and torrefied biomass as feedstocks. Three process parameters, equivalence ratio (ER), Gibbs reactor temperature and steam-to-biomass ratio (SBR), were studied. 27 cases were included in the analysis by operating the system below the carbon deposition boundary with all carbon in gaseous form in the product gas. Product gas composition in the form of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and nitrogen (N_2) was analyzed together with cold gas energy and exergy efficiencies for all the cases. Overall, mole fractions of H_2, CO, CO_2 and N_2 were between 0.23–0.40, 0.22–0.42, 0.01–0.09 and 0.14–0.36 for torrefied wood and 0.21–0.40, 0.17–0.34, 0.03–0.09 and 0.15–0.37 for untreated wood, respectively. Similarly, cold gas energy and exergy efficiencies were between 76.1–97.9% and 68.3–85.8% for torrefied wood and 67.9–91.0% and 60.7–79.4% for untreated wood, respectively. Torrefied biomass has higher H_2 and CO contents in the product gas and higher energy and exergy efficiencies than the untreated biomass. Overall efficiencies of an integrated torrefaction–gasification process depend on the mass yields of the torrefaction process. Results from this study were validated using a C–H–O ternary diagram and with results from other similar studies.

1. Introduction

Biomass is one of the most important renewable energy sources in the near future. Increased use of biomass can extend the lifetime of our fossil fuel resources. The potential of biomass to help meet the world energy demand has been widely recognized. However, problems such as low bulk density, high moisture content and relatively low calorific value, make biomass an expensive fuel to use and hinder its widespread use. Researchers are looking into solutions to overcome these drawbacks and thus, improve the properties of biomass as a fuel. A lot of research is underway to improve the fuel quality of biomass via torrefaction. Torrefaction is a pretreatment method to upgrade raw biomass to a refined fuel with improved properties such as higher heating value and carbon content and improved grindability. Torrefaction is carried out at 200–300 °C for 30–60 min, in an inert environment at atmospheric pressure. Torrefaction results in the following main improvements in the biomass properties [1–14]:

- considerable reduction in the moisture content;
- increased heating value due to reduction in the O/C ratio, and increased energy density when compressed;
- intrinsic conversion of the hygroscopic behavior of raw biomass into the hydrophobic behavior of torrefied biomass;
- enhanced grindability, which results in less energy consumption during milling.

Because of these improved properties, the value of the torrefied biomass as a fuel is significantly higher than that of the raw biomass.

A promising way to use biomass for production of heat, electricity, and other biofuels is through biomass gasification, in which, through a partial oxidation, the biomass is converted into synthesis gas and condensable compounds. During the gasification the chemical energy of the biomass is converted to the thermal and chemical energy of the synthesis gas [15]. Gasification achieves a

* Corresponding author. Tel.: +47 93818918; fax: +47 73593580.
E-mail address: dhruv.tapasvi@ntnu.no (D. Tapasvi).

http://dx.doi.org/10.1016/j.enconman.2014.11.027
0196-8904/

high carbon conversion rate for the formation of syngas [16,17]. Clean synthesis gas (syngas), produced from partial combustion of biomass, can e.g. be burnt in a gas turbine combustion chamber to run a biomass based combined cycle power plant [18]. Biomass can be gasified in various ways by properly controlling the mix of fuel and oxidant within the gasifier. The gasification of coal and biomass began in the 1800s, and by the 1850s, gas light for streets became common. Due to its high efficiency with respect to syngas formation, it is desirable that gasification becomes increasingly applied in the future for biofuels production rather than direct combustion [19].

Many studies have evaluated biomass behavior in a gasification process. Puig-Arnavat et al. [16] reviewed the various gasification models based on thermodynamic equilibrium, kinetics and artificial neural networks. According to Puig-Arnavat et al. [16], thermodynamic equilibrium models have been used widely. For example, Schuster et al. [20] studied the fluidized bed process with main focus on steam gasification; Altafini et al. [21] studied a saw dust gasifier to analyze the operating conditions of an open top stratified downdraft gasifier; Melgar et al. [22] used an equilibrium approach and studied the influence of fuel/air ratio and the moisture content of the biomass on the characteristics of the process and the producer gas composition; Jarungthammachote and Dutta [23,24] used a modified stoichiometric equilibrium approach by accounting for a deviation factor from experiments to three types of gasifiers: a central jet spouted bed, a circular split spouted bed and a spout-fluid bed; Yoshida et al. [25] applied a two-stage equilibrium model for a high temperature gasification process to predict the performance of commercial gasifiers. Similarly, Ghassemi et al. [26], Altafini et al. [21], Bassyouni et al. [27], Ravikiran et al. [28] and Li et al. [29] studied the biomass gasification process by an equilibrium approach based on the minimization of Gibbs free energy. All these authors have shown reasonable agreement between equilibrium predictions and experimental data. Commercial tools such as Aspen Plus are also very useful in predicting the behavior of a biomass gasification process as a sub-model with built-in solids properties. Mansaray et al. [30] used Aspen Plus to simulate a dual-distributor-type fluidised-bed rice husk gasifier. Paviet et al. [31] studied thermo-chemical equilibrium modeling of a biomass gasification process. Based on these studies, it can be concluded that an equilibrium model with Gibbs free energy minimization approach in Aspen Plus is an acknowledged and realistic way of simulating a biomass gasification process.

In a few recent studies, it has been reported that torrefied biomass can significantly affect the efficiency of biomass gasification. Chen et al. [32] employed a process optimization technique, the Taguchi method, for identifying optimum levels for process parameters involved during co-gasification of torrefied biomass and coal in an entrained flow gasifier. In another study, Chen et al. [33] numerically simulated an entrained flow gasifier with oxygen as the gasifying agent and the results indicated that the gasification performance of torrefied bamboo is quite similar to that of coal. Furthermore, Kuo et al. [34] evaluated a two-stage gasification process for raw and torrefied bamboo by using Gibbs minimization approach under isothermal conditions in Aspen Plus simulations. It was reported that the carbon conversion and syngas yield was higher for torrefied materials than the raw biomass, whereas, the trends for cold gas efficiency were opposite. Torrefied biomass produced at 250 °C was found to be the most feasible fuel for gasification when considering all process parameters together. However, this study did not account for tar formation and assumed char as a pure carbon. Except for these few studies, there is a considerable lack of information on the behavior of torrefied biomass under gasification conditions and therefore, better knowledge on the topic is needed. This forms the basis of this present study.

The present work extends the efforts of Kuo et al. [34] to establish a detailed equilibrium model for understanding the effect of torrefaction on the syngas compositions and efficiency of the biomass gasification process. The aim is to study a two-stage gasification process by using Gibbs free energy minimization approach in Aspen Plus with improved accuracy together with a comprehensive thermodynamic analysis. A two-stage process refers to the pyrolysis or decomposition of biomass in the first stage followed by the gasification of the pyrolysis products in the second stage. Accuracy of the model is improved by including tar formation during pyrolysis and its further cracking in the gasification reactor; actual experimental decomposition yields as inputs for both untreated and torrefied biomass; the compositions of the chars produced during pyrolysis, as calculated from the elemental balance; and a C–H–O Ternary diagram for validating the results. The model is integrated with an Excel spreadsheet to study the energy and exergy efficiencies of the process at different operating conditions of the gasifier. Exergy analysis of a process is a supplement to energy analysis and is based on the 2nd law of thermodynamics. It is a very useful tool to assess work potentials of input and output materials and heat streams, and to pinpoint irreversibility losses in a system. Ptasinski [35] studied exergetic efficiency analysis for gasification of biofuels which includes wood, vegetable oil, sludge, and manure. Rao et al. [36] reported results from an investigation of the change in exergy content of the produced gas in gasification for various biomass sources. Pellegreni et al. [37] studied the parametric effect on exergy efficiency by considering the influence of many variables inherent to the model, such as: gasification temperature, moisture content, and air temperature, among others. Abuadala et al. [38] presented an exergy analysis of hydrogen production from gasification. Hosseini et al. [39] also compared energy and exergy for steam fed and air fed gasification systems using sawdust as a fuel. The present study can be regarded as a maiden attempt to carry out a thermodynamic and exergetic efficiency analysis of a gasification process using Gibbs free energy minimization approach in Aspen Plus for comparing untreated and torrefied biomass. Overall efficiencies of an integrated torrefaction–gasification process are also provided by including mass yield in the torrefaction process.

2. Methodology

The Gibbs free energy minimization method for the C–H–O–N atom blend of the biomass fuel and oxidant mixture can be applied for predicting the thermodynamic equilibrium composition of the product gas major components: H_2, CO, CH_4, CO_2, H_2O, N_2 and char [40–43]. A thermodynamic equilibrium model for a biomass gasification system was developed using the Gibbs minimizing approach in the Aspen Plus software as shown in Fig. 1. Material and energy streams data from the Aspen Plus model were used to calculate cold gas energy and exergy efficiencies of the process.

2.1. Aspen Plus model

In Aspen Plus, streams represent mass or energy flows. Mass streams are divided by Aspen Plus into three categories: mixed, solid, and non-conventional (biomass). Mixed streams contain mixtures of components, which can be in gaseous, liquid and solid phases. The solid phase component in this simulation is solid carbon (C). Thermodynamic properties are defined in the Aspen Plus libraries for chemical components. Non-conventional components are defined in Aspen Plus by supplying standard enthalpy of formation and the elementary composition (ultimate and proximate analyses) of the components [44]. Biomass is characterized in this manner in this study.