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# Exergetic analysis of a fast pyrolysis process for bio-oil production

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ABSTRACT

This paper presents an exergetic analysis of a fast pyrolysis plant simulated in Aspen Plus, producing crude bio-oil from lignocellulosic feedstock (hybrid poplar woodchips). The simulation includes the drying and pretreatment of the biomass, the pyrolysis reactor, product recovery, and a combustion reactor that provides the process heat. Chemical and physical exergies are determined for all process streams and the exergy destruction is calculated at the component level of the plant. The overall exergetic efficiency of the plant is found to be 71.2%, with the gas-and-char combustor of the plant causing the highest exergy destruction. Relatively high irreversibilities are also calculated in the pyrolysis reactor and the bio-oil recovery section (quench and water cooler), as well as in the dryer and the mill. Further investigation shows considerable potential for improvement when introducing the hot exhaust gases of the combustor directly in the dryer without using part of their thermal energy for preheating the combustion air. This measure increases the overall plant efficiency to 73.2% by reducing the inefficiencies in the dryer and the heat exchangers. Lastly, the contribution of the compressors and pumps to the overall exergy destruction is found to be rather small.



## 1. Introduction

Biomass energy is considered a central pillar in strategies for reducing future dependency on fossil fuels and greenhouse gas (GHG) emissions. This is also reflected in policy decisions, such as the Renewable Energy Directive of the European Union [1], which sets a target of 20% renewable energy contribution by 2020, including a 10% share of biofuels. However, biomass has the important drawback of being a heterogeneous solid fuel with a relatively low density. This complicates the handling and transport processes, limiting, thereby, the potential for industrial applications. One possibility to overcome this problem is to convert the biomass into bio-oil through fast pyrolysis. The generated bio-oil has a similar heating value, but a higher density and is, as a liquid, easier to handle [2].

Pyrolysis is the thermal decomposition of a carbonaceous feedstock in a non-oxidative atmosphere that yields gases, chars and condensable vapors (tarry liquids, the bio-oil). Fast heating, short residence times and temperatures around 500 °C (fast pyrolysis) maximize the liquid yields from the pyrolysis of the biomass. The resulting yields of the fractions and their composition depend on the feedstock and the operational conditions of the process and are in average 15% gas, 15% chars and 70% liquids [3,4].

On-going research in energy applications of bio-oil obtained from biomass pyrolysis include co-combustion in natural gas power plants [5], direct combustion in stationary diesel engines [6,7] and upgrading to a high-quality engine fuel for vehicles [8–10]. An extensive review on the current activities in the field was recently published by Meier et al. [11]. However, only very few commercial energy applications for bio-oil exist up-to-date [11,12]. In order for the bio-oil to become competitive with fossil fuels, pyrolysis processes have to become as efficient as possible. Exergetic analysis is a powerful tool for optimizing energy conversion processes.

Exergetic analysis is a methodology that detects thermodynamic irreversibilities in energy conversion systems and can be used to maximize the operational efficiency. Based on the second law of thermodynamics, exergy represents the quality of energy, i.e., its maximum capability to generate work when bringing a system into equilibrium with its environment. In this way, an exergetic analysis permits the identification of the useful part of energy and pinpoints thermodynamic inefficiencies that a conventional energy analysis cannot detect [13,14].

To date, only a few publications exist on the thermodynamic performance of pyrolysis plants. To the best of the authors' knowledge, one study on the exergetic analysis of a fast pyrolysis plant has been published by Boateng et al. [15], while Kalinci et al. [16] included pyrolysis as a sub-process in their assessment of a gasification system.

The present article presents the simulation and exergetic analysis of a pyrolysis plant that produces bio-oil from lignocellulosic hybrid poplar feedstock. Using the results of the analysis, we identify the main exergetic inefficiencies of the plant and discuss ways to improve the operating efficiency of the process. The potential for improvement of specific components/processes in an energy conversion system can only be

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quantified using advanced exergy-based methods [17,18]. Here, we use the results of conventional exergetic analysis in an effort to improve the operation of the presented energy conversion system by modifying components with relatively high irreversibilities.

## 2. Process simulation

Thermodynamic data necessary for the exergetic analysis are obtained from the simulation of the process in Aspen Plus. While Aspen Plus is commercial software originally developed for the petrochemical industry for the simulation of chemical processes, it is also often used for the simulation of power plants. It is equipped with a large database of chemical compounds and a property estimation system for calculating stream properties and chemical reactions. Nevertheless, unconventional compounds like biomass or pyrolysis products are not included in the database and the corresponding properties and reaction mechanisms must be defined by the user manually.

This work presents the simulation of a fast pyrolysis plant producing bio-oil with integrated reaction mechanisms, the corresponding properties of the model compounds and the stream tables obtained and used as basis for an exergetic analysis. The biomass used in the simulation is assumed to be composed of cellulose, hemicellulose and lignin, ash, water and some N, S and Cl-containing compounds. Extractives and other substances are not considered and their fate during the pyrolysis reactions can therefore not be calculated.

The chosen configuration of the plant agrees with current existing industrial plants and existing publications on the topic [19–22]. Fig. 1 shows the flow diagram of the pyrolysis plant, which is divided into three sections: the pre-treatment (PTR), the pyrolysis (PYR) and the gas-and-char combustor (GCC) sections. This flow diagram allows the identification of all streams used in the assessment of the plant and may be used to reconstruct its configuration completely. The simulated components of the different sections of the plant are described below.

### *2.1. Pre-treatment section (PTR)*

Lignocellulosic biomass (hybrid poplar with 50%$_{wt}$ water content; Stream 86 in Fig. 1) is dried in a direct-contact dryer (DRYREACT) to a water content of 7%$_{wt}$ using thermal energy from the hot exhaust gases (Stream 18) exiting the GCC Reactor. An electric hammer mill (BMMILL), followed by a sieve (BMSIEVE; hole size 3 mm) reduces the particle size of the dry feedstock (Stream 3) to 3 mm (Stream 8), as required by the subsequent pyrolysis reactor [23]. For calculating the required mill power, Aspen Plus requires the hardgrove grindability index of the processed solids, a unit commonly used for measuring the grindability of fossil coals (high grindability values characterize brittle and easily grindable coals). For this work, the grindability index of the biomass was set to four, to provide the grinding energy consumption in accordance with the work of Jones et al. [19] and Mani [24]. The hot dry wood (Streams 9 and 10) is cooled down to a temperature close to 50 °C on the conveyor belts (represented by BMCOOLR) before it enters the pyrolysis section of the plant. The electricity consumption of the mill is included in the analysis, while that of the conveyor belts and the feeder screws is neglected.

### *2.2. Pyrolysis (PYR)*

In the pyrolysis section the dry and ground biomass (Stream 23) is decomposed into bio-oil, char and gas and the pyrolysis products are recovered and separated.

#### *2.2.1. Pyrolysis reactor configuration*

The pyrolysis reactor is a circulating fluid-bed (CFB) reactor with a sand bed operating at 520 °C [25]. The reactor bed is fluidized by recirculated pyrolysis gases (Stream 38) with a mass flow 1.5 times higher than that of the biomass feed, resulting in an average bed residence time of the particles of 2 s and a vapor residence time of 0.5 s [19]. The sand also acts as a heat carrier. After separating the sand and the char from the hot pyrolysis vapors in a series of hot cyclones, the sand is sent to the GCC, it is heated up to the temperature of the pyrolysis process, and sent back to the reactor (Stream 50/51). The remaining char, not separated in the cyclone or deposited on the sand particles, is burned in the GCC as well. The unit "PY-Reactor" (Fig. 1) contains three reactors (1BMDECMP, 1CSTIR, 1SLWYLD), described in more detail below, the sand bed heat exchanger (PYSANDHX), the flue gas mixer (1BBMIX), and the hot cyclone (PYCHRCYC). For the purpose of the analysis presented here, and since these components are inseparable parts of a CFB pyrolysis reactor, they are treated as one single component.

#### *2.2.2. Pyrolysis reaction model*

The pyrolysis yields and products are calculated based on a kinetic reaction model, which, under given reactor conditions, permits the simulation of the pyrolysis process of any lignocellulosic biomass [26]. A two-stage reaction model accounts for the primary, as well as for the complex secondary pyrolysis reactions. The produced bio-oil is modeled with a high level of detail (33 components including organic acids, aldehydes, alcohols, ketenes, phenols, sugar derivatives and degraded lignin) and the char with a realistic atomic composition. Validation

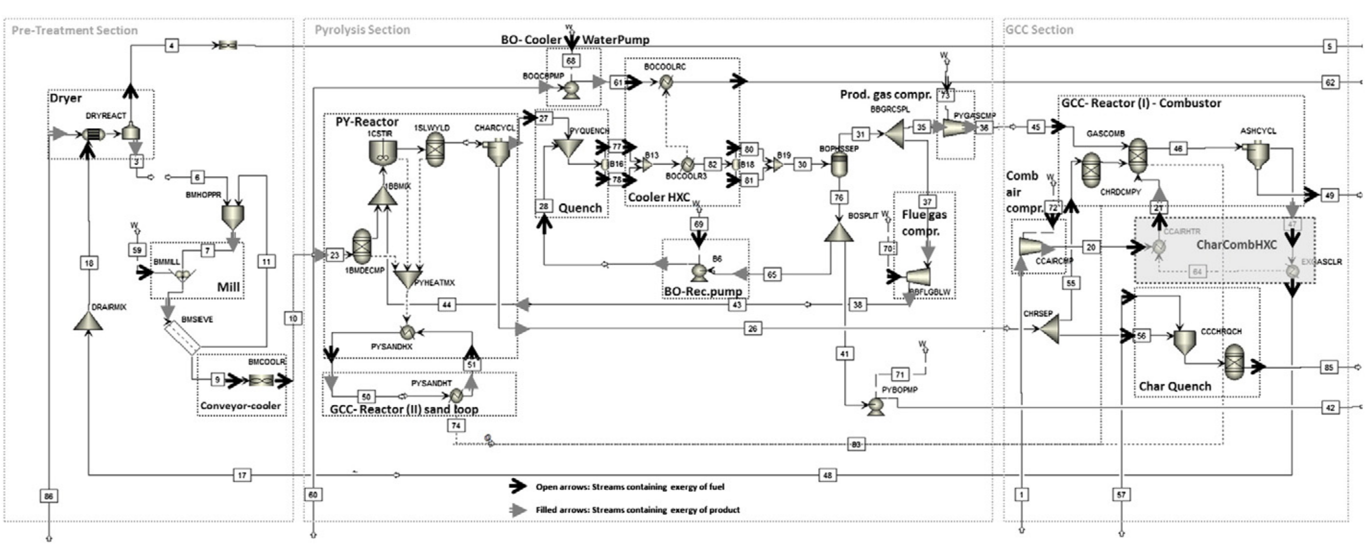


**Fig. 1.** Plant flowsheet; the process units examined in the exergetic analysis are indicated by dotted boxes.