Bioresource Technology 198 (2015) 309–315

Contents lists available at ScienceDirect

Bioresource Technology

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

Process modelling of biomass conversion to biofuels with combined heat and power

Abhishek Sharma [a], Yogesh Shinde [b], Vishnu Pareek [b,*], Dongke Zhang [c]

[a] *Department of Chemical Engineering, Manipal University, Dehmi Kalan, Jaipur, Rajasthan 303007, India*
[b] *Department of Chemical Engineering, Curtin University, Kent Street, Bentley, Perth, WA 6102, Australia*
[c] *Centre for Energy (M473), The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*

HIGHLIGHTS

- A novel process model has been developed for conversion of biomass to bioenergy.
- The products are used for production of bio-fuels with on-site heat and power generation.
- The process efficiency and product quality has been compared for different cases.

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 2 September 2015
Accepted 3 September 2015
Available online 14 September 2015

Keywords:
Biomass
Biofuel
Distributed
Modelling
Pyrolysis

ABSTRACT

A process model has been developed to study the pyrolysis of biomass to produce biofuel with heat and power generation. The gaseous and solid products were used to generate heat and electrical power, whereas the bio-oil was stored and supplied for other applications. The overall efficiency of the base case model was estimated for conversion of biomass into useable forms of bio-energy. It was found that the proposed design is not only significantly efficient but also potentially suitable for distributed operation of pyrolysis plants having centralised post processing facilities for production of other biofuels and chemicals. It was further determined that the bio-oil quality improved using a multi-stage condensation system. However, the recycling of flue gases coming from combustor instead of non-condensable gases in the pyrolyzer led to increase in the overall efficiency of the process with degradation of bio-oil quality.

1. Introduction

Biomass is gaining importance as an energy source due to its renewable nature and zero carbon footprints for the production of biofuels (Babu, 2008). There are several thermo-chemical processes such as gasification and liquefaction for conversion of biomass into various biofuels. The pyrolysis process is defined as a thermo-chemical decomposition of biomass, in an oxygen-depleted environment, into bio-oil, non-condensable gases and solid biochar. The advantage of pyrolysis over other technologies is the localised conversion of low density biomass into a high density intermediate product (bio-oil) that can be further processed into transportation fuels such as diesel and gasoline with value added chemicals such as acetic acid and methanol using centralised post-processing facilities such as gasification-FT. The product yield and quality of biomass pyrolysis depends on several process parameters, such as heating rate, temperature, particle size, and solid and vapour residence times inside the reactor (Sharma et al., 2015). Various reactor models have been proposed for optimising the product yield during the pyrolysis process (Luo et al., 2005; Xue et al., 2012; Yang et al., 2007). Based on the technological strength and market attractiveness, bubbling fluidized bed reactors (BFBRs) are most suitable for large-scale operation of biomass pyrolysis due to the intense heat and mass transfer and easy separation of the solid and vapour phase products inherent to BFBRs.

However, there have been limited studies available in the literature on the modelling of the biomass thermo-chemical conversion into biofuels with detailed information about the production, separation and storage of the products (Swanson et al., 2010; Tan et al., 2014; Tock et al., 2010; Wright et al., 2010). This is required to assess the techno-economic feasibility of the process for commercial scale utilisation of biomass to generate biofuels. Furthermore, it is also necessary to develop a platform for generating and transporting stabilized bio-oil from distributed biomass

---

[*] Corresponding author. Tel.: +61 8 9266 4687; fax: +61 8 9266 2681.
E-mail address: v.pareek@curtin.edu.au (V. Pareek).

http://dx.doi.org/10.1016/j.biortech.2015.09.014
0960-8524/

pyrolysis plants to centralised post-processing units. In the present contribution, a process model has been developed to analyse the different mechanical, chemical and thermal stages of biomass conversion to biofuels using pyrolysis at distributed level. The efficiency of the proposed design has been calculated for heat and power generation with biofuel production. The base case model was further modified to improve the product yield, quality and overall performance of the process.

2. Methods

2.1. Process description

The biomass is pre-treated before entering in the pyrolyzer. During the pre-treatment process, the large biomass particles are crushed/grinded to smaller sizes (around 1–2 mm in size) and dried to reduce the moisture content (varies from 40 to 60 wt.% in biomass samples) to less than 10 wt.%.

The pre-treated biomass is fed to a fluidized bed pyrolyzer operating at around 500 °C and atmospheric pressure conditions. The entrained biomass and char particles are removed from the volatile components using cyclone separation. The remaining fine char particles with particulate matter are separated using hot gas filtration (ceramic filters) before volatiles condensation for obtaining low levels of inorganic compounds such as alkali and alkaline earth metals in pyrolysis liquid product (bio-oil) (Baldwin and Feik, 2013; Diebold et al., 2000). A fraction of the char product is burnt to provide the heat for drying and pyrolysis with power production. The advantages of burning solid biochar instead of biomass are the lower emissions of particulate matter with higher energy density and better grindability for combustion operation (Gao and Wu, 2011). The remaining char is used for other applications such as soil improvement, carbon sequestration and as a source of activated carbon. After solids removal, the volatiles are quenched with a condensation system. A fraction of non-condensable gases (NCGs) is used as a fluidizing medium in the pyrolysis reactor after heating to the required temperature. The recycling of NCGs in the reactor instead of using inert N_2 has the benefit in terms of reduction in oxygenated compounds in the liquid phase and increase in the calorific value of bio-oil (Mullen et al., 2013; Zhang et al., 2011). The remaining amount of NCGs is utilised for providing heat energy to the process. The collected bio-oil contains oxygenated compounds such as hydroxyacetaldehyde, acetic acid and acetol that lead to chemical reactions such as oligomerization and polymerization during storage (Diebold et al., 2000). However, for this study, it is considered that the produced bio-oil has negligible storage problems for the duration of up to around 4 weeks kept in the non-corrosive stainless steel vessels (Wright et al., 2010). The bio-oil is then transported and used for direct combustion applications in industries or for further processing using technologies such as gasification and Fischer–Tropsch (FT) to produce value-added products. The flue gas generated in atmospheric pressure air combustor is used in heat recovery steam generator for superheated steam production after heating of recycled NCGs. The remaining energy from the flue gas is utilised for heating the air required in the combustion process and drying of moist biomass particles. The produced high pressure steam is used for power generation using a multi-stage turbine system. The overall process description is given in Fig. 1.

Few assumptions are made while simulating the process model:

1. The reactor hydrodynamics is not considered for biomass pyrolysis, and biochar and NCG combustion reactions in the model.
2. No heat losses are considered in the model.
3. Pneumatic conveying of solid biomass from storage to process plant and biochar from process plant to storage is not modelled.
4. The process utilities such as air and water are assumed to enter the plant at 25 °C and 1 atm.
5. Flue gases treatment plant is not considered in the model.
6. The solid and liquid storage systems are not modelled in this design.
7. The steam extracting-condensing cycle in the turbine system is not modelled in this design.

2.2. Design basis and base case study

In this case, 100 metric tonnes/day (wet basis) of the lignocellulosic biomass (mallee wood) is used for simulating the biofuel production process in Aspen Plus. The feed contains 45 wt.% moisture on dry basis (Yu and Wu, 2010). The biomass is composed of 41.5 wt.% cellulose, 27.5 wt.% hemicellulose, 29.7 wt.% lignin and 1.3 wt.% ash on dry basis (Abdullah and Wu, 2009). The proximate and ultimate analysis of this biomass sample is taken from literature (Garcia-Perez et al., 2008b).

For this study, the biomass particles of around 10 cm in size are supplied to a chopper/crusher for size reduction. After chopping, the feed (around 10 mm in size) is passed through a rotary dryer (Brammer and Bridgwater, 1999) for removing the water content. The biomass feed from dryer contains around 10 wt.% moisture on dry basis with outlet temperature around 100 °C to avoid fire hazards and organic compounds emissions (Fagernäs et al., 2010; Li et al., 2012). The dried feed is then grinded to the particle size (1–2 mm) optimal for pyrolysis reactions in fluidized bed conditions. Both the chopper and grinder are provided with a screen arrangement for separation and recycling of particles larger than the desired range. The energy requirements for size reduction process in the model are calculated using literature data (Mani et al., 2004). For the drying process, heat energy is provided directly using flue gases generated in the gas and biochar combustors. The biomass pre-treatment process is shown in Fig. 2.

The dry grinded biomass is fed to a bubbling fluidized bed reactor containing inert sand particles (pre-heated particles for steady state case; not included in this study) for allowing better solids heating and mixing during the process. The pre-heated fluidizing gas enters the reactor for providing heat energy for thermochemical degradation of biomass particles and maintaining the desired reactor temperature. For biomass pyrolysis, the operating temperature, pressure and the gas residence times are maintained at around 500 °C, 1 atm and about 1–2 s respectively to maximise the bio-oil yield. Inside the reactor, major biomass components, i.e., cellulose, hemicellulose and lignin are thermo-chemically decomposed to produce volatiles (containing bio-oil compounds and non-condensable gases) and solid char product with a series of cracking and poly-condensation reactions (reactions not included in this case study, instead products yield specified using literature data). The reactor is designed for continuous separation of biochar particles produced during the process without carry-over of sand and biomass particles from the bed due to differences in apparent densities of solid phases. For modelling this fluidized bed reactor, a RYIELD block is simulated in Aspen Plus using the given yield of the different components evolved during biomass pyrolysis. The overall product yield (Shen et al., 2009) and the composition of bio-oil (Garcia-Perez et al., 2008a), non-condensable gases (Garcia-Perez et al., 2008b) and char (Abdullah, 2010) is taken from literature. However, the final product composition is adjusted to maintain the mass and mole balance of carbon, hydrogen and oxygen inside the reactor.

The solid products are separated from the vapour phase using a cyclone separator with about 95% efficiency (weight basis) (Francois et al., 2013). The remaining solid particles are removed