Fuel 143 (2015) 361–372

Contents lists available at ScienceDirect

Fuel

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

Techno-economic performance analysis of biofuel production and miniature electric power generation from biomass fast pyrolysis and bio-oil upgrading

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HIGHLIGHTS

- Predictive process model of a biomass fast pyrolysis and bio-oil upgrading plant.
- Evaluation of energy efficiency and the impact of integrating power generation equipment.
- Evaluation of the impact of biomass composition on fast pyrolysis products and bio-fuel yield.
- Evaluation of the impact of initial biomass moisture content on power generation.
- Economic evaluation and economic sensitivity to key process parameters.

ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form 11 November 2014
Accepted 24 November 2014
Available online 5 December 2014

Keywords:
Fast pyrolysis
Techno-economic analysis
Process modelling
Biomass
Bio-oil upgrading

ABSTRACT

The techno-economic performance analysis of biofuel production and electric power generation from biomass fast pyrolysis and bio-oil hydroprocessing is explored through process simulation. In this work, a process model of 72 MT/day pine wood fast pyrolysis and bio-oil hydroprocessing plant was developed with rate based chemical reactions using Aspen Plus® process simulator. It was observed from simulation results that 1 kg s^{-1} pine wood$_{db}$ generate 0.64 kg s^{-1} bio-oil, 0.22 kg s^{-1} gas and 0.14 kg s^{-1} char. Simulation results also show that the energy required for drying and fast pyrolysis operations can be provided from the combustion of pyrolysis by-products, mainly, char and non-condensable gas with sufficient residual energy for miniature electric power generation. The intermediate bio-oil product from the fast pyrolysis process is upgraded into gasoline and diesel via a two-stage hydrotreating process, which was implemented by a pseudo-first order reaction of lumped bio-oil species followed by the hydrocracking process in this work. Simulation results indicate that about 0.24 kg s^{-1} of gasoline and diesel range products and 96 W of electric power can be produced from 1 kg s^{-1} pine wood$_{db}$. The effect of initial biomass moisture content on the amount of electric power generated and the effect of biomass feed composition on product yields were also reported in this study. Aspen Process Economic Analyser® was used for equipment sizing and cost estimation for an *n*th plant and the product value was estimated from discounted cash flow analysis assuming the plant operates for 20 years at a 10% annual discount rate. Economic analysis indicates that the plant will require £16.6 million of capital investment and product value is estimated at £6.25/GGE. Furthermore, the effect of key process and economic parameters on product value and the impact of electric power generation equipment on capital cost and energy efficiency were also discussed in this study.

1. Introduction

Crude oil remains the main source of transport fuel and is projected to continue to dominate the fuel market over the next two decades [1]. However, biofuels are being rapidly deployed globally as a sustainable substitute in an effort to reduce the world's dependence on crude oil due to the environmental implications of burning fossil fuels as well as stringent regulation on carbon emissions [2–4].

Biomass is mainly converted into biofuels via biochemical and thermochemical routes. While biochemical conversion processes have been demonstrated on a commercial scale, they are economically unsustainable and exert market pressure on food crops and

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http://dx.doi.org/10.1016/j.fuel.2014.11.078
0016-2361/

biodiversity [4,5]. On the other hand, thermochemical conversion processes which include pyrolysis, gasification and hydrothermal liquefaction have great potential for producing advanced biofuels from non-food sources that do not compete with food sources [3,4]. However, the products obtained from these processes vary in physical properties and chemical composition, and consequently present unique technical and economic challenges [6].

Among the various thermochemical processes biomass fast pyrolysis presents the best case for maximising bio-oil yields which can be subsequently upgraded into transport fuels [7,8]. Fast pyrolysis involves the anaerobic thermochemical decomposition of lignocellulosic biomass from 450 °C to about 650 °C and at a short vapour residence time of 2 s to produce liquids (bio-oil), solids (char and ash) and non-condensable gas (NCG). The fast pyrolysis by-products (char and NCG) can be combusted to provide all the energy required to drive biomass pyrolysis and drying operations, while the combustion waste heat can be exported or utilised for supplementary electric power generation [9]. The bio-oil product has a high composition of water and oxygenated organic compounds. As a result, it exhibits acidic and corrosive properties and has a relatively low HHV compared with conventional petroleum-derived fuels, making it unusable in internal combustion engines [9].

Bio-oil can be upgraded into naphtha-range transport fuels via two major conventional refinery operations that have been broadly identified and reviewed in literature, namely, hydroprocessing and catalytic cracking processes [6,10,11].

Hydroprocessing encompasses two main hydrogen intensive processes namely, hydrotreating/hydrodeoxygenation and hydrocracking. Hydrotreating/hydrodeoxygenation involves the stabilisation and selective removal of oxygen from untreated bio-oil through its catalytic reaction with hydrogen over alumina-supported, sulfided CoMo or NiMo catalysts or noble metal catalysts, while hydrocracking involves the simultaneous scission and hydrogenation of heavy aromatic and naphthenic molecules into lighter aliphatic and aromatic molecules [6,9,10].

Although various fast pyrolysis reactor configurations have been demonstrated on pilot scales in worldwide, the bubbling fluid bed reactor has been identified as the best in terms of ease of scalability, biomass heat transfer efficiency and temperature control efficiency [9]. The production of transport biofuels from the fast pyrolysis of biomass is yet to be commercialised due to the high level of investment required for production and a lack of competitiveness with fossil fuels. This makes process modelling and simulation an indispensable tool for investigating process performance and the impact of process and economic parameters on its economic viability.

The supporting solid operations required for the fast pyrolysis process consisting of grinding and drying operations are currently inadequately described in available software. Moreover, existing process models specify the product yield compositions for the pyrolysis reactor without accounting for the effect of temperature and chemical kinetics due to the complexity of the thermochemical reaction kinetics involved. In addition, most available reaction models in literature are descriptive of the intra-particle relationship rather than predictive of the product distribution [12]. As a result, a high fidelity process model is required for the analysis of the whole process with minimal assumptions.

There are several studies on the techno-economic analysis of biomass fast pyrolysis for bio-oil production available in literature; however, very few studies consider the upgrading of bio-oil into transport fuels or quantify the amount of electric power capable of being generated from fast pyrolysis by-products [13–16]. These studies report bio-oil costs ranging from US$0.62/gal to US$1.40/gal and capital costs ranging from US$7.8 to US$143 million over a 240 MT/day to 1000 MT/day plant capacity range. The significant disparity in the bio-oil costs from these studies can be attributed to the fact that different assumptions were adopted in each study.

Few researchers have conducted techno-economic analysis of the fast pyrolysis process and bio-oil hydroprocessing for transport fuel production [17,18] via a process simulation platform. In 2009, Jones et al. [17] conducted a design case study to evaluate the production of hydrocarbon biofuel from a 2000 MT/day plant of hybrid poplar wood chips. In their study, capital expenditure of US$303 million was estimated with a minimum fuel selling price of US$2.04. In 2010, another techno-economic analysis was also conducted by Wright et al. [18] on a 2000 MT/day of corn stover fast pyrolysis plant and subsequent bio-oil upgrading via hydrotreating and hydrocracking processes to obtain fuel product value and capital costs at US$2.11/gal/US$287 million and US$3.09/gal/US$200 million for hydrogen purchase and *in-situ* hydrogen production scenarios respectively.

In this study, a 72 MT/day fast pyrolysis plant of pine wood and subsequent bio-oil hydroprocessing is modelled based on rate based chemical reactions to evaluate the techno-economic performance of the process. Particularly, more emphasis is made on the detailed modelling of process equipment to ensure realistic model results. The fast pyrolysis reactor model is developed using rate based multi-step chemical reactions [19] in Aspen Plus® process simulator and validated with experimental results reported by Wang et al. [20]. Auxiliary processes consisting of grinding, screening, drying, combustion, bio-oil collection system and power generation are modelled using design specifications with the appropriate thermodynamic property methods. The hydrotreating process is modelled adopting a pseudo-first order reaction kinetic model over Pt/Al_2O_3 catalysts [21]. Based on validated process models, the effect of process and economic input parameters on the process and economic performance are further explored.

2. Material and methods

2.1. Process description

The overall process of transport fuel production from biomass is divided into eight main processing areas described by the generalised process flow diagram in Fig. 1. In the feed pre-treatment processing area (A100), the feed undergoes grinding and drying operations to meet the minimum feed requirement of 2 mm diameter and 10% moisture content in the pyrolysis reactor. Next, it is passed on to the fast pyrolysis area (A200), where the biomass feed is thermochemically converted in the absence of oxygen into NCG, hot pyrolysis vapours and char. The product from the fast pyrolysis reactor is then fed into the solid removal section area (A300), where char is separated from pyrolysis vapour and NCG before the pyrolysis vapour is subsequently condensed. The condensation of the pyrolysis vapours is achieved by quenching it into liquid in the bio-oil recovery section (A400), which contains vapour quenching process units. NCG and char separated from bio-oil are then combusted in the combustion area (A500) to generate the energy (hot flue gas) required for biomass drying and fast pyrolysis processes. The residual heat from combustion, if any, is used to generate the high pressure steam for power generation (A600). The bio-oil is upgraded into gasoline and diesel fraction products in the bio-oil hydroprocessing area (A700) containing hydrotreating and hydrocracking processes. Hydrogen required for hydroprocessing is generated in the hydrogen generation section (A800).

2.2. Model development

The biomass fast pyrolysis model is implemented in Aspen Plus® V8.2 using its improved solid modelling capabilities. The main model assumptions adopted in this study are presented in Table 1. The comprehensive process flow diagrams for bio-oil