Research paper

Techno-economic analysis of biofuel production *via* bio-oil zeolite upgrading: An evaluation of two catalyst regeneration systems

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ABSTRACT

Biofuels have been identified as a mid-term greenhouse gas (GHG) emissions abatement solution for decarbonising the transport sector. This study examines the techno-economic analysis of biofuel production *via* biomass fast pyrolysis and subsequent bio-oil upgrading *via* zeolite cracking. The aim of this study is to compare the techno-economic feasibility of two conceptual catalyst regeneration configurations for the zeolite cracking process: (i) a two-stage regenerator operating sequentially in partial and complete combustion modes (P-2RG) and (ii) a single stage regenerator operating in complete combustion mode coupled with a catalyst cooler (P-1RGC). The designs were implemented in Aspen Plus® based on a hypothetical 72 t/day pine wood fast pyrolysis and zeolite cracking plant and compared in terms of energy efficiency and profitability. The energy efficiencies of P-2RG and P-1RGC were estimated at 54% and 52%, respectively with corresponding minimum fuel selling prices (MFSPs) of £7.48/GGE and £7.20/GGE. Sensitivity analysis revealed that the MFSPs of both designs are mainly sensitive to variations in fuel yield, operating cost and income tax. Furthermore, uncertainty analysis indicated that the likely range of the MFSPs of P-1RGC (£5.81/GGE – £11.63/GGE) at 95% probability was more economically favourable compared with P-2RG, along with a penalty of 2% reduction in energy efficiency. The results provide evidence to support the economic viability of biofuel production *via* zeolite cracking of pyrolysis-derived bio-oil.

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1. Introduction

CO$_2$ emissions from fossil fuel combustion and industrial processes are the key sources of global anthropogenic greenhouse gas (GHG) emissions and have been correlated with the steep rise in global mean temperatures since the beginning of the industrial revolution [1]. Currently, the international consensus tends toward urgent implementation of emission regulations and policies to drive the deployment of sustainable alternatives to fossil fuels [2]. Moreover, the urgency for alternative fuel sources is driven by depleting fossil fuel resources and projected growths in global population and energy demand. In order to meet the emissions target set for 2050, emission reduction of 16.1 Gt CO$_2$-eq has to be made in the transport sector [3]. As part of the emission cuts

envisaged in the transport sector, biofuels are expected to supply 27% of global transport fuels by 2050, with the goal of reducing global CO$_2$ emissions (CO$_2$-eq) by 13% [3]. As of 2012, the transport sector accounted for 28% of global energy consumption, out of which biofuels constituted about 3% [4]. In pursuance of biofuels as a viable GHG emission reduction pathway, more research is required in the areas of process development and energy efficiency [1,3].

Biomass can be converted into biofuels *via* three main conversion methods, including chemical, biochemical and thermochemical processes. Biofuels derived from these conversion processes can be classified into various generations based on the carbon source of the feedstocks. First generation biofuels are derived from sugars and lipids extracted from food crops *via* chemical and biochemical conversion methods. Second generation biofuels are derived from non-food sources, including lignocellulosic biomass, agricultural waste and dedicated energy crops *via* biochemical and thermochemical conversion processes. Third and fourth generation biofuels, derived from microalgae and fast growing energy crops,

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are becoming more prevalent in research with sustainability and carbon negativity as the main drivers.

Most of the commercially available biofuels are of the first generation, comprising about 3% of global transport fuel demand [5]. However, they have been linked to several issues, including spikes in the price of food crops due to competition for the same means of production, as well as limited GHG emission savings and conflicting land use issues [6—8]. Nevertheless, current efforts towards the commercialisation of biofuels focus on second and third generation biofuels as they induce less strain on food supply and land use [6,7]. One of the thermochemical conversion routes for producing second generation biofuels that is attracting much interest is fast pyrolysis, as it produces a higher yield of bio-oil product (liquid fraction) than other thermochemical conversion pathways. Fast pyrolysis is the rapid thermal decomposition of biomass at temperatures between 450 and 600 °C in the absence of oxygen to produce non-condensable gases, bio-oil and char (solid residue). Bio-oil has been demonstrated as a suitable fuel for heat generation in boiler systems and power generation in some diesel engines [9,10]. However, it is unusable in internal combustion engines due to its adverse properties, including high oxygen content, low heating value and high acidity [11].

Bio-oil can be upgraded into advanced biofuels by traditional refinery processes, specifically hydroprocessing and catalytic cracking. Hydroprocessing encompasses two main hydrocatalytic processes, namely hydrodeoxygenation and hydrocracking. Operating conditions, such as catalyst type, reactor temperature and pressure, and weight hour space velocity can influence the quantity and quality of biofuels derived from bio-oil hydroprocessing [12]. The major shortcomings of bio-oil hydroprocessing include high hydrogen consumption and severe pressure conditions required for operation [13—16]. An alternative bio-oil upgrading route is the catalytic cracking process. Catalytic cracking involves a series of reactions, including dehydration, cracking, deoxygenation and polymerisation. The products from these reactions include gas, organic liquids, aromatic and aliphatic hydrocarbons, water and coke. An advantage of catalytic cracking over hydroprocessing is that it does not require hydrogen at high pressure. However, it presents the drawback of rapid catalyst deactivation due to high coking rate [17].

Several catalysts have been employed for the catalytic cracking of bio-oil. Several experimental studies on the catalytic upgrading of bio-oil over zeolites (HZSM-5) reported a high concentration of aromatic hydrocarbons (about 83 wt%) in the organic liquid product [18—21]. *In-situ* catalytic pyrolysis and *ex-situ* catalytic upgrading of pyrolysis vapours before condensation over HZSM-5 catalysts are gaining more ground [22—27]. The bio-oil product from catalytic pyrolysis is partially deoxygenated and contains a higher concentration of aromatic hydrocarbons and phenols than the bio-oil product of non-catalytic pyrolysis [22]. Other catalysts different from zeolites, such as Al-MCM-41, Al-MSU-F and nano metal oxides have been applied to catalytic pyrolysis, also giving rise to a partial reduction of the oxygenated compounds in bio-oil [28—31]. Nevertheless, results from these studies suggest that HZSM-5 catalysts are best suitable for upgrading biomass-derived oils as they improve the selectivity towards the hydrocarbons present in gasoline and diesel, and yield relatively more liquid than other catalysts [17,32,33].

An obstacle that could hinder the industrial deployment of bio-oil upgrading *via* zeolite cracking is the resultant high coke yield that accompanies the process [34]. The utilisation of conventional Fluid Catalytic Cracking (FCC) units (cracking reactor integrated with a single stage regenerator) has been proposed for the cracking of bio-oils [35]. Nevertheless, bio-oil generates more coke (up to 20 wt%) [19] compared with typical feeds to FCC units (1—5 wt%)

[36]. Generally, the regenerator of FCC units operates at complete or partial (incomplete) combustion modes [36]. Inevitably, typical high coke yields from the cracking of bio-oil will result in very high coke-burn temperatures in the regenerator when operating in a complete combustion mode and cause rapid deactivation of catalysts. Furthermore, extreme coke-burn temperatures in the regenerator without a proper heat rejection mechanism can upset the thermal balance between the cracking reactor and the catalyst regenerator [34,36]. Catalyst regeneration at partial combustion mode, on the other hand, leads to moderate regeneration temperatures. However, the exiting gas from the regenerator has a high concentration of CO and requires additional burning into CO_2 in order to meet emission standards. Thus, there is a need for innovative process designs for zeolite cracking of bio-oil with appropriate catalyst regeneration systems. The regeneration systems considered in this study are based on designs in the refining industry specifically used for cracking of resid (high molecular weight) feeds that are prone to severe coking [37—39]. As zeolite cracking of bio-oil is also prone to severe coking, the two main designs used for resid cracking in the refinery industry were evaluated in this study to ascertain their techno-economic potential for catalyst regeneration in the bio-oil zeolite cracking process.

Techno-economic analysis (TEA) is a valuable research tool for exploring the technical and economic feasibility of conceptual process designs. Several studies of the techno-economic analysis of fast pyrolysis of biomass and bio-oil upgrading *via* zeolite cracking have been published [40—42]. Nonetheless, to the knowledge of the authors, the TEA of bio-oil upgrading *via* zeolite cracking along with the evaluation of the regeneration system options is non-existent in literature. This study examines the techno-economic analysis of biomass fast pyrolysis and bio-oil upgrading *via* zeolite cracking, with emphasis on the catalyst regeneration system. A process scheme with two regenerators operating in sequence (P-2RG) and a scheme with a single regenerator fitted with a cooler (P-1RGC) are compared regarding energy efficiency and profitability. A sensitivity analysis is carried out to evaluate the influence of economic parameters on the profitability of the designs. In addition, Monte Carlo simulation is conducted to assess uncertainties in the estimated parameters and their effect on profitability.

2. Methods

Fig. 1 depicts the overall methodology employed in this study. It entails model development, equipment sizing and costing, profitability analysis *via* discounted cash flow method, sensitivity analysis and uncertainty analysis *via* Monte Carlo simulation.

2.1. Process overview

Fig. 2 depicts the overall process diagram. It consists of six main technical sections: (i) bio-oil production *via* fast pyrolysis (A100); (ii) zeolite cracking of bio-oil (A200); (iii) products separation (A300—A302); (iv) catalyst regeneration (A400); (v) steam cycle (A500); and, (vi) gas cleaning (A600). In A100, bio-oil is generated *via* the fast pyrolysis process. The liquid bio-oil product is then transferred to the zeolite cracking section. In A200, bio-oil is vapourised by hot zeolite catalysts and undergoes dehydration, cracking, deoxygenation and polymerisation reactions to form non-condensable gases, organic vapours and coke. The products from A200 are then fed into A300 to separate catalyst and coke from the mixture of hot vapours and gases. Zeolite catalyst is regenerated by combustion of the coke in A400. The catalyst is reactivated, and heat for the upgrading reaction in A200 is simultaneously generated. Excess heat from the regeneration system is used to generate power in A500. In the liquid recovery section (A301), the liquid