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Performance of biofuel processes utilising separate lignin and carbohydrate processing

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HIGHLIGHTS

- Separate conversion of lignocellulosic sugars and lignin to biofuels were studied.
- Several of the new processes provided better economy and a higher GHG reduction.
- Four of the processes form a Pareto curve between profitability and GHG savings.
- The new processes can utilize external low temperature heat with 100% efficiency.

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ABSTRACT

Novel biofuel pathways with increased product yields are evaluated against conventional lignocellulosic biofuel production processes: methanol or methane production via gasification and ethanol production via steam-explosion pre-treatment. The novel processes studied are ethanol production combined with methanol production by gasification, hydrocarbon fuel production with additional hydrogen produced from lignin residue gasification, methanol or methane synthesis using synthesis gas from lignin residue gasification and additional hydrogen obtained by aqueous phase reforming in synthesis gas production. The material and energy balances of the processes were calculated by Aspen flow sheet models and add on excel calculations applicable at the conceptual design stage to evaluate the pre-feasibility of the alternatives. The processes were compared using the following criteria: energy efficiency from biomass to products, primary energy efficiency, GHG reduction potential and economy (expressed as net present value: NPV). Several novel biorefinery concepts gave higher energy yields, GHG reduction potential and NPV.

1. Introduction

Biofuels can be produced from either first- or second-generation sources by various processes, as reviewed by Naik et al. (2010). The second-generation biofuels produced, e.g. from wood and straw have many advantages compared to first-generation biofuels made from food-related resources: here there is no competition with food production, the greenhouse gas emissions are potentially lower, and less land area is required due to the higher yields of the biomass per cultivated area (Kajaste, 2014). However, the investment costs of the second-generation processes are typically higher, although the lignocellulosic feedstocks are less expensive than first-generation feedstocks. The technological risk of second-generation routes is also higher since the processes are less mature: for example, no full-scale synthetic liquid fuel plants based on biomass gasification have yet been built.

Because of the large number of feedstocks and process alternatives available and the high investment cost involved, the wise selection of process concept is a key challenge. The concept selection is complicated, not only by the large number of alternatives but also by the lack of knowledge available in the early design stages of a project. This is sometimes called 'the design paradox' (Hurme and Rahman, 2005), because the route selection needs to be made at the early stage of design without full knowledge of the process, yet in later stages, when there would be much more knowledge about the process to make the

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selections, as changes in design are much more costly or even impossible as far as the process concept is concerned. Therefore, it is essential to be able to make wise conceptual design decisions as early as possible and concentrate efforts on the one with the most potential.

Many researchers such as (Cherubini and Stroemmaner, 2010) and (Voll and Marquardt, 2012) have evaluated biorefining routes by considering yield and income from products, for example. Melin and Hurme (2010) compared production routes in terms of maximum energy yield from raw materials to products. They found out that methanol, synthetic natural gas (SNG) and dimethyl ether (DME) can be produced with high selectivity and with a higher yield compared to Fischer–Tropsch diesel. Economic studies of gasification-based biofuel production processes have been done by determining production costs, see Hannula and Kurkela (2013). Forest residues based pyrolysis processes were analysed by Wright et al. (2010) and bioethanol production by Gnansounou and Dauriat (2010) and Sassner and Zacci (2008). In an earlier study, McKeogh and Kurkela (2008) found that an optimal size of a gasification-based biofuel plant is around 200–300 MW feed for forest residues in Finland. The heat integration in lignocellulosic ethanol concepts from wheat straw has been studied by Lassmann et al. (2014) using Pinch analysis.

The economy of biorefining can be improved e.g. by increasing product yields. These are limited by various factors. According to Prins et al. (2007) and Ptasinski et al. (2007) in the gasification of wood or other oxygen-containing feedstocks the biomass needs to be over oxidised in order to reach the gasification temperature, which results in production of carbon dioxide. This reduces the conversion efficiency to products. A higher yield would be obtained if a material with higher energy content would be gasified. So by gasifying lignin rich residue instead of wood a higher yield is expected. So converting the sugars part first for example into ethanol with low energy loss at low temperature and gasifying the lignin residue has a synergistic effect that should result in a high conversion efficiency to fuel product.

Another aspect is whether all the biomass fractions are actually utilised for the product desired. For example, when biomass is hydrolysed to sugars and those are converted into e.g. ethanol, theoretically not more than 35–51% of the energy present in the biomass can be converted to energy in the ethanol product if the hexose fermentation is used, as stated in Melin and Hurme (2010). Thus, combining lignin residue gasification with the conversion of sugars would result in a higher yield route to biofuels. The gasification been demonstrated for lignin from wood residue (Koido et al., 2013) and for corncob hydrolysis residue (Chen et al., 2015). Only a few studies exist on the routes combining lignin residue gasification with ethanol fermentation: for instance, Laser et al. (2009) evaluated combined ethanol production and synthetic fuel production from switchgrass by gasification of the lignin residue. For ethanol production Ammonia Fibre Explosion (AFEX) pre-treatment was used. A high-energy yield of biofuel was obtained. Also, chemical conversion to sugars by aqueous phase reforming or aqueous phase hydrogenation has been studied by Wei et al. (2014) and Zhang et al. (2014). However, no studies of combined aqueous phase reforming and lignin residue gasification for hydrogen production were found in the open literature.

In this paper, novel biofuel production pathways based on separate lignin and sugar processing are evaluated: both the fermentation of sugars to ethanol and chemical conversion by aqueous phase reforming and hydrogenation are studied and compared with conventional processes, which do not include lignin processing. The evaluation is based on the flow sheet simulation employed in the conceptual design phase.

2. Methods

2.1. Raw materials

In all cases, the raw material is softwood (pine) logging residue. The element and chemical species composition, heating values and moisture content of the feedstock are presented in Table 1. The reference state is 25 °C and 101 kPa. The sugar composition refers to the content of sugars in the non-hydrolysed form.

2.2. Process concepts studied

In this study the following biomass based process concepts are studied using process flow sheet model:

- MeOH case: Conventional methanol production by gasification and conversion of synthesis gas to methanol.
- SNG case: Conventional synthetic natural gas production by gasification and conversion of synthesis gas to methane.
- ETOH case: Conventional bioethanol production by steam explosion pre-treatment and heat and power production by combustion of residual lignin.
- ETOH&MEOH case: Enhanced ethanol and methanol production from biomass by steam explosion pre-treatment and conversion of residual lignin to syngas and methanol.
- ENHMEOH case: Novel enhanced methanol production by one-step biomass conversion to sugars, hydrogen production from sugars by aqueous phase reforming and residual lignin gasification with methanol production from hydrogen-enriched syngas.
- ENHSNG case: Novel enhanced methane production by one-step conversion to sugars for hydrogen production from sugars by aqueous phase reforming and residual lignin gasification with methane production from hydrogen enriched syngas.
- ENHHC case: Hydrocarbon production by aqueous phase hydrogenation of biomass based sugars by hydrogen obtained from gasification of lignin residues.

The MEOH, SNG and ETOH cases are conventional lignocellulosic biorefinery processes which are compared with the enhanced processes, ETOH&MEOH, ENHMEOH, ENHSNG and ENNHC; the material and energy balances are calculated for the same raw material in all of the processes. Based on the material and energy balances, the efficiencies of the processes are calculated. In addition, the carbon footprint and economic feasibility of the processes are studied based on the material and energy balances, additional investment cost and green house gas emission data. The processes ETOH&MEOH, ENHMEOH, ENHSNG and ENHHC are chosen because they are expected to give a higher yield and possibly a higher economic and environmental performance.

Two sub-cases, A and B, are considered in ETOH&MEOH, ENHMEOH, ENHSNG and ENHHC. In sub-case A, the process is adjusted so it is self-sufficient on process heat.

For example as reported for a similar case than ETOH&MEOH the heat demand of the process can be satisfied with extra fuel (coal or wood) input to a boiler that produces heat and power needed in the bioethanol process (Halladay et al., 2007). In case B, the deficiency of low temperature heat used for drying, distillation and acid gas medium regeneration is replaced by transferring heat from a nearby plant. This increases the biofuel yield since the product is not combusted in order to satisfy the process heat demand. The inputs and outputs to the processes are shown in Fig. 1. Here all the heat is used in the process, no district heat is exported and power production is maximised. Only in the ETOH and ETOH&MEOH cases, a relatively small amount of furfural is obtained. It can also be converted into a fuel product but it is not