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Biomass-based hydrogen for oil refining: Integration and performances of two gasification concepts

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ABSTRACT

In this work, two biomass-to-hydrogen concepts are designed and their integration with a large European refinery is investigated. One concept is based on indirect, atmospheric steam gasification while the second is based on pressurized direct oxygen-steam-blown gasification. The technologies chosen for gas cleaning, upgrading and hydrogen separation also differ in the two concepts. Heat integration and poly-generation opportunities are identified by means of process integration tools and four system configurations are identified. These are compared in terms of energy and exergy performances and potential for reduction of fossil CO_2 emissions at the refinery. It is found that the performance of the biomass-to-hydrogen concepts can be improved by up to 11% points in energy efficiency and 9% points in exergy efficiency. The design based on indirect gasification appears the most efficient according to both energy and exergy efficiencies. All configurations yield potential significant reductions of fossil CO_2 emissions at the refinery.

1. Introduction

The oil refining industry faces today challenges on several sides of its activity. Stringent environmental regulations, such as the Emissions Trading System in Europe, require the refining plants to reduce on-site greenhouse gas emissions. On the other hand, a steadily increasing diesel-to-gasoline ratio on the European fuel market and harsher product specifications regarding sulphur content in automotive fuels imply more thorough upgrading of crude oil, which eventually leads to increased energy and hydrogen demands in oil refineries [1,2].

The most common hydrogen production route operated in refineries is steam reforming of light hydrocarbons. Since steam reforming can be the source of up to 25% of the total refinery CO_2 emissions [3] it is crucial to find efficient and environmental friendly solutions to meet the increasing hydrogen demands. Besides improving the hydrogen recovery at the refinery [4], carbon lean technologies such as gasification of lignocellulosic biomass have the potential to decrease on-site fossil CO_2 emissions as well as dependency on fossil feedstock. To build new biomass-based processes close to existing refinery plant can also open opportunities of thermal integration that other stand-alone plants cannot benefit from. Refineries are in fact well known for their large amount of excess heat [5].

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Nomenclature

ATR autothermal reforming
$e_{CO_2,i}$ specific CO_2 emissions of fuel i, kg/GJ_{fuel} or kg/kg_{fuel}
e^{PH}, e^{CH} specific physical and chemical exergy, respectively, kJ/kg
DG concept biomass-to-hydrogen concept based on direct, pressurized oxygen-steam-blown gasification
h_{steam} specific enthalpy of HP steam, kJ/kg
HHV higher heating value, MJ/kg
HP steam high pressure steam
HT shift high temperature water–gas shift reaction
IG concept biomass-to-hydrogen concept based on indirect, atmospheric steam gasification
LT shift low temperature water–gas shift reaction
$\dot{m}_i, \dot{m}_o$ mass flow of fuel input and output, respectively
η_{el} efficiency of marginal electricity producer
η_{ex} exergy efficiency
η_{tot} first principle total efficiency
P_i, P_o electrical power input and output, respectively
P_{net} net electrical power output
PSA pressure swing adsorption
SMR steam-methane reforming
ΔCO_2 fossil CO_2 emission balance, kt/y
ΔT_{min} minimum temperature difference for heat exchange used in Pinch Analysis, °C

A broad range of alternatives appear when designing biomass-to-hydrogen processes since several options exist for each process step (e.g. gasification, gas cleaning, etc.). It is thus necessary to evaluate different process concepts in order to determine the best performing configuration.

In this work, two biomass-to-hydrogen processes were designed and compared which are representative of two opposite design approaches: atmospheric gasification and cold gas cleaning and pressurized gasification and hot gas cleaning. The performance of the conversion of biomass into hydrogen is quantified from an energy and exergy point of view and fossil CO_2 balances are determined. Particular attention is paid to opportunities for poly-generation and heat integration. This work can serve as a base to identify the most significant system parameters and for broader comparisons of various biomass conversion processes and options for recovery of industrial excess heat.

1.1. *Previous work*

Although no industrial plants have been built yet, a large body of literature has been produced on stand-alone hydrogen production through biomass gasification. Hamelinck and Faaij studied several stand-alone biomass-to-hydrogen concepts considering two types of gasifiers [6]. They published detailed simulation data and economic evaluations but process integration was not an explicit part of their work. Detailed design parameters and economic results for a process based on the Batelle Colombus Laboratory gasifier were published by Spath et al. [7]. Williams et al. [8] provide a literature review on existing gasifier concepts with focus on technological challenges associated with hydrogen production. More recently, Cohce et al. studied one concept of a hydrogen production process based on biomass gasification by applying energy and exergy analysis [9]. With the help of a multi-objective optimization framework, Tock and Maréchal designed and optimized the thermo-economic performance of stand-alone biomass-to-hydrogen concepts based on the FICFB gasifier [10]. The integration of hydrogen production with other industrial plants was also investigated in a number of publications. As an example, Andersson and Harvey compared hydrogen production via black liquor gasification and stand-alone biomass gasification [11].

Among the studies dealing with hydrogen production for refinery applications, Sarkar and Kumar [12] investigated the production of hydrogen via biomass gasification for the upgrading of bitumen from oil sands. However, they considered only stand-alone processes producing hydrogen sent via pipeline to the refining site, which was very specific to the Canadian oil sands industry. The effect of several system parameters such as emission mitigation strategies and steam consumption on this same industry was studied by Betancourt-Torcat et al. [13]. Results show that coal gasification plants, especially with carbon capture equipment, are promising for hydrogen production in a context of high natural gas prices and reduced allowed emissions. Considering the similarities between coal gasification with carbon capture and biomass gasification plants, these conclusions also show the relevance of hydrogen production processes based on biomass gasification in the context of oil refining.

In Ref. [5], Johansson et al. investigated CO_2 emission consequences of hydrogen production through biomass gasification compared to standard methane reforming in a simple oil refinery equipped only with atmospheric distillation, naphtha reformer and necessary treatment. Several process designs were included but all had dual shift and pressure swing adsorption in common. Opportunities for use of refinery excess heat were studied as well. In this latter study, the biomass gasification process was considered as a supplementary capacity installed to satisfy an increase in hydrogen demand and options to use excess heat from the biomass-to-hydrogen process were limited to steam production.

In another study that comes as a complement to the previous reference, we have already discussed the substitution of a fossil-based hydrogen production unit with a process based on biomass indirect gasification [14]. Compared to the work performed by Johansson et al. [5], a more complex refinery was considered as a case study and opportunities for recovery of excess heat from the gasification process were investigated. The present work is a direct continuation of this study.

1.2. *Objectives*

In this work, two biomass-to-hydrogen concepts and their integration with a large oil refinery are investigated and their performance in terms of efficiency and impact on refinery emission compared. Some significant system configurations based on different poly-generation options are considered.