Exergy Analysis of a Process Converting Power and Biomass to a Liquid Fuel

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A power and biomass to liquid process (PBtL) via Fischer-Tropsch synthesis is exergetically analysed. Synthesis gas is generated through an entrained flow gasifier and extra hydrogen is produced through high temperature steam electrolysis in a solid oxide electrolysis cell (SOEC). The gasification section of the process has the highest exergy destruction rate, followed by the Fischer-Tropsch and SOEC sections. To improve the process, the focus should be on the design and operation of these sections. The plant has an overall exergetic efficiency of 69 %, evaluated as the ratio of the exergy of the products to the exergy of the biomass and electricity supplied to the process.

1. Introduction

Deployment of sustainable alternative fuels is one of the strategies initiated by the aviation industry in order to fulfill their commitment to reduce global carbon emissions (CORSIA, 2019). However, the fuels must have high energy density and high specific energy to meet industry requirements. Based on this, one possible option is to produce what is called advanced biofuel from biomass via the Fischer-Tropsch (FT) synthesis. A challenge here is the low carbon efficiency, as less than 30 % of the biomass carbon ends up in the fuel. By introducing hydrogen produced from renewable energy, however, the carbon efficiency can be increased to more than 90 % (Hillestad et al., 2018).

An important factor for efficient biofuels production is the thermodynamic performance of the production process. For a process that involves different forms of energy, this may be measured in terms of exergy efficiency. Exergy is defined as the maximum theoretical work obtained from a system while bringing it into thermodynamic equilibrium with its environment. Unlike mass and energy, exergy is not conserved, as exergy is destroyed due to irreversibilities within the process. Through exergy analysis, the most inefficient parts of the process are determined.

Some exergetic investigations on biofuels have been reported in the literature. Cruz et al. (2017) investigated the exergy efficiency of a process converting biomass to Fischer-Tropsch liquid fuel and electricity. In their simulations, overall exergy efficiencies of 24 - 27 % were attained. The largest exergy destruction was observed in the gasification section. Sues et al. (2010) performed an exergy analysis of five different biowaste-to-biofuel routes via gasification. Considering the FT pathway, the exergy efficiencies were between 29 % and 37 % depending on the biomass feedstock. Prins et al. (2005) performed an exergetic evaluation of a plant cogenerating electricity and FT fuels. They reported an exergy efficiency of 46.2 %. Recently, Albrecht and Dietrich (2018) did an exergoeconomic analysis of a power and biomass to liquid process through FT. They reported an exergy efficiency of 53 % having Proton Exchange Membrane (PEM) electrolysis and oxygen blown entrained flow gasification. These two units accounted for the highest exergy destruction and losses in the PBtL process. Shifting to high-temperature electrolysis is their recommendation to increase the exergy efficiency of the process. Peters et al. (2015) evaluated the exergy efficiency of biofuel production via fast pyrolysis and hydro-upgrading. They reported an exergy efficiency of 60.1 % for the overall biofuel process and 77.7 % for the upgrading process alone.

In this study, an exergy analysis is performed for a power and biomass to liquid process, to identify important sources of irreversibilities, enabling further improvement of the process design.
The process is modeled in Aspen HYSYS® (Aspen Technology Inc., V10.0). It has been parametrically optimized in a previous study (Ostadi et al., 2019) and exergy analysis is performed for the optimized process conditions.

2. The process concept

The process flowsheet is illustrated in Figure 1. A detailed process description is given by Hillestad et al. (2018), and a short description is provided here.
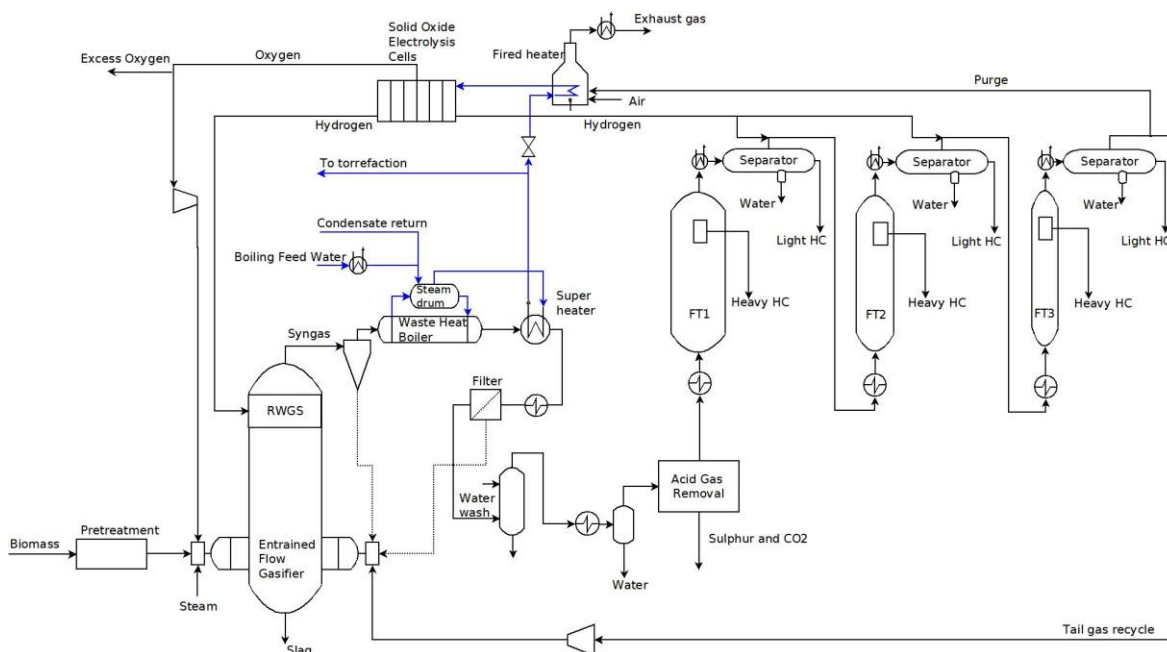

Figure 1: Process flow diagram of the power and biomass to liquid (PBtL) plant.

Syngas is generated through an entrained flow gasifier. As the H_2/CO ratio of the syngas after the gasifier is much lower than what is required in the FT synthesis, extra hydrogen is produced through high temperature steam electrolysis in a solid oxide electrolysis cell (SOEC). In order to maximize the syngas conversion and the production of heavy hydrocarbons in the FT synthesis, three reactors with distributed hydrogen feed and product withdraw is used.

In the pre-treatment section, the biomass is dried, torrefied and grinded. The elemental composition of the dry biomass feedstock on mass basis is: 51.8 % carbon, 6.04 % hydrogen, 0.17 % nitrogen, 0.09 % sulfur and 41.9 % oxygen. The 40 wt% wet biomass is dried down to 5 wt% in the drier. For the drying process, the heating requirement is assumed to be 2.8 GJ/ton H_2O removed. The heat is provided by steam at 150 °C. In the torrefaction process, a temperature of 275 °C is assumed. After the biomass is torrefied, it is grinded and the electricity consumption is assumed to be 50 kWh/ton for the given torrefaction temperature (Govin et al., 2009). The torrefaction unit is integrated with the gasifier, and that there will be no loss of carbon from this unit. An oxygen blown entrained flow gasifier is used for gasification. Oxygen at 800 °C from the SOEC is used for biomass gasification to reach the desired gasification temperature of 1, 400 °C.

By adding hydrogen from the SOEC to the Reverse Water Gas Shift reactor (RWGS), the RWGS reaction is enhanced and the H_2/CO ratio of the syngas is increased. As a result, the amount of CO_2 in the syngas stream is minimized, thus improving the carbon efficiency, which is defined as the percentage of biomass carbon that ends up in syncrude. Syncrude is the produced hydrocarbons with five or more carbon atoms, i.e. the sum of 'Heavy HC' and 'Light HC' streams for each FT stage (see Figure 1). Rapid cooling is required after the RWGS reactor, as the produced syngas is very reactive at high temperatures, generating superheated steam at 700 °C. The steam is used as feed to the SOEC, and for heating in the pre-treatment section.

In order to meet the feed gas specifications required for FT synthesis, H_2S must be removed from the syngas. Here, this is done using a physical solvent (Selexol). This process does not require intensive solvent refrigeration or thermal regeneration (Arnold and Stewart, 1999). Prior to the FT section, the syngas temperature is 210 °C.

The FT section is divided into three stages, using slurry bubble column reactors. As the fluid is well mixed, the fluid composition is assumed to be approximately homogeneous in each reactor. Boiling water at 210 °C is used as coolant in FT reactors. In order to heat up steam to a temperature of 850 °C before the SOEC and to avoid the accumulation of inert components, 10 % of the tail gas is sent to the fired heater. Product upgrading is not considered in this study.

A simplified block flow diagram of the PBtL process is shown in Figure 2. The optimized process conditions from a previous study (Ostadi et al., 2019) are reported in Table 1. The exergy analysis is performed for the optimized process.
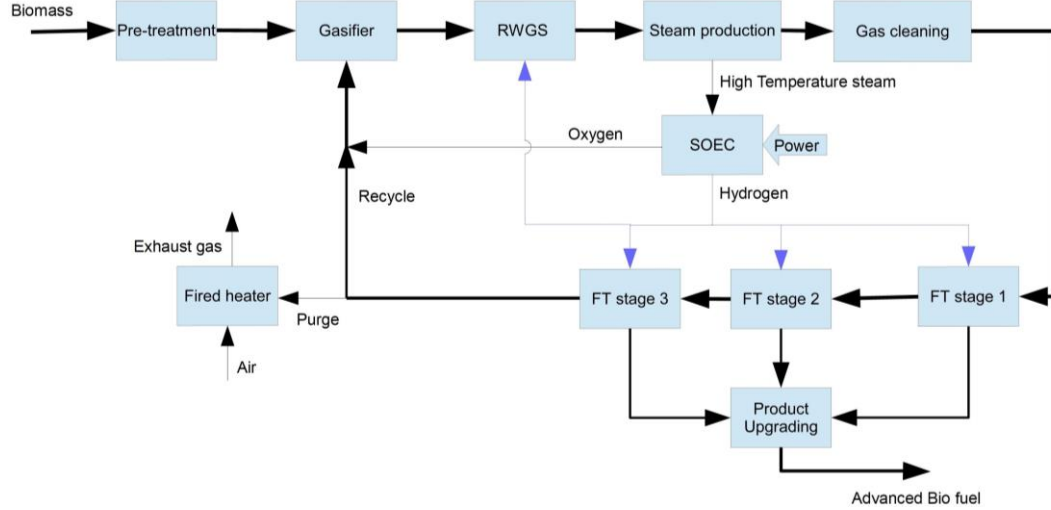

Figure 2: Block flow diagram of the PBtL process

Table 1: Optimization results for the PBtL process with 1,500 $/kW SOEC investment cost (Ostadi et al., 2019)

Variable description	Optimal values
H_2/CO ratio after RWGS [-]	1.92
H_2/CO ratio in FT2 feed [-]	1.68
H_2/CO ratio in FT3 feed [-]	1.74
Volume FT1 [m^3]	457
Volume FT2 [m^3]	299
Volume FT3 [m^3]	120
Steam to gasifier [kmol/h]	158
Temperature of gasifier [°C]	1,400
CO_2 extraction ratio in Acid gas removal [%]	96

3. Exergy analysis

Energy analysis is based on the first law of thermodynamics, while exergy analysis is based on the second law of thermodynamics. In exergy analysis, the quality of different energy forms is assessed in terms of the maximum amount of work that can be obtained by bringing a system to equilibrium with its surroundings. In that regard, thermodynamic inefficiencies in the process are determined. Only a brief introduction to exergy analysis is provided here, while more detailed explanations on the topic are given in literature (Kotas, 1985). The exergy of a stream comprises four parts: potential, kinetic, physical and chemical. In this analysis, the kinetic and potential exergies are ignored due to negligible changes in these energy forms.

The molar physical exergy of a stream is calculated as

$$\varepsilon_{ph} = (h - h_0) - T_0(s - s_0), \tag{1}$$

where h and s are the molar enthalpy and entropy, respectively. Further, the molar chemical exergy of a stream is calculated as

$$\varepsilon_{ch} = \sum x_i \varepsilon_{ch,i} + RT_0 \sum x_i \ln x_i, \tag{2}$$

where R is the universal gas constant, x_i the mole fraction of component i in the stream at T_0 and P_0, and $\varepsilon_{ch,i}$ the molar standard chemical exergy of component i. The exergy calculations are done within the process simulator where the exergy of material streams are calculated based on the code provided by Abdollahi-Demneh et al. (2011). The ambient temperature and pressure are assumed to be 25 °C and 1.013 bar, respectively. Cooling water at 25 °C is assumed as coolant if external cooling is required. For all the heat exchangers in the process, an approach temperature of 5 °C between hot and cold streams is considered.

The chemical exergy of biomass ($\varepsilon_{ch,biomass}$) was calculated from the lower heating value (LHV) using the method of Szargut et al. (1987), where the exergy of dry biomass is calculated as

$$\beta_{wood} = \frac{\varepsilon_{ch,biomass}}{LHV} = \frac{1.0412 + 0.2160 \frac{H}{C} - 0.2499 \frac{O}{C} [1 + 0.7884 \frac{H}{C}] + 0.0450 \frac{N}{C}}{1 - 0.3035 \frac{O}{C}}. \tag{3}$$

Here, C, H, N, O are the mass percentages of carbon, hydrogen, nitrogen and oxygen. By considering the LHV of pre-treated biomass (5 wt% wet biomass) to be 17.79 MJ/kg, β is 1.121 and the exergy is 19.94 MJ/kg. The chemical exergy of biomass was also calculated based on the method proposed by Peduzzi et al. (2016), and the results are within 1 % difference. In the FT reaction, hydrocarbon chains with infinite number of carbons can be produced. An appropriate approach to handle these components is to introduce lumps of components. In a simulation software like Aspen HYSYS®, a hypothetical component (or lump) must have a constant molecular weight. Since the molecular mass of the lumps will vary, each lump is modelled by three hypothetical components with a given constant molecular mass. The distribution between the lumps follows the Anderson-Schulz-Flory (ASF) distribution and the mass is conserved. The chemical exergy of each of the lumps is assumed to be equal to that of the hydrocarbon with the closest number of carbon atoms.

Here, the overall exergetic efficiency of the plant is defined as the ratio between the exergy content of the FT syncrude, and the exergy supplied to the process with biomass and electricity:

$$\eta_{overall} = \frac{\dot{E}_{FT\ syncrude}}{\dot{E}_{biomass} + \dot{E}_{electricity}}. \tag{4}$$

4. Results and discussion

The exergy destructions or irreversibilities within the process are given in Table 2 and Figure 3. The gasifier section accounts for almost 40 % of irreversibilities within the process. The FT and SOEC sections follow, with about 28 % and 16 % of irreversibilities, respectively. Therefore, these sections should be the focus to improve the exergetic efficiency of the process. The steam generation section, which includes the waste heat boiler, superheater and coolers before the acid gas removal section, accounts for 10% of irreversibilities of the process. A more detailed overview of exergy flow through the process, including the exergy destruction in each section, is given in a Grassmann diagram in Figure 4. 596 MW exergy ends up in FT syncrude from 486 MW of biomass and 382 MW of electric power resulting in an exergetic efficiency of 69 % for the PBtL process.

Table 2: Exergy irreversibilities in the process

Section	Irreversibility rate (MW)	Irreversibility (%)
Pretreatment	5.0	2.2
Gasifier	90.3	39.7
Steam production	22.4	9.9
RWGS	3.0	1.3
Acid Gas Removal	2.0	0.9
FT section 1	38.9	17.1
FT section 2	15.3	6.7
FT section 3	8.9	3.9
SOEC	37.2	16.4
Fired Heater	4.1	1.8
Total	227.1	

As can be observed in Figure 4, 60 MW of exergy is available in the form of heat from cooling the FT reactors at 210 °C. As of now, this exergy is not utilized in the process. The exergy efficiency of the process can be improved by utilizing this heat. This can be done for example by producing electricity through a steam turbine or by producing hydrogen through Reverse ElectroDialysis (RED).
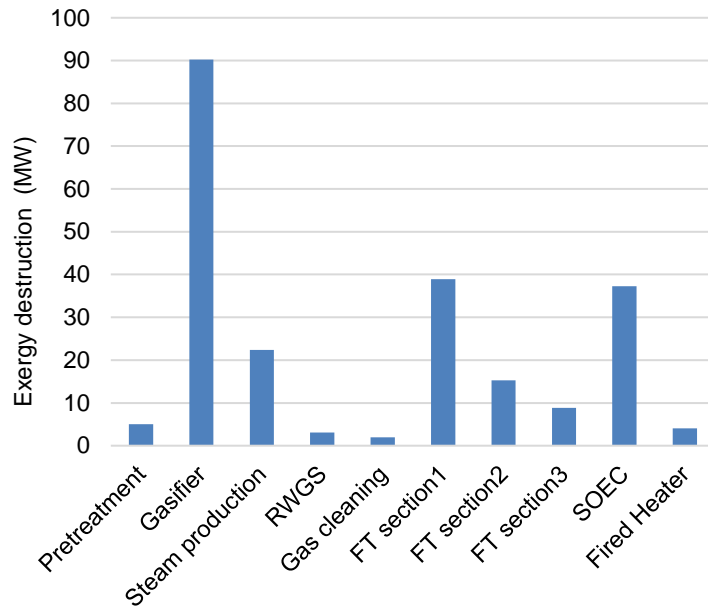

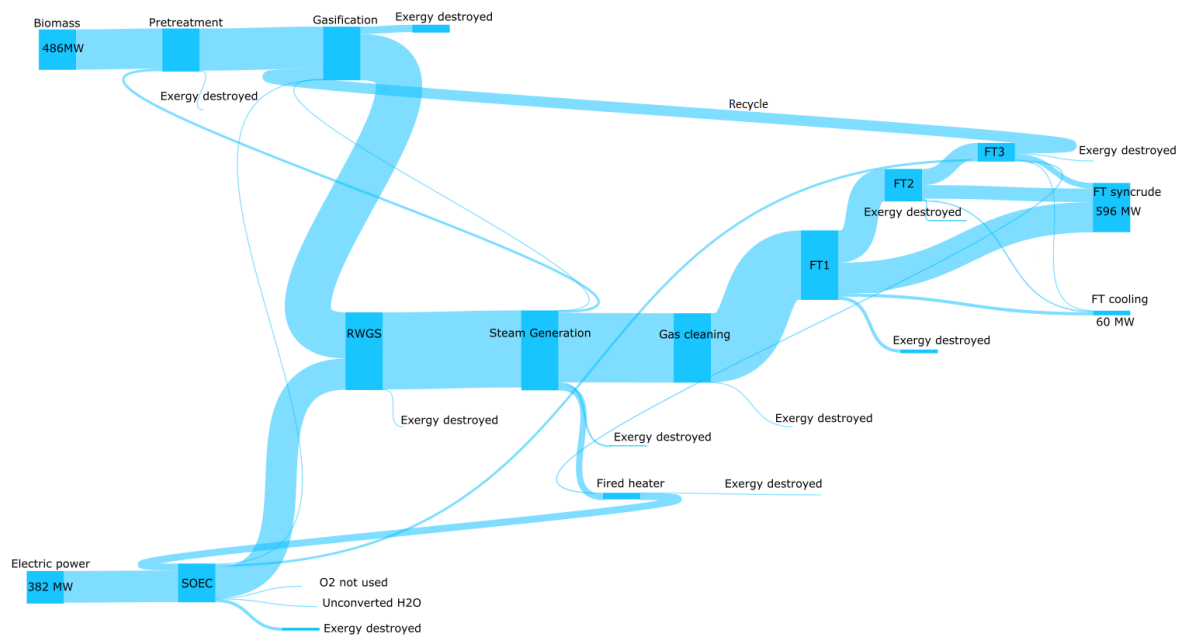*Figure 3: Process irreversibilities per section*

Figure 4: Exergy flow through the PBtL process

5. Conclusions

A power and biomass to liquid process (PBtL) with staged Fischer-Tropsch synthesis and hydrogen production in solid oxide electrolysis cell is exergetically analysed. The gasifier section has the largest exergy loss followed by the Fischer-Tropsch and solid oxide electrolysis cell sections. Therefore, to improve the process, the focus should be on the design and operation of these sections. The process has an overall exergy efficiency of 69 %. 60 MW heat exergy is available from FT cooling at 210 °C. For future investigations, this heat can be used to produce electricity in a steam turbine or to produce hydrogen via Reverse ElectroDialysis (RED).

Acknowledgments

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