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Thermodynamic evaluation of biomass-to-biofuels production systems

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ABSTRACT

Biomass is a renewable feedstock for producing modern energy carriers. However, the usage of biomass is accompanied by possible drawbacks, mainly due to limitation of land and water, and competition with food production. In this paper, the analysis concerns so-called second generation biofuels, like Fischer–Tropsch fuels or Substitute Natural Gas which are produced either from wood or from waste biomass. For these biofuels the most promising conversion case is the one which involves production of syngas from biomass gasification, followed by synthesis of biofuels. The thermodynamic efficiency of biofuels production is analyzed and compared using both the direct exergy analysis and the thermo-ecological cost. This analysis leads to the detection of exergy losses in various elements which forms the starting point to the improvement of conversion efficiency. The efficiency of biomass conversion to biofuels is also evaluated for the whole production chain, including biomass cultivation, transportation and conversion. The global effects of natural resources management are investigated using the thermo-ecological cost. The energy carriers' utilities such as electricity and heat are externally generated either from fossil fuels or from renewable biomass. In the former case the production of biofuels not always can be considered as a renewable energy source whereas in the latter case the production of biofuels leads always to the reduction of depletion of non-renewable resources.

1. Introduction

The present world's energy demand is still mainly met by fossil fuels, i.e. petroleum, natural gas and coal. There are two global problems related to the use of fossil fuels, rapid depletion of non-renewable resources and environmental damage due to emissions of various gases as CO_2, SO_x, NO_x and particulate matters. Depletion of natural non-renewable resources, particularly fossil fuels, is accelerated by a continuous increase in consumption. However, from the economic point of view the increase of consumption is also a base for further development of societies [1], but on the other hand, it provides an ecological threat to the existence of future generations. Environmental risks associated with the growth of consumption are related to depletion of non-renewable natural resources and release of harmful emission to the environment.

Environmental damages and losses caused by the rejection of waste substances from production processes can also be expressed through the impact on the depletion of non-renewable natural resources because compensation or prevention of these damages requires additional consumption. In order to reduce the consumption of non-renewable natural resources, the use of renewable ones should increase. The replacement of fossil fuels by biomass is a promising option for power technologies as well as for synthetic fuels production.

Biomass is a renewable and relatively clean feedstock for producing modern energy carriers such as electricity and transportation fuels. Transportation fuels derived from biomass, such as Fischer–Tropsch hydrocarbons, methanol, and hydrogen, are gaining currently more attention as potential substitutes for fossil fuels. However, the use of biomass is accompanied by possible drawbacks, mainly a limitation of land and water, and competition with food production. The agricultural production of biomass is relatively land intensive and involves high logistics costs due to low energy density of biomass. The average conversion efficiency of sunlight into chemical energy in biomass through photosynthesis is about 0.5–1.0% which is much lower compared to other forms of renewable energy such as photovoltaic or wind energy. For biomass-based systems a key challenge is thus to develop efficient conversion technologies which could compete with fossil fuels.

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However, the efficiency of biomass conversion to SF (synthetic fuels) should be evaluated for the whole production chain, including biomass cultivation, transportation and conversion, which is a much larger system than traditionally analyzed biomass-to-biofuel conversion plants [1]. To this end the global effects of natural resources management can be preferentially investigated applying the methods of cumulative calculus and LCA (Life Cycle Assessment) [2–5]. The calculation of the cumulative coefficients was initiated by Chapman, who introduced the concept of energy cost [6–8]. The theory of the energy cost of useful products was developed by Boustead and Hancock [9].

Nowadays, thermodynamic indicators of process performance, which based on the second law of thermodynamic and exergy concept, are generally accepted. These indicators determine the most natural way to measure the performance of different processes, ranging from energy technology, chemical engineering, transportation, agriculture, etc [10–15]. Szargut was the first who extended the exergy analysis of a single process to the whole production chain by proposing the important concept of CExC (cumulative exergy consumption) [2,10].

Subsequently he extended this concept to the TEC (thermo-ecological cost), which enables the applications of exergy analysis in the field of environmental aspects. The TEC expresses the cumulative consumption of non-renewable exergy of natural resources [4]. The Szargut's method in comparison with other methods of ecological assessment can bring all environmental impacts to one metric which is the exergy of consuming non-renewable natural resources. The TEC method fulfills the requirement of LCA; moreover, the minimization of the TEC [3] ensures a mitigation of the depletion of non-renewable resources. Such optimization can be a base of ecological economy that is in line with the concept of sustainable development which is one of the main goals of EU energy policy up to 2020.

The purpose of this paper is to demonstrate how the various indicators, which are based on the second law of thermodynamics, as exergy and TEC can be applied for the assessment of biofuels production. In section 2 the production of the selected biofuels, including FT (Fischer–Tropsch) hydrocarbons, methanol, hydrogen and SNG (Substitute Natural Gas) is described. Next, in Section 3 the production processes of these biofuels are analyzed within the system which include the biomass as a feedstock and the biofuel as the final product. This analysis is extended in sections 4 and 5 to the TEC of biomass-to-biofuel within the whole production chain, which also includes biomass cultivation and the effect of emissions. Finally, both evaluation methods are compared and their specific advantages are highlighted.

2. Production of the selected biofuels

2.1. Overview

Biomass can be converted to biofuels using various methods, including thermochemical as well as biochemical processing. The most promising route is a two-step process which comprises production of synthetic gas by biomass gasification and synthesis of transportation fuels. This route is particularly suited for production of second generation biofuels, such as Fischer-Tropsch fuels, methanol, hydrogen or SNG. The second generation biofuels are considered as medium and long term options for biomass utilization as they can be produced from a variety of biomass feedstocks, like lignocellulosic or waste biomass, which do not compete with the food production. The first generation biofuels are made directly from agricultural crops (e.g. corn ethanol, rapeseed methyl ester) which can be also used for the production of food.

In this section the production methods of typical second generation biofuels, including liquid, such as Fischer–Tropsch fuels and methanol as well as gaseous biofuels, such as hydrogen and SNG is described. Fig. 1 shows a scheme of biofuel production from biomass which is based on the above-mentioned steps of biomass gasification and biofuel synthesis. The process starts with the biomass drying in the case of wet biomass as the biomass gasifier is more suitable for conversion of dry feedstocks. In the biomass gasifier the synthesis gas containing CO, H_2, CO_2, H_2O, and CH_4 as the main components is produced. Biomass can be gasified using various gasifying agents, including air, oxygen, or steam.

The syngas (synthetic gas) from the gasifier is cooled and cleaned from impurities, such as solid particles and tars, which can be harmful for the biofuel synthesis. Subsequently, the synthetic gas is conditioned to meet the requirements specified by the biofuel conversion. To this end syngas is compressed to the synthesis

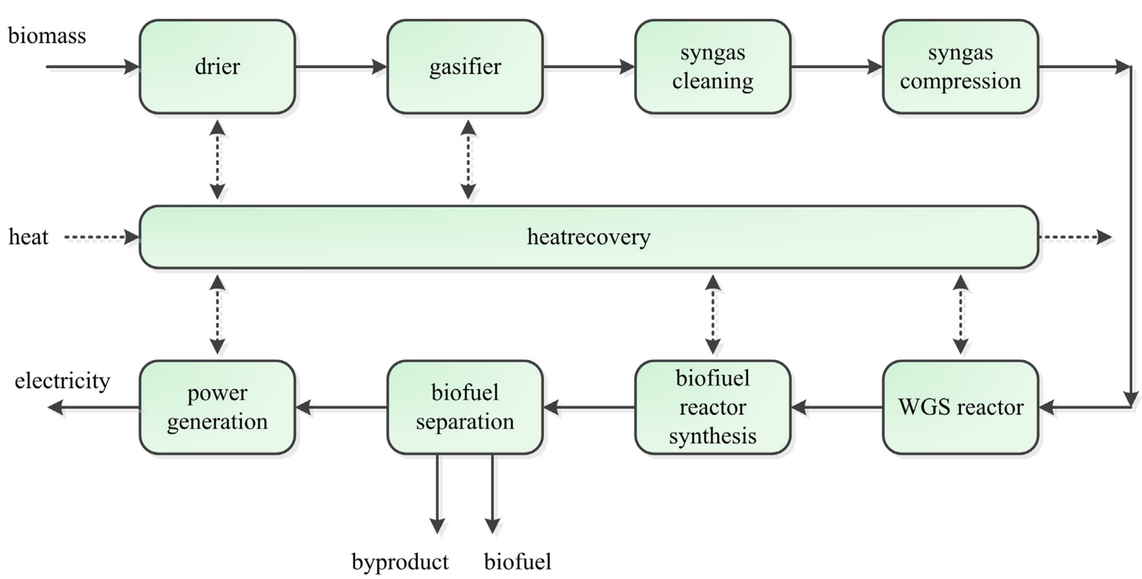

Fig. 1. Schematic of biomass-to-biofuels process.