



Exergy analysis of synthetic natural gas production method from biomass

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ABSTRACT

The paper presents the results of exergy analysis for a biomass-to-synthetic natural gas (SNG) conversion process. The presented study is based on wood gasification, which is analysed for different gasification conditions like temperature and/or pressure. The analysed temperature was varied in the range from 650 to 800 °C and the pressure range was from 1 to 15 bar. The main process units of biomass-to-SNG conversion technology are gasifier, gas cleaning, synthesis gas compression, CH₄ synthesis and final SNG conditioning. The results showed that the largest exergy losses take place in the biomass gasifier, CH₄ synthesis part and CO₂ capture unit. The overall exergetic efficiency of the biomass-to-SNG process was estimated in the range of about 69.5–71.8%.

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1. Introduction

Most of the world energy consumption is supplied by non-renewable energy sources such as oil, coal and natural gas. The global major problems related to the use of fossil fuels are a fast depletion and environmental concerns about global warming due to CO₂ emissions. In recent years there is a growing interest in biomass as a potential source of renewable energy, mainly due to renewability and neutral CO₂ impact of biomass. Biomass can be used to produce various energy carriers, such as electricity or bio-fuels, based on biomass gasification as the most promising conversion method. One can distinguish two groups of problems in the development of future biomass systems. The first group is more 'chemically' oriented and relates to the development of effective conversion technologies, including design of biomass gasifiers, reduction of tar content and development of catalysts for conversion of syngas into biofuels.

The second group of problems relates to the selection of the most efficient conversion chains: biomass feedstock–conversion technology–biofuel. The latter problems arise from a large variety of possible biomass feedstocks, conversion technologies, and bio-fuels, such as methanol, Fischer–Tropsch hydrocarbons, hydrogen, and SNG, as the final products. Therefore the future biomass systems can be designed almost from scratch. The problems of selection of the most efficient bioenergy chains are very relevant

due to serious drawbacks of biomass, such as limited availability due to limitation of land and water and competition with food production.

In many countries the main energy source is natural gas. For instance, in the Netherlands, about half of the energy input comes from the natural gas, particularly present in the Groningen gas field. In order to solve the problems of depletion of fossil fuels and their destructive influence on the environment, synthetic natural gas (SNG) is suggested as the important future energy carrier. Sustainable SNG produced from biomass can provide an attractive option for renewable biofuels.

There are various routes for methane rich gas (biogas or SNG) production based either on biomass gasification or anaerobic digestion and exergy analysis can contribute to select the optimal method. The conventional route for SNG production is based on gasification of biomass to produce synthesis gas and the subsequent methanation of the synthesis gas to SNG. Biomass gasifiers typically produce a synthesis gas containing CO, H₂, and CH₄ as the main components that carry the majority of energy in addition to remaining components as CO₂, H₂O and N₂, and also a variety of potential contaminants like tars, ammonia, alkalis, etc. First of all, gas cleaning is needed. Secondly, subsequent chemical processing of the synthesis gas requires specific gas conditions, such as desired H₂/CO ratio, temperature and pressure. Subsequently the syngas enters the CH₄ synthesis step. The methanation is a catalytic reaction and there is a substantial risk of catalyst overheating or deactivation due to carbon formation. Finally, the product gas from the CH₄ synthesis is processed to meet the requirements specified for SNG.

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Nomenclature

I	irreversibility (exergy loss) [MW]
ΔH°	standard reaction enthalpy [kJ/mol]
HHV	higher heating value [MJ/kg]
LHV	lower heating value [MJ/kg]
E_{SNG}	exergy flow rate of SNG product [MW]
$E_{\text{steam,prod}}$	exergy flow rate of produced steam [MW]
$E_{\text{heat,prod}}$	exergy flow rate of produced heat released [MW]
$E_{\text{tot,in}}$	total exergy input necessary to produce SNG [MW]
Ψ_1	exergetic efficiency defined by Eq. (5) [dimensionless]
Ψ_2	exergetic efficiency defined by Eq. (6) [dimensionless]
Ψ_3	exergetic efficiency defined by Eq. (7) [dimensionless]

2. Objectives

One of the difficulties of selection of the most efficient biomass chains is a lack of consensus on evaluation of future renewable energy systems. In practice various evaluation criteria are applied, usually based on energy efficiency, environmental performance and economical aspects. Nowadays, the most commonly accepted criteria of energy efficiency are based on the second law of thermodynamics and exergy analysis is used as the most natural way to measure performance of energy and chemical systems. In addition to thermodynamic criteria, also environmental and economic performance of a process should be evaluated to find the final judgment on process feasibility.

However, in most cases the analysis of process performance has 'one-dimensional' character as it refers only to a single aspect, from among thermodynamic, environmental and economic performance. More complex energy efficiency indicators that are 'multi-dimensional' must be still demonstrated in order to become sustainability tools in engineering practice and energy policy. This paper relates to evaluation of thermodynamic efficiency based on exergy analysis of biomass-to-SNG route in order to select the most convenient process conditions and moreover to provide data needed for efficiency comparison with production of other biofuels.

The objective of this paper is to determine the exergetic efficiency of the biomass-to-SNG conversion process under different operational conditions, and select the most convenient one. Exergy analysis indicates the process units where the largest inefficiencies (exergy losses) take place and therefore it makes substantial contribution to improvement of technical aspects of the process.

In the investigated technology a woody stream was chosen as a feedstock to produce SNG, which has to meet the local quality requirements. In addition to the thermodynamic efficiency, the economic aspects of biomass-to-SNG process are also discussed shortly in this paper.

This work is focused on the north part of the Netherlands, where the Groningen gas is distributed. The main requirements for the SNG produced are: gross calorific value (HHV) 31.6–38.7 MJ/Nm³ and Wobbe index 43.4–44.4 MJ/Nm³ [1]. Wobbe index is the main indicator of the interchangeability of fuel gases such as natural gas or SNG.

3. Biomass-to-SNG process

Natural gas is a major energy source for electricity generation and heating systems, and it has also gaining interest for the automotive sector. However, natural gas sources are limited and several programs are now under development to produce natural gas

substitute from renewable resources, in particular SNG. The main difference among these programs is the design of the gasifier as well as the operational conditions, steam being the preferred gasifying agent in order to achieve higher methane yields. For instance, the FERCO SilvaGas process [2] employs the low-pressure Battelle gasification process which consists of two physically separate reactors; a gasification reactor in which the biomass is converted into a gas and residual char at a temperature of 820–850 °C, and a combustion reactor that burns the residual char to provide heat for gasification at 1050 °C. Biomass reacts in the gasifier with steam (steam conditions are 150 °C and 2 bar). Heat transfer between reactors is accomplished by circulating sand between the gasifier and combustor. The Battelle process has been tested on a large scale with a biomass input of 200 tons per day [2]. On the other hand, Energy research Centre of the Netherlands (ECN) is developing a system for the conversion of dry biomass into natural gas quality gas called BioSNG or Substitute Natural Gas. This concept is based on so-called MILENA indirect gasification, which operates at a temperature of about 850 °C and under higher pressure [3–5]. However, due to the relatively low temperature the syngas will contain tars as well. These tars can be removed using OLGA tar removal technology developed by ECN [6]. The tars are recycled to the gasifier in order to increase efficiency, whereas the tar free syngas is cleaned from other contaminants (e.g. sulphur and chlorine). The clean syngas can then be fed to a combined shift and methanation process, converting the syngas into SNG. A lab-scale system is available at ECN, and a 1 MW pilot system at ECN is under commissioning.

The Swiss–Austrian consortium has constructed a 1 MW SNG demonstration plant in Güssing (Austria) for the conversion of woody biomass into SNG [7]. The vital component of the plant, i.e. the FICFB (fast internal circulating fluidized bed) gasifier consists of two fluidized bed systems that are connected with each other. Biomass is gasified with steam at the temperature of approximately 850 °C in the gasifying zone. Using steam instead of air as gasifying medium results in a nitrogen-free, low-tar product gas with high calorific value. Part of the residual char is conveyed, by the circulating bed material (sand), which also serves as heat storing medium, to the combustion zone and is burned there. The heat transferred to the bed material is needed to maintain the gasification reactions. After several pre-cleaning steps to remove some products toxic for the catalysts in the later processing step, syngas is converted to mainly CH₄ in a series of methanation reactors. Commercial plants are expected to be in the scale from 20 to 200 MW_{SNG}.

Under the GoBiGas project (Gothenburg Biomass Gasification Project), Göteborg Energi AB plans to build a plant that will process 140 MW of forestry residues to produce SNG [8,9]. The capacity of the plant will be around 10.95 Mm³ of SNG per year.

Thermal efficiencies of the aforementioned processes are in the range of 55–70%. However, in order to make SNG more attractive and competitive with other biofuels as well as natural gas, a major issue is to enhance the overall exergetic efficiency of the plant. There are many options that can be applied in order to improve the performance of the process, i.e., from changing the gasification design or varying the operational parameters. To this end some authors have simulated and analysed the efficiency of the SNG under different operational conditions and gasification designs [10–12], although only few analyses have been conducted to study the influence of operating parameters of the gasification and methanation units.

From an economic point of view, several studies reveal that SNG is an interesting option among other biofuels, although its production price is still notably higher than that of natural gas. Investment costs of SNG are estimated to be lower than that for other biofuels such as Fischer–Tropsch hydrocarbons, methanol or hydrogen [13]. In terms of production costs, SNG seems to be also

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