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Exergy analysis of biomass-to-synthetic natural gas (SNG) process via indirect gasification of various biomass feedstock

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A B S T R A C T

This paper presents an exergy analysis of SNG production via indirect gasification of various biomass feedstock, including virgin (woody) biomass as well as waste biomass (municipal solid waste and sludge). In indirect gasification heat needed for endothermic gasification reactions is produced by burning char in a separate combustion section of the gasifier and subsequently the heat is transferred to the gasification section. The advantages of indirect gasification are no syngas dilution with nitrogen and no external heat source required. The production process involves several process units, including biomass gasification, syngas cooler, cleaning and compression, methanation reactors and SNG conditioning. The process is simulated with a computer model using the flow-sheeting program Aspen Plus. The exergy analysis is performed for various operating conditions such as gasifier pressure, methanation pressure and temperature. The largest internal exergy losses occur in the gasifier followed by methanation and SNG conditioning. It is shown that exergetic efficiency of biomass-to-SNG process for woody biomass is higher than that for waste biomass. The exergetic efficiency for all biomass feedstock increases with gasification pressure, whereas the effects of methanation pressure and temperature are opposite for treated wood and waste biomass.

1. Introduction

1.1. General background

Major global energy problems related to the use of fossil fuels are a fast depletion and environmental damage due to emission of various gaseous compounds, mainly CO_2, SO_x, and NO_x. Moreover, worldwide energy demand is growing which also increases the need for renewable energy sources. With respect to global issues of sustainable energy, biomass is getting increased attention as a potential source of renewable energy. The key features of biomass are renewability and neutral CO_2 impact. Generally, all organic material that stems from plants, trees, and crops is named biomass. Biomass is a relatively clean feedstock for producing modern energy carriers such as electricity and transportation fuels. Thermochemical biomass conversion, particularly gasification, is considered as the most promising technology for a large scale biomass conversion. Biomass gasification offers a higher efficiency compared to combustion or pyrolysis but this process is still in the early stage of development. During gasification process biomass is partially oxidized to a syngas, which can be used to produce electricity in gas turbines, engines, and fuel cells or chemicals and transportation fuels in catalytic reactions. Transportation fuels derived from biomass, such as methanol, Fischer–Tropsch hydrocarbons and hydrogen are gaining currently more attention as potential substitutes for fossil fuels [1].

Recently, a renewed interest has grown in many countries in Synthetic Natural Gas (SNG) as an energy carrier [2,3]. The original interest in SNG stems from coal-to-SNG technology developed in the early 70s. However, most of this development has been cancelled in the 80s. The only one commercial plant was commissioned in 1984 in Great Plains (North Dakota, United States) and have been producing 4.8 Mio m^3 SNG per day ever since [4].

Nowadays, bio-SNG can be produced from biomass in a renewable way using various routes, including gasification and also anaerobic digestion or supercritical biomass gasification. Today biomass supplies about 50 EJ globally, mainly as the traditional biomass use for cooking and heating. The technical potential of biomass for diverse range of feedstock is estimated between 200 and 500 EJ/year by 2050 (excluding aquatic biomass) [5]. Forestry and agricultural residues and other organic wastes (including MSW (Municipal Solid Waste)) would provide between 50 and 150 EJ/year. Worldwide oil consumption was 161 EJ (82.5 million barrels oil per day) in 2005 according to BP Statistical Review of World Energy.

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Nomenclature

ΔH	enthalpy change (kJ/mole)
E_i	exergy flow rate of “i” material stream (MW)
E^Q	thermal exergy flow rate (MW)
E^W	flow rate of work interaction (MW)
Ψ	exergetic efficiency (-)

Acronyms

HHV	higher heating value
ICI	imperial chemical industries
MR	methanation reactor
MSW	municipal solid waste
SNG	synthetic natural gas

The major advantage of SNG as an energy carrier is the potential to use the existing natural gas infrastructure. SNG can replace natural gas as a green alternative in households and can be used as an alternative fuel in transportation. Currently, several research institutes are developing biomass-to-SNG technology, including Energy Research Center of the Netherlands (ECN), Center for Solar Energy and Hydrogen Research (ZSW) Baden Würtenberg, and Paul-Sherrer Institute (PSI) in Switzerland [4]. In the Netherlands annually 3280 PJ of primary energy is consumed whereas natural gas contributes in 46% to this amount. The Dutch Ministry of Economic Affairs has defined the ambition to replace 20% of natural gas by SNG in 2030, and substitution target of 50% has been suggested for 2050 [6]. A 20% substitution would correspond to 300 PJ of SNG with a current annual consumption on natural gas being 1500 PJ. Currently ECN operates a biomass-to-SNG pilot plant unit (Milena indirect gasifier technology) of 160 kg/h (0.8 MW_{th}) input. A demonstration plant of 10 MW_{th} is planned for the near future. The scale foreseen for a commercial SNG production facility is between 50 and 500 MW_{th} which corresponds to 3–30 ton/h of SNG [7].

However, the use of biomass is accompanied by possible drawbacks, mainly 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 photovoltaics or wind energy. For biomass-based systems a key challenge is thus to develop efficient conversion technologies which can also compete with fossil fuels. Moreover, in future more attention should be devoted to conversion of various waste biomass streams, such MSW and sludges, which do not compete with food production.

There are two key aspects in the development of future biomass-to-energy systems, namely development of chemical conversion technologies and selection of the most efficient chains: biomass feedstock-conversion process-biofuel. The first aspect relates to solving relevant chemical and chemical engineering problems, such as the reduction of tar content in the syngas from biomass gasification, design of biomass gasifiers, and development of catalyst for chemical conversion of syngas to biofuels. The scientific challenges belonging to these problems show similar character to those encountered for current fossil fuel technology. On the other hand the scientific and engineering challenges resulting from the second development key-aspect are quite unique for biomass. Due to a large variation of biomass feedstocks, conversion technologies, and biofuels, the future bio-energy systems can be designed almost from scratch. To this end the selection of the most efficient biomass conversion processes and synthesis of biofuels requires a correct use of thermodynamics. The latter aspect forms the main motivation for this paper.

One of the difficulties with measuring energy efficiency is the lack of consensus on the evaluation of performance of different stages of energy systems. Energy efficiency is a rather general term and in practice various performance indicators are used, usually grounded in thermodynamics or economics. Thermodynamic indicators of process performance based on the second law (exergy analysis) are nowadays commonly accepted as the most natural way to measure the performance of different processes, ranging from energy technology, chemical engineering, transportation, agriculture, etc.

1.2. Objectives

The objective of this paper is to evaluate the exergetic efficiency and propose recommendations for improvement of the biomass-to-SNG conversion process via indirect gasification. Various biomass feedstock are used in this study, including virgin biomass – treated wood as well as waste biomass – municipal solid waste and sludge. The final SNG product relates to the Dutch situation, particularly Groningen natural gas. From this point of view the main requirement for the produced SNG is a Wobbe-index of about 44 MJ/Nm^3 which characterizes quality and interchangeability of various gaseous fuels, including natural gas.

The special attention in this paper is devoted to the influence of main process parameters on the overall exergetic efficiency. The investigated process parameters are gasification pressure, pressure in the methanation section, and temperature of the first methanation reactor, which operates as a cooled reactor.

2. Biomass-to-SNG-route

2.1. Main process steps

A block diagram of biomass-to-SNG process is presented in Fig. 1. The principal process steps are biomass gasification, where a syngas is produced, followed by methanation of the produced syngas [6]. A wide range of biomass sources, such as traditional agricultural crops, residues from agriculture and foresting can be used to make SNG. These biomass feedstocks vary greatly in chemical composition, energy content, ash and moisture content. This is generally regarded as a real advantage, because it means that the best and economically attractive feedstock can be selected. In this paper SNG is produced from various biomass feedstock, including treated wood, MSW and sludge.

2.2. Biomass gasification

Generally, several pre-treatment techniques, such as size reduction, drying or torrefaction can be applied before biomass gasification. In the case of SNG production from the treated wood which is relatively dry and high quality feedstock, biomass pre-treatment is not needed. However, in the case of waste biomass (MSW and sludge) which are wet feedstock, biomass pre-

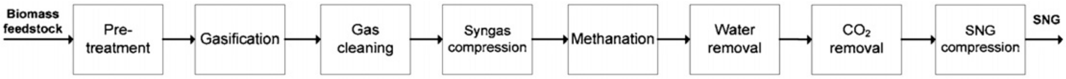

Fig. 1. Block diagram of the biomass-to-SNG process.