INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–19

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Integration of solid oxide electrolyser, entrained gasification, and Fischer-Tropsch process for synthetic diesel production: Thermodynamic analysis

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ARTICLE INFO

Article history:
Received 29 March 2017
Received in revised form
18 January 2018
Accepted 22 January 2018
Available online xxx

Keywords:
Solid oxide electrolyser
Entrained gasification
Fischer-Tropsch
Synthetic fuel production
Energy analysis
Exergy analysis

ABSTRACT

A novel integrated renewable-based energy system for production of synthetic diesel is proposed and simulated in this study. This system merges solid oxide electrolyser (SOE), entrained gasification (EG) and Fischer-Tropsch (FT) technologies. Two case scenarios are considered here. In the first case, the electrolyser unite produce syngas through co-electrolysis of steam and carbon dioxide, while in the second case only steam is electrolyzed. The effects of SOEC and EG operating pressure and temperatures on the system performance in each case are investigated and compared. It is shown that the operating condition of electrolyser subsystem has a more considerable effect on the performance of the integrated system as compared to the gasification subsystem. Also waste heat recovery results in about 43 and 2 percentage point increase in energy and exergy efficiency, respectively. It is also shown that internal recovering of oxygen has the best effect on the system performance.

Introduction

National energy security concerns and significant fluctuation of fossil fuel prices in the global energy markets direct the societies towards utilizing the renewable energy resources. In addition, there is a significant scientific consensus that anthropogenic activities cause rapid and severe climate change beyond the adaption potential of ecosystems [1]. For example, transportation sector contributes to about 22% of global emissions worldwide [2]. The majority of greenhouse gas emissions in this sector is related to the CO_2 produced in internal combustion engines from combustion of fossil fuel based fuels like gasoline and diesel. Production of CO_2- neutral transportation fuels is one alternative towards reducing the

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https://doi.org/10.1016/j.ijhydene.2018.01.138

Nomenclature

Abbreviation

abs	Absolute pressure
ASR	Air specific resistance
EG	Entrained gasification
FT	Fischer-Tropsch process
FTS	Fischer-Tropsch Synthesis
GHG	Greenhouse gas
HTE	High temperature electrolyser
LHV	Lower heating value
LTE	Low temperature electrolyzer
RES	Renewable energy systems
SOEC	Solid Oxide Electrolysis Cells
WGS	Water gas shift

Greek symbols

α	Relative mole fraction of methane
β	Biomass exergy constant
$\Psi_{biomass}$	Exergy content of biomass, MW
$\Psi_{F,sys}$	Exergetic fuel, MW
$\Psi_{P,sys}$	Exergetic product, MW
η_s	Energy efficiency of the system

Latin symbols

b	Exergy content of stream, MW
b_{ph}	Physical exergy content of stream, MW
b_{ch}	Chemical exergy content of stream, MW
E_s	Exergy efficiency of the system
F	Faraday constant, 96485 J/V. gram equivalent
$\Delta G_{f,\ i}$	Gibbs free energy of formation, (i: water, CO_2), kJ/kmol
i	Current density, A/cm^2
I_F	Faradic current, A
m	Mass flow rate, kg/s
n_{O2}	production rate of oxygen, mol/s
P	Operating pressure of the electrolyser, bar
P_{std}	Pressure at the standard condition 1.013 bar
Q_{tot}	Total heat input to the system, MW
R	Universal gas constant, 8.31451 J/mol.K
S	Entropy, kJ/kg.K
T	Temperature, °C
V_N	Nernst Voltage, V
V_o	Operating cell voltage, V
V_{OC}	Open circuit voltage, V
V_{TN}	Thermo-neutral Voltage, V
$W_{el,tot}$	Total electrical power demand of system, MW
y_i	Molar fraction of each component in flow stream

dependency on fossil fuels as well as lowering net CO_2 emissions from road transportation.

Entrained flow gasification (EG) of biomass integrated with Fischer-Tropsch (FT) processing is one of the suggested routes for the production of CO_2-neutral gasoline and diesel [3]. Entrained flow gasifiers operate at high temperatures and enable the possibility of production of high quality syngas with low or no tar production [4–6]. These gasifiers also benefit from fuel flexibility, so second-generation feedstocks like lignocellulosic biomass and agricultural residues can be considered. One of the main obstacles in this approach lies in biomass resource availability as related to the relatively high transportation fuel demand. For example, considering 50% yield from biomass to biofuel, Sweden's annual potential for production of biofuels from lignocellulosic biomass is estimated to be in range of 25–30 TWh while the transport sector used around 32 TWh gasoline and 45 TWh diesel in 2013 [4]. In order to close the gap between supply and demand, another pathway can be added to the system for boosting production of the required syngas. For this purpose, high temperature solid oxide electrolysis units can be used to supply syngas from co-electrolysis of steam and carbon dioxide alongside gasifier units. Provided that the required electricity for co-electrolysis comes from renewable sources such as sun or wind, this approach allows storing the excess electrical energy in form of chemical energy of the hydrocarbon fuels. Then in return, using these synthetic fuels results in increase of renewable share in transportation system since direct use of solar power or wind in vehicles is challenging to achieve. The required carbon dioxide can be provided from carbon capturing technologies integrated with coal power plants or steel industry. The produced synthetic hydrocarbon fuels then may be considered as renewable fuels due to reuse of CO_2 as well as reduction of fossil fuel consumption for chemical and fuels production.

So far most of the proposed systems for synthetic diesel production include gasification of biomass [7–14], while there are only a handful of studies that investigate the aspects of integration between SOEC and FT systems. As an example, Becker et al. [15] developed a theoretical model of an integration between a high temperature co-electrolysis process and FT technology. The results showed system efficiencies as high as 54.8% (HHV base), rendering the concept as promising. In a more recent study, Stempien et al. [16] investigated performance of a simplified integration between SOEC and FT systems using a thermodynamic model. They showed possibility of achieving high system efficiencies (about 66%) provided that recovery turbines are included in the integrated system. Chen et al. [17] performed a numerical study on SOEC-FT for methane production at pressures of 1–5 bar. In this pressure range, they suggested optimal pressure of 3 bar where methane production would be at its peak value. However, the main focus of their study was the reactor and reactions and they did not consider other elements that are required for the system.

In this study, however, a novel integration between SOEC, EG and FT technologies is suggested as a pathway for synthetic hydrocarbon liquid fuel production from renewable sources. The main output of the system is FT diesel while inputs are biomass, surplus electricity from renewables such as solar and wind, and carbon dioxide. Naphta, wax, light hydrocarbons, and hydrogen produced during the FT process and product upgrading are considered as byproducts. The system is designed in such way to be able to produce 30 m^3/h