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Integration of biomass gasification with a solid oxide fuel cell in a combined cooling, heating and power system: A thermodynamic and environmental analysis

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ABSTRACT

A biomass-fueled combined cooling, heating and power (CCHP) system is proposed and thermodynamically assessed. The system consists of a biomass gasifier (as the primary energy source), a solid oxide fuel cell (as the power generation unit), a double effect absorption refrigeration cycle (for cooling production) and a HRSG (for steam production for heating purposes). Taking into account the environmental considerations, energy and exergy analyses are conducted for the proposed system and its performance is compared with the corresponding power generation unit and the CHP system. Through a parametric study it is observed that the current density and fuel utilization factor play key roles on the system performance. In addition, considering the system as a combination of three subsystems, i.e. the SOFC, CHP system and CCHP system, an environmental impact assessment in terms of CO_2 emission is conducted. Municipal solid waste is examined as biomass and it is observed that maximum exergy efficiency of the CCHP system is 37.92% with a CO_2 emission of 20.37 t/MWh which shows an increase of 49.88% in exergy efficiency and 64.02% decrease in CO_2 emission, compared to the solo SOFC system. It is concluded that the air heat exchanger and the gasifier are two major sources of irreversibility in the system and the exergy loss is considerable compared to after burners' exergy destruction.

Introduction

In recent years, environmental concerns arising from fossil fuel combustion has increased interest in non-fossil energy resources among which biomass energy is an emerging alternative. Also, the rapid industrial development leads to higher fuel consumption for electricity generation as well as heating and cooling production. In this respect, the application of combined cooling, heating and power (CCHP) generation systems can be considered as a major opportunity to reduce fuel consumption and air pollution.

Biomass is one of the few renewables widely dispersed, indigenous that is a natural energy source with net zero CO_2

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Nomenclature

G-SOFC	Gasifier coupled SOFC
SOFC	Solid oxide fuel cell
HRSG	Heat recovery steam generator
AHX	Air heat exchanger
FHX	Fuel heat exchanger
FuelB	Fuel blower
AirB	Air blower
P	pump
K	equilibrium constant
ΔG	Change in Gibbs function
S	entropy
H	enthalpy
$\dot{W}$	Power
$\dot{Q}$	Heating load

Subscript and abbreviations

0	dead state
1,2,3, …	state points

Greek symbols

η_{th}	thermal efficiency
η_{II}	exergy efficiency
η_{I}	energy efficiency
η_{is}	isentropic efficiency

emission rate and low SO_2 emission [1,2]. Biomass resources are sporadically dispersed everywhere with localized availability. Thus, the power generation systems can be located nearby the end-users decreasing grid losses and expands the potential of usage of the generated heat and cooling. Besides, the local conversion of biomass to electricity, heat and cooling reduces the biomass feedstock's transportation costs [3].

There are a number of different methods for fuel production using biomass, such as fermentation, anaerobic digestion, combustion, pyrolysis and gasification [4]. Among these methods, gasification has lower pollutant emission and higher efficiency of power and heat generation. Also, the gasification process can produce a higher volume of gas comparing with the pyrolysis [1,5]. Thus, this method is more suitable to utilize the biomass energy in power generation or CCHP systems for medium to large scale applications [6]. The fuel gas mixture produced from biomass gasification mostly contains hydrogen (H_2), carbon monoxide (CO) and insignificant amounts of carbon dioxide (CO_2), water (H_2O), nitrogen (N_2), methane (CH_4), ethane (C_2H_6), carbon particulates, tar, ash and higher hydrocarbons. The composition of the gasses and the quality of the biomass fuel (syngas) can be varied via changing temperature, pressure and the gasifying agent in gasification process and also the design of the gasifier [1,7–9].

In order to increase the efficiency of biomass energy conversion systems, they can be coupled with high efficiency power generation units such as fuel cells [1]. Due to the direct conversion of the chemical to electrical energy, fuel cells have the least environmental effects and higher electrical efficiency than the conventional power plants [9–11]. Among different types of fuel cells, Solid Oxide Fuel Cell (SOFC) is an emerging technology for small and large power generation systems due to its high efficiency, low emissions and excellent load following characteristics [12–15]. Table 1 presents the properties of SOFC briefly.

SOFC is a high-temperature fuel cell that makes it suitable for co- or tri-generation systems and combined cycles [16,17]. The conventional power plants efficiency which are based on single prime movers are mostly less than 40%, so around 60% of the input energy is wasted in the form of thermal energy [6]. The SOFC-CCHP biomass fueled systems not only are capable of generating electricity and useful heat, but also have the potential to increase the power generation efficiency and reduce the air pollutant emissions. The application of biomass energy in cogeneration systems is investigated in some research works [18,19]. Zhao et al. [20] designed and analyzed an integrated SOFC-CCHP system fueled by coke oven gas. Their results showed that the SOFC electrical efficiency can be more than 60% and the power generation efficiency and the overall system efficiency of SOFC-CCHP system can reach 70% and 90%, respectively. Al-Sulaiman et al. [21] assessed the feasibility of integrating SOFC with organic Rankine cycle (ORC) and analyzed different efficiencies, power and electricity to heating and cooling ratios. According to the results, there is at least a 22% gain in efficiency in the tri-generation system, compared to the power cycle. The maximum efficiency of the tri-generation plant, heating cogeneration, cooling cogeneration and net electricity is calculated as 74%, 71%, 57% and 46%, respectively. Campitelli et al. [22] investigated the integration of a biomass gasification process with the SOFC operation. The main focus was to identify the role of SOFC H_2 utilization to maximize the system efficiency and avoid gasifier bad operation issues. The study reveals that SOFC H_2 utilization, which has a direct impact on gasifier operating conditions, plays a significant role in electrical power output. Gong and Huang [23] investigated the performance of a tubular SOFC which uses gaseous fuels gasified from clean Coconut shell carbon. Their key objective was to examine the catalyst effects on the production of gaseous fuels and SOFC performance. Based on the results, adding catalysts in the carbon gasification process increases the conversion rate of solid carbonaceous materials into gaseous fuels and thus improves the SOFC performance. Bocci et al. [24] analyzed the most innovative reliable technologies of the biomass-fuel cell. The biomass and fuel cell conversion systems were evaluated from different perspectives including processes, technologies and plant configurations and the research challenges of these systems were discussed. An integrated system consisting of a municipal solid waste (MSW) gasification plant, SOFC and a Stirling engine is proposed by Rokni [25]. . The thermodynamic analyses show that depending on the plant detail and the MSW composition, the system electrical efficiency of up to 48% and the combined heat and power efficiency of up to 95% is accessible implying that the solid waste gasification can compete with incineration technologies. Ozcan and Dincer [26] evaluated three different gaseous fuels from three different biomass gasification systems (including Thermo-Chembubling fluidized bed gasifier (TRI), CUTEC circulating fluidized bed gasifier and SilvaGas&Taylor dual fluidized bed gasifier) for an SOFC based trigeneration system. Theyshowed

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