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A conceptual process design towards CO2 emission reduction by integration of solar-based hydrogen production and injection into biomass-derived solid oxide fuel cell

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Abstract

Integration of biomass gasification with Solid Oxide Fuel Cell (SOFC) is a promising technology, particularly for small scale decentralized power systems. In this paper, to reduce the CO_2 emission and biomass consumption of this system, it is incorporated with solar-based hydrogen production. The produced hydrogen is injected into the biomass gasification-SOFC system, proposing two different configurations. In the first configuration, the hydrogen is injected into the anode inlet (to provide a hydrogen rich fuel), while in the second proposed configuration it is injected into the afterburner of the SOFC (to increase the gas turbine inlet temperature). The two proposed configurations are comprehensively assessed and compared from thermodynamic, environmental and economic standpoints. In thermoeconomic analysis, the negative environmental damage costs of CO_2 emission, as the primary greenhouse gas, is taken into account. Also, a parametric study is conducted to ascertain the major design variables after which tri-objective optimization is performed based on CO_2 emission, levelized cost of electricity and exergy efficiency. The results indicated superior performance for the system with hydrogen injection into the anode compared to the injection into the afterburner. The former configuration has 20.6% higher exergy efficiency with 23.2% lower emission and 14.0% lower levelized electricity cost. For this configuration under the optimum operation, the exergy efficiency, CO_2 emission and electricity cost are found to be 24.85%, 0.257 kg/kWh and 0.0911 $/kWh, respectively.

Introduction

The world's industrialization absolutely depends on energy supply, where fossil fuels are the primary energy source at present. Harmful impact on the environment of these resources has urged researchers to emphasis on alternative technologies and renewable energies. Utilization of fossil fuels is the main source of CO_2 emission as the foremost contributor to greenhouse effect, while it is increasing by 2.5% annually since the last decade (Bhattacharya and Selvaraj, 2021).

To decrease the CO_2 emission in power generation systems, replacement of fossil fuels by the renewables is a major alternative. Amongst renewable resources, the biomass is an important and promising one as it is available worldwide and power generation from biomass can be considered as a net zero CO_2 emission system (Glushkov et al., 2021). Another major renewable energy source is the solar one which is the most abundant energy resource on the earth, however it has a major drawback which is its discontinuity and fluctuations. One solution to this problem is the utilization of solar energy for green hydrogen production. The produced hydrogen can be stored and used for continuous power generation by appropriate power production systems.

Between the novel power technologies, the Solid Oxide Fuel Cell (SOFC) is an attractive device with some advantages as: higher efficiency, lower emissions, quiet operation, and variety of fuels.

They operate under intermediate temperature levels ($600 - 800℃$), which provides favorable conditions for electrochemical reactions for direct electricity generation. Fuel cells are typically fed by hydrogen, meanwhile their integration with biomass gasification establishes progressive route in utilizing bio-resources. Gasification is a partial oxidation of biomass which converts carbonaceous feedstock into a gaseous fuel using a gasifying agent. The produced gas is called syngas consisting of H_2, CO_2, CH_4, CO and N_2, which can be efficiently utilized to fuel a SOFC system (Balu et al., 2015).

Regarding the significance of SOFC-based systems, numerous research works have been conducted investigating their various features and aspects. In this respect, integration of SOFCs with biomass gasification is an important topic on which much attention is paid. Due to the complexity and relatively high-cost of such systems, theoretical modeling has been noticed as a useful method to simulate and predict their performances (Mei et al., 2021). The first study was probably conducted in 1994 by Alderucci et al. (1994), who analyzed thermodynamic performance of an Integrated Biomass Gasification-SOFC (IBG-SOFC) system and compared its performance for steam and CO_2 as the agents. Then, an IBG-SOFC system with 200 kWe capacity for Combined Heat and Power (CHP) applications is suggested by Omosun et al. (2004). He compared the cold gas and hot gas cleaning scenarios and reported electrical efficiencies of 20.8% and 22.6%, respectively. For an IBG-SOFC coupled to a micro Gas Turbine (GT), exergy efficiency of 35.60% is reported under CHP mode (Fryda et al., 2008). Di et al. (2013) evaluated a combined IBG-SOFC and micro-GT system using steam and oxygen enriched air as the gasifying agents. They reported overall efficiency ranging from 36% to 44%, depending on O_2 purity in gasifying air.

There are other related studies conducted on IBG-SOFC systems in recent five years with some novelties in system configuration and/or investigation methods. Santhanam et al. (2016) proposed incorporation of heat pipes in an IBG-SOFC system and using anode gas recycle as the gasifying agent. They indicated some performance improvement by employment of these methods and reported electrical efficiency of higher than 55%, by significant reduction of exergy loss in the gasifier. For an IBG-SOFC system with steam gasification, Doherty et al. (2015) revealed that the steam to carbon ratio must be selected as lower as possible to attain the best performance. Tan et al. (2017) investigated combination of a Kalina cycle with IBG-SOFC-GT system and indicated an efficiency of 64.20% based on the syngas lower heating value. An IBG-SOFC system is combined with an absorption refrigeration cycle for CCHP applications, for which a maximum exergy efficiency of 37.92% is reported (Gholamian, 2016). To evaluate the short- and long-term operating features of the syngas fueled SOFC from a downdraft gasifier, Suboti et al. (2020) performed an experimental study and showed that the most favorable system integration and highest fuel utilization occurs at operating temperature of 750°C. Jia et al, (2018) evaluated a IBG-SOFC-GT system in which the co-gasification of animal manure and wood is examined to produce syngas fuel. They found that, the integrated system efficiency can be improved by decreasing manure mass fraction and increasing the air flow rate as the gasifying agent. A hybrid

SOFC-GT performance is compared for various biofuels (including agricultural waste, industrial waste, sewage biogas, and gasified biomass) and natural gas from the energy and exergy viewpoints. It is found that, although using the natural gas brings about higher exergy efficiency, however, utilization of biofuels causes much lower environmental impacts (Beigzadeh et al., 2020). Detchusananard et al. (2019) applied sorption enhanced steam gasification for an IBG-SOFC and conducted multi-objective optimization to obtain Pareto-optimal solutions for various operating scenarios. Mojaver et al. (2019) proposed incorporation of high-temperature heat pipe in an IBG-SOFC, between the afterburner and the gasifier. They reported exergy efficiency values of 28.5–32.5% under various operating conditions. Behzadi et al. (2019) proposed combination of an IBG-SOFC system with an absorption refrigeration system and reverse osmosis unit for trigeneration of freshwater, cooling, and power. An interesting feature of this study is the CO_2 capture and recycle into the gasifier as the agent. They reported 38.1% exergy efficiency and 69.4 $/GJ product cost, at the optimum conditions. A comparison is made between air and steam as the gasifying agents in an IBG-SOFC system, indicating that using steam instead of air increases the exergy efficiency by 24.9% as a results of which the cost of power is decreased by 8.9% (Shayan and Mirzaee, 2019). Hossein et al. (2019) combined the IBG-SOFC system with an ORC for waste heat recovery and reported exergetic efficiency of 35.10% and 329 kW electricity generation. Emre et al. (2020) proposed combination of IBG-SOFC system with Proton Exchange Membrane Electrolyzer (PEME), reverse osmosis and ejector cooling units for multi-generation of electricity, hydrogen, cooling and freshwater, for which an overall energy efficiency of 56.17% is reported. A novel combination of IBG-SOFC with externally fired GT and a steam generator for CHP applications is investigated by Roy et al. (2020), who reported Levelized Cost Of Electricity ($LCOE$) and exergy efficiency as 0.045 $/kWh and 46.6%, respectively. For an IBG-SOFC system employment of four gasifying agents (air, oxygen-enriched air, pure oxygen, and steam) is evaluated and compared. It is found that, using pure oxygen yields the highest exergy efficiency for the overall system compared to the other gasification agents (Hosseinpour et al., 2020). An experimental set-up is designed to investigate commercial operation of IBG-SOFC system by Gadsbøll et al. (2017) at the Technical University of Denmark. They conducted some tests to examine both the full- and part-load operations and reported the highest value of biomass-to-electricity efficiency of up to 43%. Coupling of a ground source heat pump with an IBG-SOFC system, for its waste heat recovery, is suggested by Li (Li et al., 2020), who calculated exergetic efficiency of 29.2% for the overall system at a case study condition in China. A comprehensive exergy analysis on the IBG-SOFC system is conducted by Jia et al. (2015) using various gasification agents. They calculated the exergy efficiency of CHP mode as 29%, using oxygen-enriched air as the agent. Gha et al. (2018) proposed combination of the IBG-SOFC with a steam power cycle and conducted an exergoeconomic evaluation. They compared the system performance for three types of biomass feedstock and showed that, utilization of pine saw dust results in the best system performance with exergetic efficiency of 28.98% and power cost of 27.66 $/GJ.

In recent years, hydrogen is paid much attention as a promising energy carrier for its great capability of pollution reduction (Khalil, 2018). The water electrolysis is a favorable hydrogen production method, however the required electricity is a major problem (Hadelu et al., 2022). Utilization of H_2 as a co-feed fuel for blending with other fuels, such as Natural Gas (NG), is investigated by some researchers. The main advantage of using such fuel blends is to decrease the environmental impacts, particularly the CO_2 emission, however it would result in additional costs and probably efficiency reduction (Janès et al., 2017).

A comprehensive literature survey on IBG-SOFC systems and also on hydrogen co-fired power plants has shown that, feasibility assessment of hydrogen injection into the IBG-SOFC system has not been investigated. The literature review shows that, almost all the relevant research works have been devoted on blending hydrogen with NG in GT plants. In this paper, the produced hydrogen via integration of solar Photovoltaic-Thermal (PVT) and PEME is proposed to be injected into the IBG-SOFC system with two different scenarios. In the first proposed system the hydrogen is mixed with the fuel mixture at the anode inlet (Fig. 1), while in the second system the hydrogen is proposed to be combusted in the afterburner (Fig. 2). In order to reveal the practical feasibility of the proposed configurations detailed thermodynamic assessment based on the first and second laws is essential to explore the systems' operation without violation of thermodynamic laws. Also, in order to indicate the practical significance from economic perspective, an assessment is necessary to evaluate the trade-offs between additional costs (via adding the hydrogen injection) and power enhancement. If the power enhancement dominates the added costs, then the system would be applied in practice regarding economic criteria. In addition, an environmental evaluation is conducted to determine practical importance of the proposed configurations based on CO2 emission. The major design/operating variables are determined by a comprehensive parametric study, after which a tri-objective optimization is performed based on exergy efficiency, CO_2 emission and $LCOE$.

Section snippets

Systems' description

Fig. 1 illustrates schematics of the first proposed system which consists of five main sub-systems including: gasifier, SOFC, GT, PVT, and PEME. Both the cathode and anode gas recycling is considered in SOFC configuration to improve its performance and to make a more sustainable operation. Also, for the SOFC the internal reforming is adopted due to its lower costs and higher potential for extra cooling of the stack (Shayan and Mirzaee, 2019).

As shown in Fig. 1, biomass feedstock (stream 1) with ...

Modeling and analysis

To evaluate the performance of the considered IBG-SOFC systems, exergy, energy, environmental and economic analyses are carried out. The exergy and energy appraisals reveal the system feasibility based on the first and second law principles. However, economic features play important role in development of novel systems and hence, thermo-economic analysis is necessary to inspect economic characteristic of the systems helping to perceive a cost-effective design. In addition, environmental impact...

Validation

To demonstrate the accuracy of applied models, the obtained results are compared with available theoretical and experimental data. Table 3 indicates the comparison of obtained results in this work with experimental results from Tao (Tao et al., 2005), for the standalone SOFC which reveals a good agreement.

In order to validate the IBG-SOFC system, the values of output power obtained in this paper are compared with the given results by Habibollahzade et al. (2018) as shown in Fig. 4. Referring to ...

Conclusions

The integrated biomass gasification-SOFC system is incorporated with solar-based hydrogen production unit in order to provide hydrogen rich fuel for the SOFC. Regarding the way how the produced hydrogen would be injected into the integrated system, two configurations are proposed, investigated and compared. In the first system hydrogen is mixed with gaseous fuel at the anode inlet, whereas in the second configuration it is injected into the afterburner of the SOFC. It is revealed that, the main...

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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