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Thermo-economic analysis of a solid oxide fuel cell and steam injected gas turbine plant integrated with woodchips gasification

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ABSTRACT

This paper presents a thermo-economic analysis of an integrated biogas-fueled solid oxide fuel cell (SOFC) system for electric power generation. Basic plant layout consists of a gasification plant (GP), an SOFC and a retrofitted steam-injected gas turbine (STIG). Different system configurations and simulations are presented and investigated. A parallel analysis for simpler power plants, combining *GP*, *SOFC*, and hybrid gas turbine (GT) is carried out to obtain a reference point for thermodynamic results. Thermodynamic analysis shows energetic and exergetic efficiencies for optimized plant above 53% and 43% respectively which are significantly greater than conventional 10 MWe plants fed by biomass. Thermo-economic analysis provides an average cost of electricity for best performing layouts close to 6.4 and 9.4 c€/kWe which is competitive within the market. A sensitivity analysis of the influence of SOFC stack cost on the generation cost is also presented. In order to discuss the investment cost, an economic analysis has been carried out and main parameters such as Net Present Value (NPV), internal rate of return (IRR) and Time of Return of Investment (TIR) are calculated and discussed.

1. Introduction

The primary aim of the present study is to investigate the thermodynamic performance and estimate the economic profitability of an advanced system for electric conversion of woodchips with high electric efficiency. The system is intended to be an improvement of standard solid oxide fuel cell (SOFC) plants integrated with simple gas turbines (GTs), for which the thermodynamic efficiency is limited by the gas cycle performances. In this paper it is proposed to replace the gas turbine with a higher efficient gas cycle based on a steam-injected gas turbine (STIG) which utilizes the heat in the exhaust gases to vaporize water for injection purposes. The overall system considers the coupling of the gasification plant with the SOFC section and a STIG cycle. The plant presented here is termed as integrated gasification SOFC and STIG cycle (IGSST). Some concepts presented here are new and have not been studied previously. Furthermore both thermo-economic and economic analyses are carried out to provide a wider view on the studied plants. The target for net power production is set to 10 MWe based on cultivation area requirements as shown in Section 2. For thermodynamic comparison, other simpler plants have also been studied, which are presented in detail in Section 3.

The woodchips are gasified in a gasification plant based on an upscale of a two-stage gasifier [1] currently in operation at the Technical University of Denmark. The syngas produced in such gasifier is principally composed of hydrogen and carbon monoxide, and after a simple gas cleaner, the syngas is suitable to feed an SOFC, as reported in Ref. [2].

Much research on fuel cells has focused on SOFC as an electrochemical reactor aimed at power and heat generation applications. Its high operating temperature (ca. 700-1000 °C) allows light hydrocarbon fuels (e.g. methane) and CO to be internally reformed within the cell through reforming and water–gas shift reactions. As a result SOFC can be fed with many different gaseous fuels such as methane, natural gas (reformed) and syngas despite of its size [3–8]. Besides recovering the heat for CHP (combined heat and power) applications, another way to utilize the high temperature waste heat from SOFC is to combine it with a bottoming cycle for additional power production which results in improved overall efficiency when compared to an individual stand-alone system.

Gas turbines have been often investigated as bottoming cycles, for instance in Ref. [9] for CHP applications, in Ref. [10] with internal biomass gasification and in Refs. [11–13] for small scales (200–300 kWe). Characterization, quantification and optimization of hybrid SOFC and gas turbine systems were studied in Refs. [14,15].

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In Ref. [16] a hybrid plant producing combined heat and power from biomass by use of a two-stage gasification plant, SOFC and micro gas turbine was considered. In Ref. [17] it was proposed to couple a micro-GT with an SOFC fed by the syngas produced from gasification of municipal solid waste.

In the future, perspective of lower temperature SOFCs (e.g. around 600 °C), steam plants and organic Rankine cycles (ORCs) plants offer a better thermal coupling as bottoming cycles, for large and small power scales respectively. Indeed, at large scales, combined SOFC and steam cycles were investigated in Ref. [18], while in Refs. [4,19] an integrated system consisting of an SOFC and steam plant fired by natural gas was presented and computational results show a thermal efficiency of 62%. Later the performances of the same system integrated with a gasification plant were investigated in Ref. [20]. At smaller scales (less than about 500 kW), the performances of such plants are significantly lower due to the decrease in the steam turbine isentropic efficiency, which can be affected by blade corrosion due to moisture at turbine outlet.

SOFC–ORC systems were studied in Ref. [21] where an energetic performance analysis was presented, while in Ref. [22] three different systems were investigated for trigeneration applications. Organic Rankine cycle systems were investigated in Ref. [23] to recover the heat from a ship-onboard 250 kWe SOFC fueled by methanol. In Ref. [24] the performances of a 100 kWe SOFC–ORC system coupled with a gasification facility was carried out by means of a multi-objective optimization. Their results show that efficiencies in the range of 54–56% can be achieved by wisely selecting the organic fluid properties.

Low temperature SOFCs seem to be far from being produced and at present the operating temperatures are in the range of 750–850 °C, which make current SOFCs more suitable to be thermally coupled with high temperatures cycles such as gas cycles. Nevertheless in an SOFC–GT power plant, the gas turbine can only partially recover the waste heat from the SOFC, and the exhaust gases from the gas turbine still present relatively high temperatures. For this reason, the study on SOFC-based power plants has been focused on SOFC–GT-based systems to investigate further improvements. In this perspective one can either improve the primary bottoming gas cycle or add a second one to recover the waste heat from the gas turbine. The former approach is used in the present study while the latter was considered in Ref. [25] where an SOFC–GT power plant was coupled with an ORC cycle to further increase the efficiency of the overall plant by using liquefied natural gas (LNG) as heat sink. Such triple section plant coupled with LNG at −161 °C as cooling fluid at the condenser allows achieving an electrical efficiency above 67%. However, adding a third plant after the gas turbine and the difficulty of managing such low temperature cooling fluid will also affect the cost of the entire plant and in turn the cost of produced electricity will increase. This is especially true when the overall system is designed for powers of hundreds of kW which cannot benefit by the components cost reduction related to a size scale-up.

2. Methodology

2.1. Software

Thermodynamic and exergy analyses have been carried out by means of Dynamic Network Analysis (DNA) which is a text-based simulation tool for energy systems analysis, written in FORTRAN language, see Ref. [26].

It is the current result of an ongoing research at the Department of Mechanical Engineering, Technical University of Denmark, started with a Master Thesis work by Ref. [27] in 1989 and since then it has been developed to be generally applicable to thermal energy systems.

A component library has been developed with models for a large number of different devices existing within energy systems. Besides general components (e.g. heat exchangers, turbo machinery, valves, controllers and utility devices), the user may also select more specialized components and implement new ones.

Finally the commercial software EES (Engineering Equation Solver) has been used to carry out the thermo-economic analysis. EES also includes parametric tables that allow the user to compare a large number of variables at a time [28]; feature that is extremely convenient to investigate the effect of different SOFC investment costs and woodchips prices in the cost of the generated electricity, as reported in Sub-section 6.3.

2.2. Gasifier model

The gasification plant used in this study is based on the two-stage Viking gasifier [1], which was built in 2002 at Risø-Technical University of Denmark. Its model has been presented in detail in Ref. [20], main features of which are repeated here for the sake of clarification. The pyrolysis and gasification processes are divided into two separate reactors, as shown for instance in Fig. 1. In Ref. [29] it was reported that the two-stage gasification process offers some interesting features such as low tar content in produced syngas (<5 mg/Nm^3), stable unmanned operation, high cold gas efficiency (>95%), low environmental impact (clean condensate, high carbon conversion ratio) and operating pressure at ambient conditions. In the same study a schematic diagram of the Viking gasification plant is also presented. In this work the words “biogas” and “syngas” equally refer to the gas produced via gasification of ligno-cellulosic biomass.

Pyrolysis process requires a certain amount of moisture (around 10%) inside the fuel; therefore superheated steam makes gasification process applicable for fuel with high humidity content (up to 60%). Since produced steam from the dryer is used as the heat carrier for the pyrolysis process, the two-stage gasification process is applicable for high moisture content fuels. This makes woodchips ideal for this process. Steam and air, as a gasification agents, are used to lower the operating temperature and increase the process rate and hydrogen (H_2) content. The syngas produced in such gasifier is suitable to feed an SOFC, as reported in Ref. [2], although its LHV (Lower Heating Value) is quite low, being 5.54 MJ/kg which

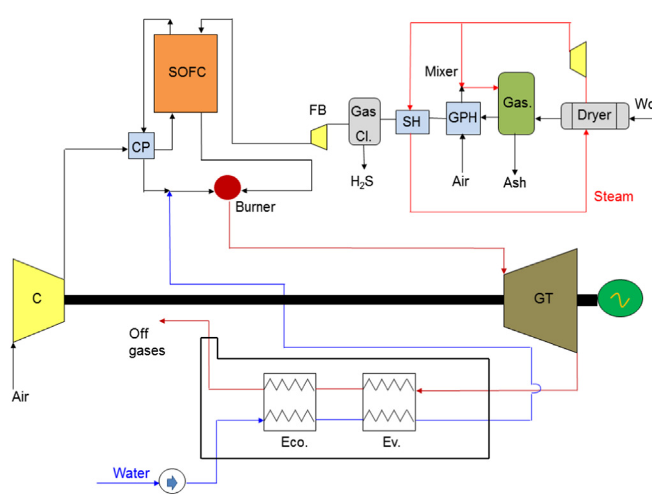

Fig. 1. IGSST: layout 1 without supplementary firing.