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Plant characteristics of an integrated solid oxide fuel cell cycle and a steam cycle

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ABSTRACT

Plant characteristics of a system containing a solid oxide fuel cell (SOFC) cycle on the top of a Rankine cycle were investigated. A desulfurization reactor removes the sulfur content in the fuel, while a pre-reformer broke down the heavier hydrocarbons in an adiabatic steam reformer (ASR). The pre-treated fuel then entered to the anode side of the SOFC. The remaining fuels after the SOFC stacks entered a catalytic burner for further combusting. The burned gases from the burner were then used to produce steam for the Rankine cycle in a heat recovery steam generator (HRSG). The remaining energy of the off-gases was recycled back to the topping cycle for further utilization. Several parameter studies were carried out to investigate the sensitivity of the suggested plant. It was shown that the operation temperature of the desulfurization and the pre-reformer had no effect on the plant efficiency, which was also true when decreasing the anode temperature. However, increasing the cathode temperature had a significant effect on the plant efficiency. In addition, decreasing the SOFC utilization factor from 0.8 to 0.7, increases the plant efficiency by about 6%. An optimal plant efficiency of about 71% was achieved by optimizing the plant.

1. Introduction

The solid oxide fuel cell is an electrochemical reactor currently under development by some companies for power and heat generation application. Depending on the type of the electrolyte, they are operating at temperature levels of more than about 750 °C up to 1000 °C. The lower temperature alternative is now being developed for market entry during this decade, e.g. Topsoe fuel cells. Due to material complications in the BoP (balance of plant) components many companies are trying to find new materials for the SOFC cells to decrease their operating temperature. Temperatures of about 650 °C have also been mentioned.

The biggest advantage of the SOFC in comparison with other types of fuel cells may be in its flexibility in using different types of fuels such as biogas, natural gas, methanol, ethanol, DME (Di-Methyl Ethyl), diesel, and the like. However, in planar SOFCs one needs to pre-process most kind of fuels in order to break down the heavier hydrocarbons because they cannot be reformed in the SOFC cells. Such a pre-reforming process can be done in a reactor. Other harmful particulates must also be removed, e.g., sulfur, in a separate reactor unit, e.g., desulfurization unit. The operating temperatures of these reactors differ from each other and are indicated by the respective reactor manufacturers. In other words, the fuel must be pre-processed before entering the anode side of the SOFC cells.

SOFC-based power plants have been studied for a while and some companies, such as Wärtsilä, are trying to realize such a system for CHP (combined heat and power) applications; see, e.g., [1]. The SOFC is also combined with CC (combined cycles) in the literature to achieve ultra high electrical efficiencies; see [2] and [3]. Due to the current operating temperature of the SOFC stacks (more than about 750 °C), hybrid SOFC and GT (gas turbine) systems have also been studied extensively in the literature, e.g. in [4] for CHP and in [5] with internal biomass gasification. The characterization, quantification and optimization of hybrid SOFC–GT systems have been studied by, e.g., [6] and [7]. The dynamics and control concept of a pressurized SOFC–GT hybrid system have also been studied, such as in [8]. In [9] modeling results are compared with measured data for a 220 kW hybrid SOFC–GT power plant. Details of the design, dynamics, control and start-up of such hybrid power plants are studied in [10]. Part-load characteristics of a SOFC–micro GT were also studied in [11].

While hybrid SOFC–GT plants have been extensively studied by many researchers, the investigations on combined SOFC and ST (steam turbine) are very limited, see, e.g., [12]. In addition, the SOFC manufactures are trying to decrease the operating temperature of the SOFC stacks, which means that the combination of a SOFC–ST hybrid system would be more attractive than SOFC–GT systems. By decreasing the operating temperature, the material cost for the

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SOFC stacks will decrease, and many problems associated with the BoP components will be diminished.

In hybrid SOFC–GT plants the SOFC stacks must be pressurized in an extremely large vessel (depending on the size of the plant which is usually in mega watt classes). Such a practical problem will be diminished in hybrid SOFC–ST systems because the stacks will work under atmospheric pressure.

Fuel pre-reforming can be done in different reactors, such as ASR, CPO (catalytic partial oxidation) and ATR (auto thermal reactor). In this study, the ASR type of reactor was chosen for the pre-reforming process. It shall be mentioned that an ASR reactor has a disadvantage, which is that it needs superheated steam during start-up (depending on the operating temperature of the reactor, i.e., 450 °C). As is well known, it is an extremely energy consuming process which must be provided through an external superheater maker. However, during normal operation steam is available after the anode side of the SOFC stacks, which can be recycled into the system. In a SOFC–ST combined plant the Rankine cycle can be started up first to provide the steam for the SOFC cycle (topping cycle).

In the bottoming Rankine cycle, a simple single pressure level was used in this study. In addition, the off-gases from the HRSG were used to preheat the incoming air in the SOFC stacks. Such a treatment is called hybrid recuperation, which was shown to increase plant efficiency by a few point percentages depending on the temperature of the off-gases in the chimney [13]. Plant characteristics of the proposed system configuration were then investigated to study the effect of the operating temperature of the desulfurization unit and pre-reformer reactor on plant efficiency and output power. Furthermore, the effect of anode and cathode inlet temperatures on the plant performance was also studied. In addition, the operating temperature of the SOFC and utilization factor was varied to study their effect on the plant performances. All the parameters studies here are within the available data for the unit considered and are novel in terms of designing new plants with very high efficiencies.

It should be noted that the system presented here was studied thermodynamically and the objective of this study was not to present or discuss associated costs. The current investigation is regarded as a continuation study presented in [13]. Note that the presented system configuration in this study differs from the one presented in the previous study in terms of fuel recycling in the SOFC plant.

2. Methodology

The results of this paper were obtained using the simulation tool DNA (Dynamic Network Analysis), see [14], which is a simulation tool for energy system analysis. It is the present result of an ongoing development at the Department of Mechanical Engineering, Technical University of Denmark, which began with a Master's Thesis work in [15]. Since then the program has been developed to be generally applicable covering unique features and hence supplementing other simulation programs.

Some of the important features are the following:

- Simulation of both steady state (algebraic equations) and dynamic models (differential equations)
- Handling of discontinuities in dynamic equations
- Use of a sparse-matrix-based simultaneous solver for algebraic equations
- No causality implied on the model input, i.e., no restriction of the choice of inputs and outputs
- Medium compositions can be variables
- Models of thermodynamic states, transport variables and radiative properties for relevant fluids, e.g., steam, ideal gases and refrigerants
- Features for modeling solid fuels of arbitrary components

The component library includes models of heat exchangers, burners, gasifiers, turbo machinery, dryers, decanters, energy storages, engines, valves, controllers and more specialized components and utility components. The user may also implement additional components.

In short, the procedure is:

- Write all the equations for each component
- Set the boundary conditions such ambient temperature, ambient pressure, etc.
- Provide the set-points such operational temperature, pinch temperature, pressure drops, etc.
- Provide some guess values for the unknown parameters
- Solve the set of equations by iteration.
- The iteration is stopped when the error conditions (about 10^{-16}) are fulfilled.

In DNA, the physical model is formulated by connecting the relevant component models through nodes and by including operating conditions for the complete system. The physical model is converted into a set of mathematical equations to be solved numerically. The mathematical equations include mass and energy conservation for all components and nodes as well as relations for thermodynamic properties of the fluids involved. In addition, the components include a number of constitutive equations representing their physical properties, e.g., heat transfer coefficients for heat exchangers and isentropic efficiencies for compressors and turbines.

During the development of DNA, the four key terms portability, robustness, efficiency, and flexibility were kept in mind as the important features for making a generally applicable tool for energy system studies. In recent years, DNA has been introduced into education at the department and has been applied to numerous different types of systems. The program is written in FORTRAN.

2.1. Modeling of SOFC

The SOFC model used in this investigation is based on the planar type developed by DTU-Risø and TOPSØE Fuel Cell. The model was calibrated against experimental data in the range of 650 °C–800 °C (SOFC operational temperature) as described in [16]. The operational voltage (E_{FC}) was found to be

$$E_{\mathrm{FC}} = E_{\mathrm{Nernst}} - \Delta E_{\mathrm{act}} - \Delta E_{\mathrm{ohm}} - \Delta E_{\mathrm{conc}} - \Delta E_{\mathrm{offset}}, \quad (1)$$

where E_{Nernst}, ΔE_{act}, ΔE_{ohm}, ΔE_{conc} and $\Delta E_{\mathrm{offset}}$ are the Nernst ideal reversible voltage, activation polarization, ohmic polarization, concentration polarization and the offset polarization respectively. The activation polarization can be evaluated from the Butler–Volmer equation (see [17]). The activation polarization is isolated from other polarizations to determine the charge transfer coefficients and exchange current density from the experiment by the curve fitting technique. It follows that

$$\Delta E_{\mathrm{act}} = \frac{RT}{(0.001698T - 1.254)F} \sinh^{-1}\left[\frac{i_d}{2\left(13.087T - 1.096\times 10^4\right)}\right], \quad (2)$$

where R, T, F and i_d are the universal gas constant, operating temperature, Faraday constant and current density respectively.