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Research Paper

Comparative evaluation of viable options for combining a gas turbine and a solid oxide fuel cell for high performance

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HIGHLIGHTS

- Options for combining SOFC, GT and ST for a very high efficiency are compared.
- The triple combined cycle is generally more efficient than the dual combined cycle.
- With optimal designs, the triple combined cycle provides at least 3% points higher efficiency.
- The optimal efficiencies of the recuperated and non-recuperated systems are almost the same.

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ABSTRACT

We investigated several viable options for combining a gas turbine and a solid oxide fuel cell to achieve very high power generation efficiency. The backbone of the combination is the solid oxide fuel cell/gas turbine dual combined cycle and the solid oxide fuel cell/gas and steam turbine triple combined cycle. The object of analysis is central power plants on the order of hundreds of MW. The gas turbine parameters were taken from an F-class commercial engine, and state-of-the-art parameters of the SOFC were used. In each of the two cycles, the use of a recuperative heat exchanger was considered as a design option. The performance of the combined cycles using the commercial gas turbine was estimated in the first part of the study, and optimal design performance was predicted in the second part assuming a completely revised gas turbine design. Overall, the triple combined cycle was expected to provide better efficiency than the dual combined cycle. Its optimal efficiency was predicted to be over 75%, which is about three percentage points higher than that of the dual combined cycle. The optimal efficiencies of the recuperated and non-recuperated systems were almost the same, which provides flexibility in selecting a system configuration.

1. Introduction

Various research activities are being performed on renewable power generation methods, such as wind, solar, tidal, and geothermal power generation [1]. These methods emit less greenhouse gas than conventional technologies that use fossil fuels and help reduce global warming [2]. Another method for reducing global warming is improving the efficiency of power plants, which also helps to conserve natural resources.

Many studies have been done to enhance the efficiency of conventional power plants recently and have led to considerable accomplishments. The highest efficiency currently available is over 60% (based on a lower heating value) using a gas turbine/steam turbine combined cycle (GTCC) with natural gas as fuel [3,4]. It is expected that further efficiency improvement up to at least 65% is quite possible with the GTCC. The emergence of shale gas and efforts to use other by-product gases such as bio-gas [5,6] have made the future of the GTCC promising.

Another important future power source is the fuel cell. Solid oxide fuel cells (SOFCs) in particular are the most promising type of fuel cell for electric power plant applications [7]. Depending on the fuel cell configuration, the efficiency is currently 45–60% [8,9] and is usually independent of the power generation capacity. Efficiency

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as high as 60% is possible with a 10-kW SOFC [9]. The power generation capacity of current SOFCs is generally limited to less than 1 MW, and the realization of 100-MW SOFCs is a long-term goal [10].

SOFCs operate at the highest temperature (600–1000°C) among various fuel cells [11] and have many advantages that include fuel flexibility, low emissions, high-quality exhaust gases, and no need for a catalyst due to the high operating temperature [12]. The biggest advantage of SOFCs is their potential for combination with other schemes for high efficiency (usually with heat engines owing to the high operating temperature).

Diverse combined cycle configurations have been suggested [13,14]. The most studied layout is the hybrid system, which combines an SOFC with a gas turbine. Various studies have been performed on the impact of the operating pressure of the SOFC [15], the possibility of using a commercial gas turbine [16], and the influence of gas turbine design parameters on system performance [17,18], among others. There have also been several proof-of-concept studies for hybrid systems driven by companies seeking commercial developments [19–21]. Another design option is to combine the SOFC with the GTCC. In such a system, electric power is produced by the SOFC, a gas turbine, and a steam turbine at the same time. The necessity and feasibility of developing a triple combined cycle were reported recently [22], and the possibility of achieving over 70% efficiency was shown in a recent theoretical study [23].

There are several different options for the combination of an SOFC and a gas turbine as summaries in the last paragraph. The backbone of the combination is SOFC/GT and SOFC/GTCC. To guide development, a detailed theoretical comparative study of the two cycle layouts assuming consistent component technologies is required. This work is aimed to compare the performance of the two cycles using a systematic simulation with state-of-the-art technology assumptions. The design parameters are for central power plants rated for hundreds of MW. In each of the two cycles (SOFC/GT and SOFC/GTCC), the use of a recuperative heat exchanger was considered as a design option. Therefore, four cycle layouts were compared. The performance expectation of the cycle design using a high-performance F-class commercial gas turbine was predicted. Then, the effect of varying gas turbine design parameters was investigated, such as the turbine inlet temperature and the pressure ratio (representing totally new gas turbine designs). Optimal design conditions are also suggested.

2. Cycle layout

The cycle layouts are shown in Fig. 1. The simple combination between an SOFC and a GT (SOFC/GT dual combined cycle) is shown in the inner box, and the triple combined cycle (SOFC/GTCC) is the entire system inside the outer box. The dual combined cycle considered is a pressurized SOFC/GT hybrid system similar to that in a previous study [15]. In most previous hybrid system studies, small gas turbines rated for hundreds of kW were investigated [15–18]. However, we adopted a larger 200 MW class gas turbine to predict the performance of central power stations.

The SOFC sub-system is composed of a cell stack and auxiliary equipment such as a preheater, reformer, and afterburner. The gas turbine compressor supplies compressed air to the SOFC. The raw fuel is natural gas, which is converted to a hydrogen-rich fuel in the reformer. The cell stack supplies the heat required at the reformer via thermal contact. Some of the SOFC anode gas is recirculated to the reformer to supply steam required for the reforming reaction. Some fuel remains unreacted after the cell reaction and is oxidized at the afterburner. In cases where the required turbine inlet temperature of the gas turbine is higher than the naturally obtainable temperature after combustion at the afterburner, some extra fuel (natural gas) can be supplied to the combustor. The exit gas from the turbine is exhausted to the ambient environment in the simple layout of the non-recuperated system. In the recuperated system, the compressor exit air is heated by the recuperator (see the dotted line in the figure). The purpose of the recuperator is further enhancement of the system efficiency by decreasing the fuel supply.

The SOFC/GTCC triple combined cycle includes a steam turbine. The integration between the gas turbine and the SOFC is exactly the same as in the SOFC/GT system. The heat recovery steam generator (HRSG) extracts the heat of the GT exhaust gas and produces steam that drives the steam turbine. The optional use of the recuperator is also the same as in the SOFC/GT cycle.

3. Modeling

3.1. SOFC

ASPEN HYSYS version 7.3 [24] was used for the simulation. Standard ambient conditions were adopted (ISO conditions: 15°C,

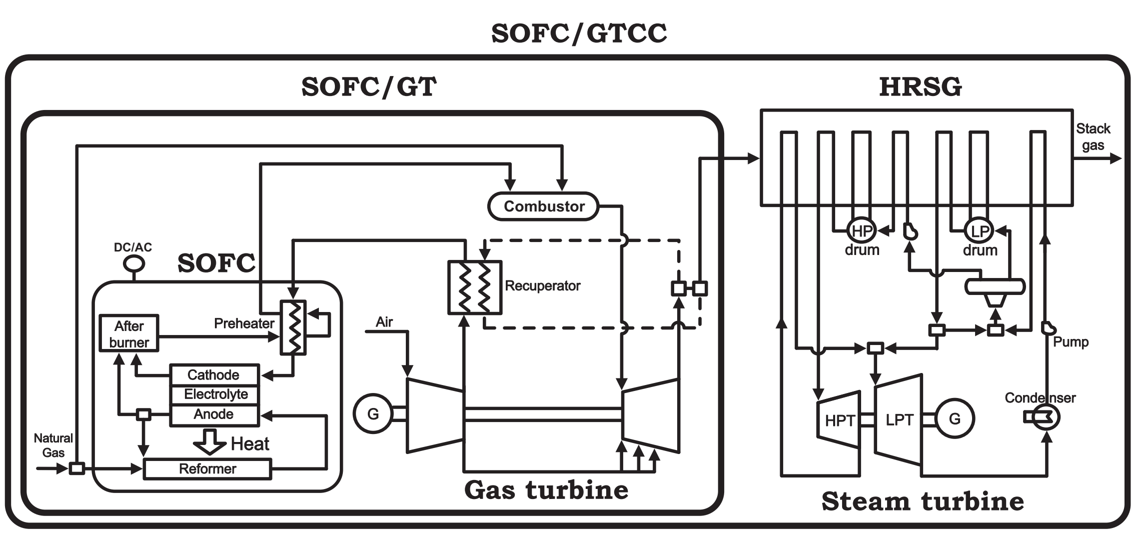

Fig. 1. Layouts of the dual and triple combined cycles.