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Effect of operating parameters on a hybrid system of intermediate-temperature solid oxide fuel cell and gas turbine

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ABSTRACT

In this work, detailed mathematical models of a hybrid system of an IT-SOFC (intermediate-temperature solid oxide fuel cell) and a GT (gas turbine) that is fueled by gasified biomass gas are built. Under the constraints of the working temperature of the fuel cell, mean axial temperature gradient, compressor surge, and turbine inlet temperature, the effects of operating parameters on the hybrid system are investigated mainly including RS (rotational speed), F/A (fuel/air) ratio, and S/C (steam/carbon) ratio. The electrical efficiency is 59.24% under the design condition. The power and efficiency of the system both decrease as the RS increases, with the latter decreasing from 60.95% to 49.08%. If the RS is too low, the system operation goes beyond the safety zone. In this situation, both the fuel cell and the turbine may be subjected to excess temperatures, and the compressor may easily surge. The efficiency increases from 56.5% to 61.34% with increasing F/A ratio, but an extremely high F/A ratio can cause the turbine to suffer from excess temperature. The efficiency decreases from 61.12% to 56.8% with increasing S/C ratio. The following two conclusions are drawn. First, the F/A ratio has the greatest influence on the performance of the hybrid system, i.e., its adjustment can effectively change the load in a wide range. Second, the RS and S/C ratio are suitable for load adjustment in a narrow range.

1. Introduction

IT-SOFCs (intermediate-temperature solid oxide fuel cells) can operate between 873 K and 1073 K. They can not only maintain the advantages of conventional HT-SOFCs (high-temperature solid oxide fuel cells, 1073 K–1273 K), such as high efficiency and zero emission, but also decrease starting temperature and time, and improve stability performance and lifetime. Moreover, the use of stainless steel as connection material for IT-SOFCs further reduces manufacturing costs and thus boosts the commercialization feasibility of these fuel cells [1,2]. Studies on electrode materials and mathematic models for IT-SOFCs have been extensively carried out [3–7], thereby providing a fundamental basis for their wide application. Bedogni et al. [8–10] conducted a theory analysis and experimental tests on the electrochemical performance, distribution of temperature field, and durability of fuel cells. Their work serves as a reference for improving the electrical performance of IT-SOFCs. At present, the applied research on IT-SOFCs mainly focuses on vehicles [2,11,12] and power stations [13–15]. Zhu et al. [13] built an IT-SOFC/GT model to carry out an energy balance analysis and exergy analysis and provided reference data for the application of IT-SOFCs in small-scale power stations. Campanari et al. [14] evaluated the performance of an IT-SOFC on the basis of the gasification combined cycle fueled by coal gas. The system consisted of two steam shift reactors, a methanation reactor, and CO_2 capture and other equipment; its electrical efficiency can reach up to 51.6%. Paepe et al. [15] studied the performance of a two-stage hybrid system consisting of an HT-SOFC and an IT-SOFC fueled by CH_4 and analyzed the effect of the operation temperature, pressure, and current density of the fuel cells.

Several researchers have carried out studies on integrated systems based on biomass gasification and HT-SOFC/GT [16–19]. These works provide the research foundation for the utilization of biomass gas in hybrid systems. Integrated systems can overcome biomass dispersion and transport challenges while satisfying the varied fuel requirements of SOFC/GT hybrid systems. In addition, integrated systems cover relatively small areas; thus, the investment cost is low [20,21]. However, because of their high complexity, the coordination control technologies of the integrated system are extremely difficult [22,23].

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As for the commercial development of hybrid systems integrated with HT-SOFCs, it remains limited by the high working temperature and by other factors, including difficult component matching, short system lifespan, and high generation cost. The aforementioned issues can be successfully overcome with the hybrid system consisting of an IT-SOFC and a micro GT. In addition to its high efficiency and low NO_X emission, the IT-SOFC/GT hybrid system is also adaptable to resources such as natural gas, coal gas, biomass gas, methanol, ethyl alcohol, and other hydrocarbons [14,24].

China has abundant biomass energy resources with great potential for commercial development. The IT-SOFC/GT hybrid system can utilize these biomass resources according to local conditions and form small-scale off-grid or grid-connected distributed power stations. Thus, this hybrid system shows high application potential [25].

Current research on the hybrid system fueled with biomass gas is mainly focused on system modeling [17,26], system integration and optimization design [19,27,28], effect of biomass fuel [29–31], selection of component operation parameters [32], etc. However, the hybrid system is a complicated system with various parameters, nonlinearity, strong thermodynamic coupling, and multiple objectives. It is thus essential to study the system performance and load change caused by varying operation parameters, such as fuel and air flows, fuel utilization, and RS.

Assuming a constant RS, Costamagna et al. [33–36] investigated the performance of the hybrid system using natural gas and discussed the effect of fuel and air flows, current density, and fuel utilization. However, they ignored the variation of air flow, compressor SM (surge margin), and FTG (fuel cell temperature gradient). Stiller et al. [37] studied the methods for safely operating a hybrid SOFC/GT system under part load and load change without considering the influence of SM and FTG on each RS. Diamantis et al. [32] studied the matching relation between GTs and fuel cells with consideration of system lifespan. They thus proposed two types of operating strategies used in the condition of constant fuel cell temperature or TIT (turbine inlet temperature).

At present, the studies on the safe operation of hybrid systems mainly focus on natural gas or HT-SOFCs. The effects of operation parameters such as FWT (fuel cell working temperature), SM, and TIT on system safety are serious because biomass gas has a lower heat value than natural gas. On the one hand, compressors easily surge because of extremely low TIT. On the other hand, system performance can easily decline because of extremely low FWT. Therefore, the effects of GT RS, fuel/air (F/A) ratio, and steam/carbon (S/C) ratio on the IT-SOFC/GT hybrid system fueled by biomass gas must be investigated with consideration of the constraints of SM, FWT, FTG, and TIT.

In the present work, detailed mathematic models of the hybrid IT-SOFC/GT system fueled by gasified biomass gas were built in MATLAB SIMULINK. Accordingly, the performance of the hybrid system under design and off-design conditions was analyzed. The operation parameters of RS, F/A ratio, and S/C ratio were modified to quantify the output and electrical efficiency of the system, with the constraints of FWT, FTG, SM, and TIT. The simulated results can benefit the design and application of IT-SOFC/GT hybrid systems fueled by biomass gas.

2. Mathematical models

2.1. IT-SOFC/GT hybrid system structure

An IT-SOFC/GT hybrid system mainly consists of an IT-SOFC, a GT, a catalytic combustor, a reformer, and a heat exchanger (Fig. 1). Biomass gas is heated and then mixed with steam before it enters the reformer. Then, the reformed gas enters the SOFC anode to trigger an electrochemical reaction. The air pressurized by the compressor is heated by the heat exchanger and then enters the SOFC cathode to provide O_2 for the electrochemical reaction. The exhaust gas from the SOFC anode contains incompletely reacted fuels, which will continue to be combusted in the catalytic combustor. The high-temperature gas enters the turbine to generate power. The exhaust gas from the turbine preheats the fuel and air and then heats the evaporator before being released into the atmosphere.

2.2. Mathematical models of IT-SOFC

A 2D anode-supported IT-SOFC model was introduced in the literature [6]; this model includes an electrochemical model and a thermodynamic model based on mass and energy balance equations. The electrochemical model describes the function relation between the fuel cell voltage, various polarization losses, and current density. These models consider the influence of reactant and product concentrations on the Nernst potential and the mass/heat transfer and diffusion limitations. On the basis of these two models, we form two assumptions: 1) zero leakage exists, and 2) only H_2 is involved in the electrochemical reaction, and the electrochemical reaction of CO is not considered. Fuel cell output voltage can be reduced because of irreversible losses caused by ohm, activation, and concentration [38]. Open-circuit voltage can be calculated with a Nernst equation, which describes the relationship between reversible electrochemical voltage, chemical substance concentration, and gas pressure. This phenomenon occurs on the boundary between electrodes and electrolyte. The equations for the anode-supported IT-SOFC model are listed in Table 1.

Ohm loss is caused by the movement of ions and electrons along the component resistance and contact resistance between cell components. The phenomenon is closely related to electrode material, geometrical property, and electronic conduction characteristics [6].

Activation polarization is the over-potential needed to overcome the activation energy of the electrochemical reaction on surfaces [24,38]. It is represented by the non-linear Butler–Volmer equation. The polarizations of the anode and cathode can be solved by the equations [6] in Table 1 because of the effect of the reactant and product concentrations on electrode/electrolyte interfaces.

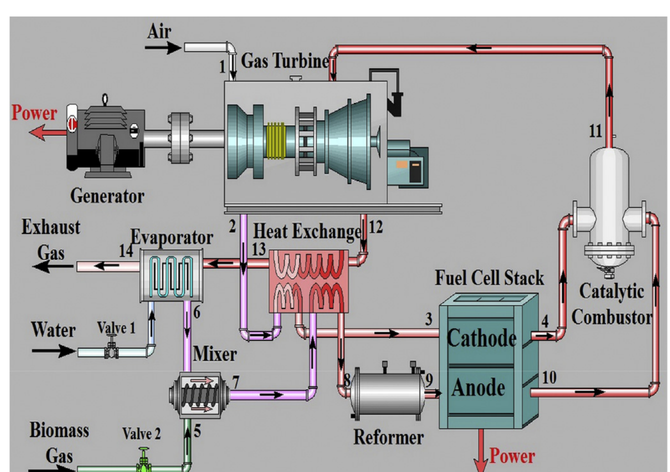

Fig. 1. Schematic of IT/SOFC-GT hybrid system.