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# Effect of gasified biomass fuel on load characteristics of an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system

*Xiaojing Lv* [a], *Chenghong Gu* [b], *Xing Liu* [a], *Yiwu Weng* [a,*]

[a] *Key Laboratory for Power Machinery and Engineering of Ministry of Education, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *Department of Electronic and Electrical Engineering, University of Bath, Bath, BA2 7AY, UK*

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ABSTRACT

This work uses the mathematical model of an intermediate-temperature solid oxide fuel cell and gas turbine (IT-SOFC/GT) hybrid system to study the effects of gasified biomass fuels on system load characteristics. The system performance is investigated by using four types of fuels in each adjusting mode. The relation between the fuel type and load adjusting mode is obtained for users and designers to select the appropriate fuel for reasonable operation modes. Results show that the hybrid system of 182.4 kW has a high electric efficiency of 60.78% by using wood chip gas (WCG). If cotton wood gas (CWG) and corn stalk gas (CSG) are used, both boundary values of steam to carbon ratio ($S/C_{bv}$) and system power are higher, but system efficiencies decrease to 57.36% and 57.87% respectively. In the designed three load adjusting modes, the system can reach maximum efficiency over 59% with four types of biomass gases. If high efficiency and a wide range of load adjustment are required, users can select Case B to use fuels like WCG and GSG. When higher efficiency and low load is expected, Case A is more desirable. With fuels like CWG and CSG, the system has good safety performance in Case C.



## Introduction

Solid oxide fuel cell and gas turbine (SOFC/GT) hybrid systems are thought to be the most attractive energy conversion systems in future energy markets because of high efficiency, low pollution, and fuel flexibility (such as natural gas, biomass gas) [1,2]. Biomass is rich and important renewable energy and it has the characteristics of low net $CO_2$ emission rate and $SO_2$ emission rate. For this reason, biomass fueled SOFC/GT hybrid systems are regarded as one of the most promising power generation equipment [3,4].

In recent years, some theoretical and experimental research has been carried out in the integrated systems based on biomass gasification and SOFC/GT systems [5–9]. These works mainly focus on system modeling [5,6], integration and optimization design [7,8], and selection and impact analysis of component operation parameters [9], providing the basis for utilizing biomass gas in hybrid systems. Unlike fossil fuels, the components and quality of biomass gas fuels are mainly affected by gasification process, process control parameters and raw materials [10]. In biomass gasification, fuel compositions depend on the gasification agent. For example, the concentrations of $H_2$, $CH_4$, CO, and $N_2$ vary greatly when oxygen, air, or steam is used as gasification agent [10,11].

* *Corresponding author*. Tel./fax: +86 21 3420 6342.
E-mail address: ywweng@sjtu.edu.cn (Y. Weng).

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However, the variation of fuel type (or composition) has a great impact on system performance. The main reasons are as follows: 1) fuel cell electrochemical reaction is mainly affected by temperature and fuel composition, and the composition variation will cause a large fluctuation in fuel cell performance [10]; 2) Reforming reactions in reformers are reversible thermodynamic equilibrium [12], which will occur automatically due to the changes in fuel compositions; 3) The combined effect of the previous two factors can cause changes in the thermodynamic performance of other components, and the design and layout of hybrid systems.

Magistri et al. [13] showed that when the designed fuel $CH_4$ was completely replaced by synthetic gas and biomass gas, system efficiency decreased from 61.7% to 53.5% and 49.2% respectively, and the selection of parameters for gas turbines and injector should also be changed. Santin et al. [14,15] investigated the SOFC/GT hybrid system with two liquid fuels (methanol and kerosene) and developed four layouts by considering different fuel processing strategies. They also conducted thermodynamic and investment analysis for the hybrid system. Van herle et al. [16] studied a process flow model of an SOFC system supplied with sewage biogas. For partial oxidation of biogas or pure hydrogen feeding, electric efficiency dropped under 43%. Zabihian et al. [10] compared the output power, specific work, and efficiency of the SOFC/GT hybrid system fueled with methane and various types of biomasses. Zabihian et al. [17,18] further investigated the effect of fuel composition on the hybrid system performance from the perspective of inlet fuel energy content. Sucipta et al. [11] found that the change of $H_2O$ and $H_2$ concentration in fuel from 0% to 50% slightly reduced the efficiency of hybrid systems. An increase of CO concentration produced similar effects as that of $CO_2$ and resulted in a decreasing efficiency of both SOFC module and hybrid system significantly. Sucipta et al. [19] analyzed the electric performance of a biomass SOFC/GT hybrid system by comparing typical air, oxygen, and steam-blown biomass gasification processes. Results showed that the electric efficiencies of the three biomass fuel cases were lower than that of pure methane case. Rokni et al. [20] showed that the electric efficiency of a hybrid SOFC-Stirling plant was 60%. With a slight decrease in fuel utilization factor, the power of Stirling engine was found to increase. By lowering SOFC working temperature, the plant efficiency decreased for all fuels except ammonia. Similar research could be found in Refs. [21–24].

All previous work has identified the change of fuel type and composition to be important factors for a hybrid system at designed condition. However, the hybrid system is a strongly-coupled thermoelectric system. With different types of inlet fuels, there are some important issues will appear when the system operates under variable conditions due to the constraints of component matching and characteristic parameters. For example, the issues could be the influence of change in fuel type on variable load operation and safety issues of a hybrid system, and the coupling relationship between different types of fuels and various operations. But, research in this field is very limited. Weng [25] studied the performance of a hybrid system using $CH_4$, $H_2$ and ethanol as fuel. It was found that when the hybrid system operated with $H_2$, the net power output at the design point decreased to 70% of the $CH_4$, while the design net efficiency dropped to 55%. Similar to $H_2$, the net output power of the ethanol-fueled system fell below 88%.

Based on the previous research, this work studies the operating characteristics of the main components (such as fuel cell, gas turbine, and reformer) of a hybrid system and its variable load characteristics under design and off-design conditions, when the system is fueled with different types of gasified gases. Then, the matching relationships between load adjusting mode and fuel type are obtained by analysis and comparison. The results are very beneficial for designers and users to select the most appropriate fuels for reasonable operation of a hybrid system.

## IT-SOFC/GT calculating method and parameter selection

### *IT-SOFC/GT hybrid system structure*

A schematic of the IT-SOFC/GT hybrid system is shown in Fig. 1, which mainly includes IT-SOFC, single-shaft GT, external reformer, catalytic combustor (CC), fuel compressor, water syringe pump, generator, and other components. To avoid carbon deposition, water is added for maintaining the ratio of steam to carbon [16,26] by adjusting valve 1. To prevent seal and vibration caused by the pressure difference between anode and cathode in the fuel cell [27], biomass gas needs to be compressed by a fuel compressor before entering the fuel cell for electrochemical reaction, which is adjusted by valve 2. The air flow is controlled by GT adjustment system, and the rotational speed of GT is controlled by generator equipment. Air pressurized by the compressor is heated by heat exchangers (HE) 1 and 2, which then enters the SOFC cathode to provide $O_2$ for electrochemical reaction. Water is first heated in the evaporator to be converted into steam and then mixed with biomass gas in the mixer. The mixed gas enters the reformer after being heated by HE 1. Reformed gas enters the anode of the fuel cell to provide $H_2$. The unreacted fuel from the SOFC anode will be completely combusted in the CC. High-temperature gas enters the turbine to generate power after heating air. The exhaust gas of the turbine preheats fuel and air, and then heats the evaporator before being released into the atmosphere.

### *IT-SOFC/GT hybrid system modeling*

The mathematical model of the IT-SOFC/GT established in this study was described in detail in the previous literature [28,29]. This model has been partially experimentally verified [36–38] and fully theoretically verified [25,30,32,36–38]. In order to provide a better understanding the established mathematical model, we briefly introduced the model development through a series of important equations illustrated in Appendix A. The modeling approach, mathematical formula, specific geometric parameters, physical parameters, and operating conditions can be found in the literature [28,29].

In this paper, the anode-supported IT-SOFC (873–1073 K) developed by Aguiar [30] is used to fit into the hybrid system, where the parameters of electrodes and electrolyte are from experimental results and whose investigation result has been