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Research Paper

# Control strategy design for a SOFC-GT hybrid system equipped with anode and cathode recirculation ejectors

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## HIGHLIGHTS

- A control system of a SOFC-GT system with anode and cathode ejectors is designed.
- Six control loops are implemented to prevent unsuitable conditions.
- Control loops for anode and cathode inlet temperature are necessary.
- A compressor/turbine bypass valve is introduced to control TIT.
- Control system 1 is effective and appropriate.

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## ABSTRACT

The ejectors equipped for anode and cathode recirculation loops are more reliable and low-cost in maintenance than blowers in a solid oxide fuel cell-gas turbine hybrid system. However, an effective control system is one of the technical challenges associated with the development of the hybrid system. In present work, a novel control strategy was designed to restrict the hybrid system equipped with anode and cathode recirculation ejectors to a safe and feasible zone. Six control loops were carried out to control the vital parameters including power, rotation speed, fuel utilization, anode and cathode inlet temperature, and turbine inlet temperature. At the same time, the performance of another control system without anode inlet temperature control loop was also investigated. A comparison results of the two control systems reveal that both anode and cathode inlet temperature loops are necessary. If there is no anode inlet temperature control loop, the system efficiency decreases by 0.18%, the fuel cell inlet temperature differences between anode and cathode increases by 9 K and the compressor surge margin decreases by 1.8% at 95% system load. It not only causes a little reduction in efficiency but also may cause some latent dangers of the hybrid system at a part load condition. Consequently, the control system with all six control loops is effective and appropriate.



## 1. Introduction

Fossil fuels will continue to supply the vast majority of the world's energy consumption in the next decades, and will contribute about 78% of the total energy consumption [1]. However, utilization of the fossil fuels brings the issues of environment and energy [2–4]. The solid oxide fuel cell-gas turbine (SOFC-GT) hybrid system is an advance power generation cycle with high efficiency as well as ultra-low pollutions, and is regarded as a promising solution to the problems of fossil fuels consumption [5–9]. Moreover, the anode and cathode recirculation loops are performed by introducing ejectors instead of blowers to avoid carbon deposition, as well as to preheat the fuel cell inlet gas. Because it is without any rotating parts, the ejector is more reliable and low-cost in maintenance than high temperature blower [10,11].

Nevertheless, one of the technical challenges associated with the development and commercialization of hybrid system is to implement an effective control system to restrict the hybrid system to a feasible zone at different operating conditions. Especially during load variation, a feasible control system not only can keep high efficiency but also should avoid dangers of key components, such as great thermal stress, carbon deposition, excessive temperature, and compressor surge [5,12]. In addition, another key consideration of designing a feasible control system is the highly coupled hybrid system and the huge differences between the response times of fuel cell and gas turbine [13].

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**Nomenclature**

| | |
|---|---|
| SOFC | solid oxide fuel cell |
| CTFR | current to fuel flow ratio |
| GT | gas turbine |
| $F$ | Faradays constant |
| FU | fuel utilization |
| $G$ | Reduced flow rate |
| HE | heat exchange |
| $\bar{I}$ | average current density |
| INTC | interconnector |
| $L$ | fuel cell length |
| $m$ | mass flow rate |
| $n$ | molar flow rate, rotation speed |
| NETL | National Energy Technology Laboratory |
| $p$ | pressure |
| $P$ | power |
| PEN | positive-electrode/electrolyte/negative electrode |
| PID | proportion–integration–differentiation |
| RHE | reform heat exchange |
| $SM$ | surge margin |
| SOFC-GT | solid oxide fuel cell-gas turbine |
| STCR | steam-to-carbon ratio |
| $T$ | temperature |
| TIT | turbine inlet temperature |
| $U$ | voltage |
| $W$ | fuel cell width |
| $x$ | molar fraction |
| $\pi$ | compression ratio |

*Subscripts*

| | |
|---|---|
| 1 | compressor inlet |
| *a* | assistant fuel |
| *air* | bypass air |
| *an* | anode |
| *by* | bypass valve |
| *ca* | cathode |
| *f* | fuel |
| *gt* | gas turbine |
| *p* | primary fuel |
| *r* | recirculation |
| *s* | compressor surge point |
| *sofc* | solid oxide fuel cell |
| *SP* | set point |

*Superscripts*

| | |
|---|---|
| *in* | inlet of anode and cathode |

In the last few years, several authors have designed different control systems for different configurations of SOFC-GT hybrid systems. Ferrari et al. [5,14] first investigated the transients of a hybrid system with an anode recirculation ejector, then implemented a control system with five controllers for the hybrid system. A bypass valve was introduced to solve the huge response-time differences between solid oxide fuel cell (SOFC) and gas turbine (GT). The bypass valve fractional opening was kept at 0.05 by regulating the power sharing coefficient between SOFC and GT. In the thermal control system, the SOFC average temperature was controlled by adjusting the rotation speed set point. Wu et al. [15] also designed a control strategy with three control systems for a hybrid system with an anode recirculation ejector which included thermal control, power control, and fuel utilization (FU) control. The turbine inlet temperature (TIT) and SOFC operating temperature were controlled by a decoupling controller adjusting the fuel flow rate and air flow rate in the thermal control system. Stiller et al. [16] developed a control system for a hybrid system with an anode recirculation ejector. The power, FU, air flow rate, and mean SOFC temperature were controlled in the control system. The mean SOFC temperature was associated with the fuel outlet temperature through a characteristic line of power, ambient pressure and temperature. Mueller et al. [17] designed a control system with six controllers for a 100 MW-class SOFC-GT hybrid system

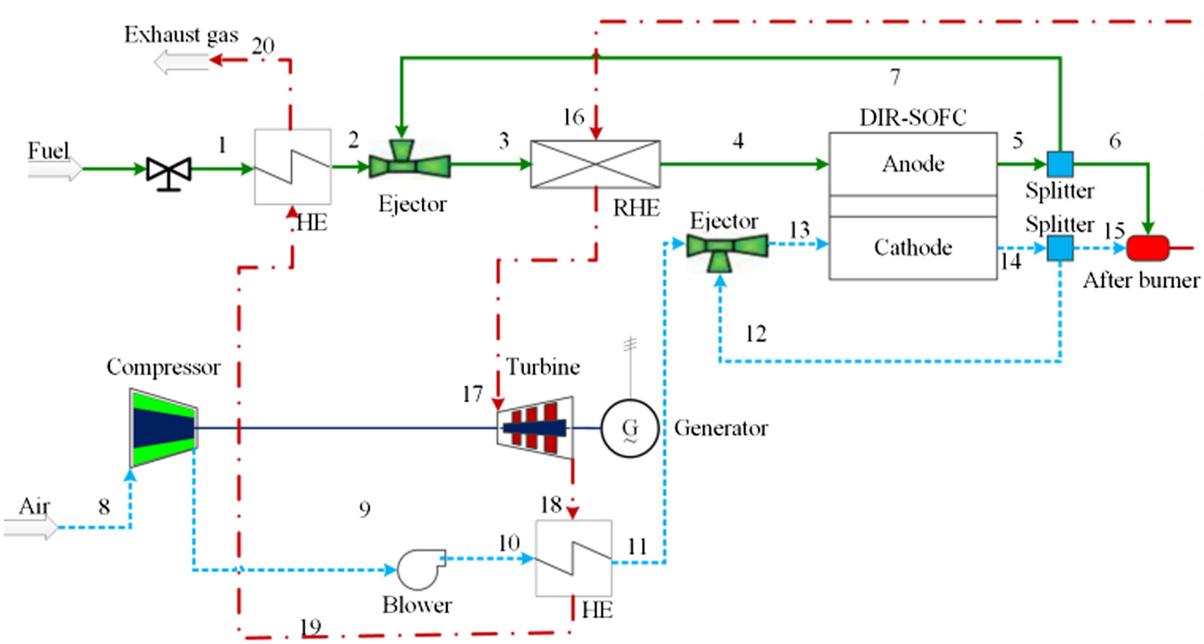


**Fig. 1.** The integration scheme of the SOFC-GT system.