Integrating a Gas Turbine System and a Solid Oxide Steam Electrolyzer for Hydrogen Production

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ABSTRACT

In this paper, the performance of a gas turbine (GT) system coupled with a flameless boiler for steam generation for hydrogen production in a solid oxide steam electrolyzer (SOSE), is evaluated. In this design, the GT exhaust gases are conducted to the flameless boiler in which diluted and preheated exhaust gases are applied as an oxidizer in this process. By using a small amount of fuel in the flameless boiler, the hybrid system is enabled to produce the required steam for the SOSE process. The whole generated electrical power by GT is employed in SOSE and produces hydrogen. The effects of fuel flow rate, turbine inlet temperature (TIT), steam temperature, and electrode characteristics on the hybrid system's performance are assessed. The results indicate that at the constant electrical power in the GT system, when steam temperature increases, the overall SOSE potential decreases. Consequently, the current of the SOSE enhances, resulting in the enhancement of the overall hydrogen production in high steam temperatures. The presented analysis in this paper can perform more analyses to achieve an insightful understanding of green hydrogen production using hybrid systems.

Keywords: Gas Turbine, Flameless combustion, Solid Oxide Steam Electrolyzer, Hydrogen

1 INTRODUCTION

Hydrogen fuel will play a crucial role in the world's energy mix in the future [1]. The main reason for that is attributed to fossil fuel depletion and environmental concerns. Hence, developing efficient and environmentally-friendly hydrogen production technologies has garnered attention to obtain a prosperous hydrogen economy [2]. In the electrochemical electrolysis process, electricity is used to split water into hydrogen and oxygen. In traditional hydrogen production systems such as coal gasification or methane steam reforming (MSR), hydrocarbons are used as the feedstock. Therefore, substantial amounts of carbon dioxide (CO_2) is released into the atmosphere. In contrast, water is the feedstock of an electrolyzer, and the electrolysis process is carbon-free. Currently, 96% of the worldwide hydrogen consumption is produced by fossil fuel-based hydrogen production methods, and approximately 4% is generated by electrolysis processes [3].

Alkaline water electrolyzers (AWE), proton-exchange membrane (PEM) electrolyzer and solid oxide steam electrolyzer (SOSE) are the main electrolysis technologies where AWE and PEM electrolyzers work at low temperatures (<373K) while SOSE operates at high temperatures (800–1273K) [4]. There are two advantages for high-temperature electrochemical decomposition process: First, its higher efficiency compared to conventional room-temperature electrolysis because the energy supplied as heat is cheaper than electrical power. Secondly, low theoretical decomposition voltage makes the system consume lower amounts of electrical power [5]. The electrolysis process's major drawback of hydrogen production is its high cost compared to the MSR process [6]. A high-cost metal oxide electrolyte is required to operate at the high SOSE working temperature, and considerable thermal energy is needed to warm up the SOSE [7].

In the 1980s, research about solid oxide fuel cells (SOFCs) was started, and simultaneously, studies about the SOSE have noticed. The SOSE is the reverse operation of the same SOFC process. Both employ similar technology and materials; two electrodes (porous composite ceramic) surrounding a gas-tight electrolyte [8]. The reverse process not only changes the SOSE reaction directions but also impacts the cell thermal and electrochemical behavior, which is far from SOFCs operation [9].

At the SOSE cathode, steam is dissociated, producing hydrogen and oxygen ions. After crossing the electrolyte within the anode, the oxygen ions are oxidized to constitute oxygen [10]. The overall energy demand (ΔH) of the SOSE process is expressed as $\Delta H=\Delta G+T\Delta S$
Where ΔG is the required electrical power (free Gibson energy change) and $T\Delta S$ is the thermal energy demand (J/mol H_2).

While the SOSE operating temperature increases, the process electrical power demand decreases and the needed thermal energy increases [11]. As the SOSE systems operate at high temperatures, the expensive catalysts are not required. However, strict chemical, thermal and structural requirements should be met [12]. Using the SOSE systems, CO2 emissions decrease by recycling and converting them to syngas [13].

The energy and exergy efficiencies of the SOSE system can be increased up to 53% and 60%, respectively [14]. Using renewable energy in the SOSE systems is a promising technology for clean hydrogen production in the future [15].

The idea of integrating a high-temperature SOSE with a power plant has been discussed by several researchers [16], [17]. A nuclear power plant or a solar power generation system is coupled to a SOSE to generate electricity and hydrogen simultaneously in these combined systems.

This paper aims to design and analyze a gas turbine unit for electrical power generation integrated into the SOSE hydrogen production system. A flameless boiler is coupled to the gas turbine system to make steam. In this context, a part of the gas turbine exhaust gases is used as the oxidizer in the flameless boiler. In the flameless boiler, fuel consumption for steam making reduces drastically, making the hydrogen production process more efficient.

The specific contributions of this paper are summarized as follows:

- The idea of integrating a GT system with a SOSE is developed.
- The characteristics of a flameless boiler for steam generation for a SOSE are evaluated.
- The performance of the hybrid GT-SOSE system is evaluated.

2 GAS TURBINE-SOSE SYSTEM

Power generation by gas turbines (GTs) is one of the high-reliability methods of electrical power generation. The essential characteristics of GT systems are their low complexity, high flexibility, fast-starting acceleration, and low capital cost to power ratio. However, the GT open-cycles release a considerable amount of high-grade heat to the surroundings. Therefore, a heat recovery steam generator is recommended to attach a Rankine cycle to the GT system and make a combined heat and power (CHP) generation system [18]. To improve the overall power generation of a CHP, hosseini et al. [19] used a flameless duct burner before HRSG. The enthalpy of exhaust gases from a GT was employed in the MSR process to produce hydrogen [20]. To produce hydrogen in a SOSE, both electricity and steam are required. Considering the considerable amount of fuel for steam making and losses in electrical power transmission, it is more efficient to integrate the GT system to the SOSE in the power plant to produce hybrid electrical power- hydrogen fuel.

2.1 System Design and Modeling

Figure 1 illustrates a schematic of the hybrid GT-SOSE system. Initially, a CH_4-fueled GT system generates electrical power. At the design conditions, 23% of the GT exhaust gas is conducted to the flameless boiler to make steam, and the rest is charged to the preheater. To operate both the GT combustor and the flameless boiler, CH_4 is used. Fifty percent of the power and the produced steam in the flameless boiler are used in the SOSE to make hydrogen. An AC/DC converter is used to prepare the needed electricity for the SOSE.

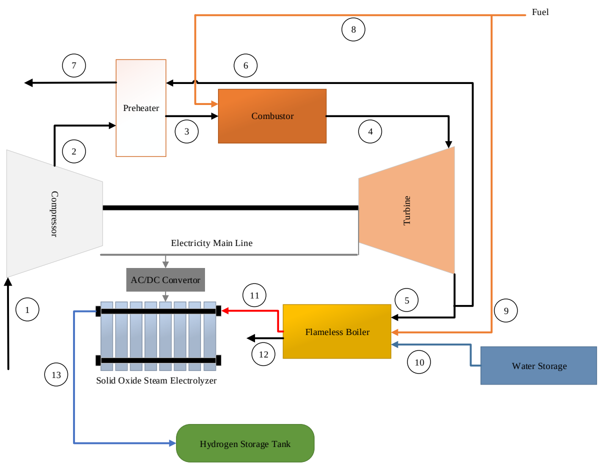


Figure 1: Schematic of the hybrid electrical power generation-hydrogen production unit

The simulation code of this research was developed by Hosseini [21] to analyze various parameters of the combined system. The current paper presents the effects of varying design parameters on the rate of overall electrical power generation and hydrogen production. The following assumptions were considered in the simulation of this system:

- It is assumed that the GT system generates 50 MW of electricity, in which 25 MW of that is used in the SOSE system for hydrogen production.
- The whole power generation process is considered steady-state.
- The ambient conditions are assumed as P0 = 1.013 bar and T0 = 298.15 K.
- Isentropic efficiency of the compressor and turbine is considered 86%.
- The oxidizer and combustion products are considered ideal gas mixtures.
- CH_4 is injected into the GT combustion chamber and flameless boiler.
- The pressure drop and heat loss from both the GT combustor and the flameless boiler is assumed 3% of CH_4 lower heating value (LHV) respectively, and the other components are considered adiabatic.
- The potential and kinetic energy variations are neglected.
- The design parameters of the GT system and flameless boiler are summarized in Table 1.

3 RESULTS AND DISCUSSION

The J-V characteristics diagram of the proposed SOSE system were compared with the theoretical analysis and experimental results presented by Ni et al. [10] and Momma et al. [22], and a good agreement was found between them which could be considered a validation of the model.

3.1 Effects of GT power on the characteristics of SOSE

Figure 2 depicts the impacts of power input to the SOSE on the water/fuel consumption in the flameless boiler and the rate of hydrogen production in the SOSE. Increasing the SOSE power input from 20 MW to 50 MW increases the produced hydrogen from 76.2 mol/s to 134 mol/s. To produce more hydrogen, more water is needed; therefore, more fuel should be burned in the flameless boiler to make steam. Using full GT power in the SOSE, the required fuel and water for the SOSE are respectively 2.5 and 1.76 times more than the conditions that just 20 MW of the GT power is employed in the SOSE system. By increasing the transferred power to the SOSE, the cell potential and current augment.

Parameter	Design value
Compressor pressure ratio (r_{AC})	10
Compressor isentropic Efficiency (η_{SC})	86%
GT combustor and flameless boiler efficiency	97%
GT combustor inlet temperature	850 K
Gas turbine inlet temperature (T_4)	1520 K
Gas turbine isentropic Efficiency (η_{ST})	86%

Table 1: The design parameters of GT system and flameless combustor

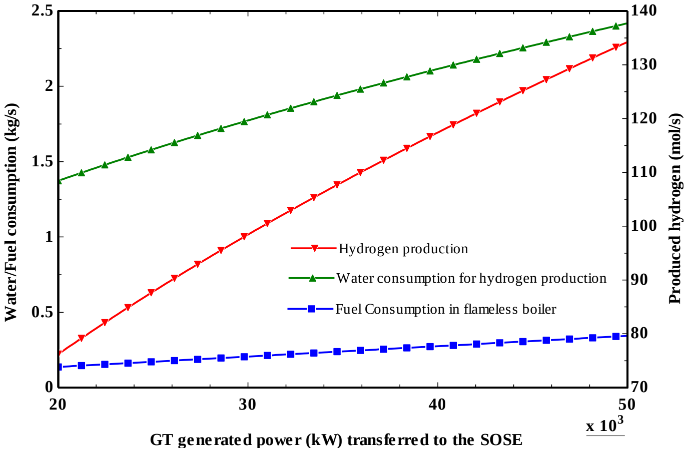
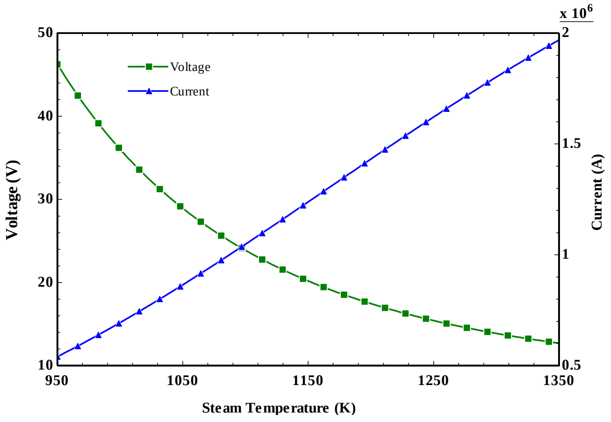


Fig3. Effects of power input to the SOSE on the water/fuel consumption in the flameless boiler and the rate of hydrogen production in SOSE

Using high-temperature steam in the SOSE can promote electrode activity and decrease the overpotential. Hence, the electric current density decreases which mitigates the polarization losses at high temperatures (Fig4). Consequently, the hydrogen production density and the electrolysis efficiency are improved. The outlet flowrate of H_2 from the SOSE directly depending on the current density of the SOSE and enhancement of steam temperature increases the current density of the SOSE, which results in higher rates of H_2 production.



4 CONCLUSION

In the proposed system, the turbine inlet temperature should be set at temperatures higher than 1314 K to achieve the turbine outlet temperature higher than 870K, which is higher than the fuel's auto-ignition temperature. In this condition, the flameless boiler can be operated successfully. By increasing the turbine inlet temperature, the flameless boiler works at higher temperatures, increasing the SOSE steam temperature. By increasing the SOSE steam temperature, the overall voltage of the SOSE decreases, which conducts the system to produce higher amounts of hydrogen. By increasing the transferred GT power to the SOSE, the SOSE current increases and consequently the amount of produce hydrogen increases. The electrolyte thickness is a crucial factor in the overall SOSE hydrogen production where enhancement of the electrolyte thickness conducts the SOSE system to the higher amounts of hydrogen production. Although, the large pore size and large electrode porosity are desirable in the SOSE system to abate gas transport resistance, their effects on the overall hydrogen production rate are not significant.

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