

Thermal Management and Performance Analysis of Hydrogen- and Ammonia-Fueled Solid Oxide Fuel Cell Systems

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Abstract

This study developed and validated thermodynamic models for 10 kW hydrogen- and ammonia-fueled solid oxide fuel cell (SOFC) systems to investigate the effects of fuel type on system performance, thermal management, efficiency, and exergy characteristics. The developed SOFC stack model was validated against a commercial stack with an average error of less than 10%. The hydrogen-fueled SOFC system achieved a maximum efficiency of 60.0% at 6 kW and 55.39% at 10 kW, whereas the ammonia-fueled SOFC system reached 63.32% at 7 kW and 58.38% at 10 kW. The endothermic ammonia cracking reaction improved the system thermal balance and reduced the burner thermal load, resulting in higher efficiency under medium and high operating power. Exergy analysis indicated that the cathode heat exchanger and burner were the major sources of exergy destruction in both systems. Although the ammonia-fueled SOFC system achieved higher electrical efficiency, the additional irreversibility introduced by ammonia cracking resulted in lower exergy efficiency. The proposed model provides a useful reference for the thermal management and design optimization of SOFC systems and indicates the potential of ammonia as a carbon-free hydrogen carrier for future green hydrogen applications.

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INTRODUCTION

Since the Industrial Revolution, the rapid growth in global energy demand has relied heavily on fossil fuels, resulting in resource depletion, greenhouse gas emissions, and global warming. Consequently, many countries have promoted renewable energy and low-carbon technologies to achieve carbon neutrality. In Taiwan, renewable energy currently accounts for approximately 10% of electricity generation and is expected to exceed 50% by 2050, mainly through solar, wind, and geothermal energy (Yağlı, H. et al. 2016). However, the intermittent nature of renewable energy introduces challenges in balancing electricity supply and demand, making long-term energy storage an essential issue for future energy systems (Gils, H. C. et al. 2017).

Current solutions for renewable energy integration mainly include: (1) combining conventional power generation with smart grids, (2) storing surplus electricity using battery energy storage systems, and (3) converting excess renewable electricity into chemical fuels such as hydrogen, ammonia, and methane through electrolysis for long-term storage and distributed power generation (Al-Khori, K. et al. 2021, Cinti, G. et al. 2016). Hydrogen is regarded as an attractive clean fuel because of its high energy density and zero-carbon emissions, but its storage and transportation remain costly. In comparison, ammonia offers a higher volumetric energy density, mature transportation infrastructure, and lower storage costs, making it a promising hydrogen carrier for large-scale energy storage and transportation (Zamfirescu, C. et al. 2016).

Solid oxide fuel cells (SOFCs) are considered one of the most promising power generation technologies because of their high electrical efficiency, fuel flexibility, and low emissions. Owing to their high operating temperature, SOFCs can directly utilize hydrogen, natural gas, biofuels, and ammonia. Ammonia can be thermally cracked into hydrogen and nitrogen before electrochemical reactions, reducing the challenges associated with hydrogen storage while maintaining high power-

generation efficiency (Xu S.H. et al. 2025, Chan Y.H. 2024). Recent studies have also evaluated high-temperature solid oxide systems from the perspectives of system efficiency, energy management, and exergy performance (Lai H.Y. et al. 2025, Chung P.H. et al. 2026).

Several studies have demonstrated the feasibility of ammonia-fueled SOFCs. The Haber–Bosch process has been the dominant industrial ammonia synthesis technology since the early twentieth century (Smil, V. 2004). Cairns first investigated ammonia in alkaline fuel cells, while Vayena et al. studied ammonia reactions in YSZ-based solid electrolyte reactors (Sigal C T& Vayenas C G 1981). Wojcik et al. demonstrated a direct ammonia-fueled SOFC with a maximum power density of approximately 50 mW cm⁻² at 1073 K and confirmed that ammonia could be decomposed over a Ni–YSZ anode without NOx formation (Wojcik A. et al. 2003, Staniforth, J. et al. 2003). Meng (Meng, G. et al. 2007) reported that SOFCs with a Ce_{0.8}Sm_{0.2}O_{1.9} electrolyte could operate directly on ammonia at 550–650 °C with performance close to that of hydrogen-fueled SOFCs. Cinti et al. (Cinti, G. et al. 2014) further demonstrated that ammonia cracking provides an internal cooling effect, reducing cathode airflow requirements and improving overall stack performance.

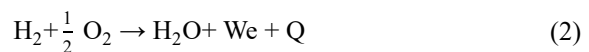
Although previous studies have mainly focused on electrochemical performance at the cell or stack level, comprehensive investigations of hydrogen- and ammonia-fueled SOFC systems from a system-level thermodynamic perspective remain limited. Exergy analysis has also been applied to SOFC systems to identify major sources of irreversibility and evaluate system efficiency (Bedringås K.W. et al. 1997, Lai H.Y. et al. 2025, Chung P.H. et al. 2026). However, the effects of different fuel types on thermal management, system efficiency, and exergy characteristics have not been systematically compared. Therefore, a numerical model integrating electrochemical and thermodynamic analyses is required to evaluate the influence of fuel type on overall SOFC system performance.

In this study, a 10 kW SOFC system model fueled by either hydrogen or ammonia is developed. System performance, thermal management, energy efficiency, and exergy efficiency are analyzed under different operating conditions. Unlike previous studies focusing mainly on cell or stack performance, this study provides a system-level comparison of hydrogen- and ammonia-fueled SOFC systems, particularly considering the effects of fuel type on thermal management and exergy characteristics. The results offer useful guidance for the design and optimization of high-efficiency SOFC power generation systems.

Methodology

Operating Principles of Solid Oxide Fuel Cells

The primary system investigated in this study is the SOFC. Therefore, this section focuses on the operating principles and electrochemical characteristics of the SOFC, with particular emphasis on hydrogen- and ammonia-fueled systems. The performance of an SOFC is strongly influenced by its operating conditions and electrochemical characteristics. An SOFC converts the chemical energy of the fuel directly into electrical energy through electrochemical reactions. Under ideal thermodynamic conditions, the fuel cell operates reversibly and is capable of delivering the maximum electrical work together with the maximum potential difference between the anode and cathode. In practical operation, however, irreversible electrochemical losses reduce both the output voltage and power. The electrochemical reaction of an ammonia-fueled SOFC is expressed by Eq. (1), and the corresponding energy balance is given by Eq. (2):



Where W_e is the electrical power generated by the system, and Q is the heat released under constant-pressure and constant-temperature conditions.

Before discussing the electromotive force (EMF) generation mechanism of the SOFC, several fundamental thermodynamic concepts should be introduced. Gibbs free energy represents the maximum useful work that can be extracted from a system operating at constant temperature and pressure while neglecting volume changes. In fuel cells, the change in Gibbs free energy (ΔG) corresponds to the difference in Gibbs free energy between the reactants and products and determines the maximum electrical work available from the electrochemical reaction (Tuyen, N. D., & Fujita, G. 2012). The relationship between Gibbs free energy and the cell voltage can be expressed as Eq. (3):

$$\Delta G = -n_e F E_{\text{cell}} \quad (3)$$

Accordingly, the reversible cell voltage can be obtained from the Nernst equation, as expressed in Eq. (4). For the hydrogen electrochemical reaction occurring in an SOFC, the Nernst equation is given by Eq. (5) (Chen, X. et al. 2013).

$$E_{\text{cell}} = -\frac{\Delta G_0}{n_e F} + \frac{RT}{n_e F} \ln \frac{P_A^a P_B^b}{P_M^m P_N^n} \quad (4)$$

where P_{H_2} , P_{O_2} , $P_{\text{H}_2\text{O}}$, P_{NH_3} , and P_{N_2} represent the partial pressures of hydrogen, oxygen, steam, ammonia, and nitrogen at the cathode, respectively. During practical SOFC operation, the actual cell voltage is always lower than the theoretical Nernst voltage because of irreversible electrochemical losses. These voltage losses consist of activation overpotential, ohmic overpotential, and concentration overpotential. Since each overpotential varies with the operating current, they directly influence the

output voltage, power generation, and overall efficiency of the SOFC.

Activation Overpotential

Activation overpotential is associated with the electrochemical reaction kinetics at the electrode surface and represents the voltage loss caused by the finite reaction rates of the anodic and cathodic reactions. It is defined as the additional potential required to overcome the activation energy barrier and initiate the electrochemical reaction.

For hydrogen-fueled SOFCs, the oxygen reduction reaction (ORR) at the cathode generally exhibits slower kinetics than the hydrogen oxidation reaction (HOR) at the anode under low current densities. Consequently, the activation overpotential is mainly dominated by the cathode. The relationship between activation overpotential and current density can be described by the Butler–Volmer equation (Huang C.L. et al. 2025), and the activation overpotentials at the anode and cathode are expressed by Eqs. (6) and (7), respectively.

$$V_{act,a} = \frac{2 \times R \times T}{n_e \times F} \times \sinh^{-1} \left(\frac{i}{2 \times i_{0,a}} \right) \quad (6)$$

$$V_{act,c} = \frac{2 \times R \times T}{n_e \times F} \times \sinh^{-1} \left(\frac{i}{2 \times i_{0,c}} \right) \quad (7)$$

where i is the operating current of the SOFC, and $i_{0,a}$ and $i_{0,c}$ are the exchange current densities of the anode and cathode, respectively. A higher exchange current density indicates faster electrode kinetics and a lower activation overpotential

Ohmic Overpotential

Ohmic overpotential results from the resistance to electron transport through the electrodes and interconnects, as well as ion transport through the electrolyte. It exists whenever current flows through the SOFC and contributes to the voltage loss. Although it is generally smaller than the activation and concentration overpotentials, its effect on cell performance cannot be neglected. The ohmic overpotential is expressed by Eq. (8) (Huang C.L. et al. 2025):

$$V_{ohm} = i \times \tilde{R} \quad (8)$$

where R is the total internal resistance of the SOFC. The ohmic resistance can be reduced by using thin electrodes and electrolytes with high electrical and ionic conductivities. Since the electrical conductivity of the electrodes and interconnects is much higher than that of the electrolyte, their contributions to the overall ohmic overpotential are generally negligible.

Concentration Overpotential

Concentration overpotential, also referred to as mass transport overpotential, is caused by limitations in the transport of reactants and products at the electrode surface. It becomes significant at high current densities when the reactant consumption rate exceeds the mass transfer rate, resulting in a decrease

in cell voltage. The concentration overpotential is expressed by Eq. (9) (Huang C.L. et al. 2025):

$$V_{con} = -C \ln \left(1 - \frac{i}{i_L} \right) \quad (9)$$

where C is the concentration overpotential coefficient, and i_L is the limiting current density. The concentration overpotentials at the anode and cathode are calculated using Eqs. (10) and (11), respectively.

$$V_{con,a} = -\frac{R \times T}{n_e \times F} \ln \left(1 - \frac{i}{i_{L,a}} \right) \quad (10)$$

$$V_{con,c} = -\frac{R \times T}{n_e \times F} \ln \left(1 - \frac{i}{i_{L,c}} \right) \quad (11)$$

where $i_{L,a}$ and $i_{L,c}$ are the limiting current densities of the anode and cathode, respectively. The concentration overpotential of each electrode is therefore determined by its corresponding limiting current density

SOFC Power Output and Electrical Efficiency

The actual output voltage of an SOFC is obtained by subtracting the activation, ohmic, and concentration overpotentials from the reversible voltage calculated using the Nernst equation. Accordingly, the cell voltage can be expressed as Eq. (12):

$$V_{cell} = E_{cell} - \Delta V \quad (12)$$

By substituting Eqs. (5)–(11) into Eq. (12), the actual operating voltage of the SOFC can be determined. The output power of the fuel cell is then calculated using Eq. (13):

$$P_{FC} = V_{cell} \times i \times A \times N \quad (13)$$

where A is the active electrode area of the fuel cell, and N_{cell} is the number of cells in the stack. Finally, the electrical efficiency of the SOFC is calculated using Eq. (14):

$$\eta_{FC} = \frac{P_{FC}}{-\Delta H} = \frac{P_{FC}}{-(\frac{i \times A \times N}{n_e \times F}) \times LHV} = \frac{n_e \times F \times V_{cell}}{LHV} \quad (14)$$

The operating parameters of the SOFC stack used in the hydrogen-fueled SOFC system and the ammonia-fueled SOFC system integrated with a cracker are summarized in Table 1.

Table 1. Operating parameters of the SOFC stack (Chung, P.-H et al. 2026)

parameter	value	unit
activation energy of air electrode	1.2×10^5	J/mol
activation energy of fuel electrode	1.0×10^5	J/mol
air electrodes	8400	Ω
electrical conductivity		m^{-1}

electrolyte electrical conductivity	17800	$\Omega\text{-m}^{-1}$
fuel electrodes electrical conductivity	80000	$\Omega\text{-m}^{-1}$
pre-exponential factor for anode exchange current density, γ_{air}	9×10^8	Am^{-2}
pre-exponential factor for anode exchange current density, γ_{fuel}	7×10^8	Am^{-2}
pressure	1	bar
temperature	1023	$^{\circ}\text{C}$
thickness of air electrode	0.07×10^{-6}	m
thickness of electrolyte	0.01×10^{-6}	m
thickness of fuel electrode	1.5×10^{-6}	m

Thermodynamic Analysis of SOFC System Components

The SOFC system consists of several thermally coupled components, including the SOFC stack, heat exchangers, cracker, and burner. Since the performance of each component directly affects the thermal balance and overall system efficiency, a thermodynamic analysis is conducted to evaluate the heat transfer characteristics and energy interactions among these components. The calculation methods for each component are described in the following sections.

Heat Exchangers

Since not all inlet reactants participate in the electrochemical reactions, both reacted and unreacted gases leave the SOFC stack. The reaction products are assumed to exit at the stack operating temperature, whereas the outlet temperatures of the unreacted gases are estimated using a heat exchanger model (Tuyen, N. D., & Fujita, G. 2012). Accordingly, the SOFC stack is treated as a heat exchanger to determine the outlet temperatures of the gas streams. The heat capacity rates of the hot and cold streams are first calculated using Eqs. (15) and (16):

$$C_h[\text{H}_2\text{O}] = \dot{n}_{\text{H}_2\text{O}}^{\text{out}} \times C_{\text{H}_2\text{O}} \quad (15)$$

$$C_c[\text{H}_2 + \text{N}_2 + \text{NH}_3 + \text{O}_2] = \dot{n}_{\text{H}_2}^{\text{out}} \times C_{\text{H}_2\text{O}} + \dot{n}_{\text{N}_2, \text{anode}}^{\text{out}} \times C_{\text{N}_2} + \dot{n}_{\text{NH}_3}^{\text{out}} \times C_{\text{NH}_3} + \dot{n}_{\text{O}_2}^{\text{out}} \times C_{\text{O}_2} + \dot{n}_{\text{N}_2, \text{cathode}}^{\text{out}} \times C_{\text{N}_2} \quad (16)$$

The maximum heat transfer rate is then determined, and the actual heat transfer rate is calculated based on the heat exchanger effectiveness, as expressed in Eq. (17):

$$q_{\text{max}} = C_{\text{min}}(T_{h,1} - T_{c,1}), q = \epsilon_{\text{SOFC}} \times q_{\text{max}} \quad (17)$$

Ammonia Cracker

The primary function of the ammonia cracker is to convert ammonia into hydrogen for SOFC operation. Three reforming methods are commonly employed: steam reforming, partial oxidation reforming, and autothermal reforming. Each method exhibits different thermal characteristics and is therefore suitable for different system configurations and operating conditions.

The ammonia conversion ratio at different cracker operating temperatures is shown in Fig. 1 (Per Morten Hansen P. M. et al. 2024), and the ammonia cracking reaction is expressed by Eq. (18):

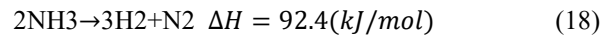
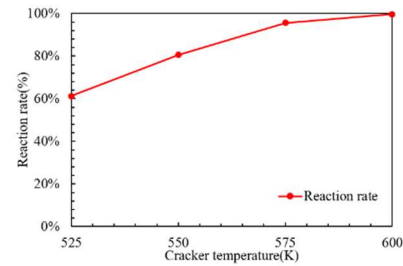
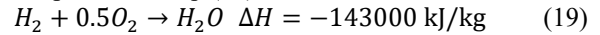


Figure 1. Ammonia conversion ratio of the cracker under different operating temperatures

Burner

The burner is the primary heat source in the SOFC system. Since the fuel is not completely consumed in the SOFC stack, the remaining fuel is supplied to the burner for combustion. The high-temperature combustion products are subsequently transferred to the heat exchangers to preheat the inlet fuel and air streams, thereby providing the thermal energy required for stable SOFC operation. The combustion reaction and the corresponding heat release are calculated based on the high heating value, as expressed in Eq. (19):



Electrical Efficiency of the SOFC System

Based on the thermodynamic models of the system components described above, the overall performance of the SOFC system is evaluated using the first law of thermodynamics. The electrical efficiency of the SOFC system is calculated by Eq. (20):

$$\eta_l = \frac{W_{\text{sys}}}{q_{\text{fuel, in}} \times \text{LHV}} \quad (20)$$

where P_{out} is the total electrical power output of the system, $\dot{m}_{\text{fuel}}$ is the fuel flow rate supplied to the system, and LHV is the lower heating value of the fuel.

Exergy Analysis of SOFC System Components

Exergy is defined as the maximum useful work that can be obtained when a system undergoes a reversible process from a given state to the dead state. In this study, exergy analysis is performed to evaluate the irreversibility and exergy destruction of each system component. The exergy calculation method follows previous studies on SOFC system exergy analysis (Bedringås et al. 1997; Xu et al. 2025; Lai et al. 2025). The thermodynamic properties required for the exergy calculation are determined according to the actual inlet and outlet temperatures of each stream. The total exergy of a fluid stream is expressed as the sum of physical and chemical exergy, as given by Equations.

$$\dot{E}X^{tot} = \dot{E}X^{ph} + \dot{E}X^{ch} \quad (21)$$

$$\dot{E}X^{ph} = \sum_i \{ \dot{m}_i [(h - h_0) - T_0(s - s_0)] \} \quad (22)$$

$$\dot{E}X^{ch} = \sum_i \dot{n}_i \sum_i [x_i (\bar{e}x_i^{ch,0} + RT_0 \ln(x_i))] \quad (23)$$

where the subscript "0" denotes the reference state, and ex_0^{ch} is the standard chemical exergy. Under steady-state conditions, the exergy balance for each component can be expressed by Eq. (24):

$$\dot{E}_d = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q}_j - \dot{W}_{CV} + \sum_i \dot{m}_i ex_i \quad (24)$$

$$- \sum_e \dot{m}_e ex_e$$

where Ex_{des} is the exergy destruction, ex is the specific exergy, and $\dot{Q}$ is the heat transfer rate. The exergy destruction of the SOFC stack, cracker, heat exchanger, and burner is calculated using Eqs. (25)–(28), respectively.

$$\begin{aligned} \text{SOFC stack} \quad \dot{E}_{d,SOFC} &= (\dot{E}_{in,a} + \dot{E}_{in,c}) - (\dot{E}_{out,a} + \dot{E}_{out,c}) - W_{out,SOFC} \end{aligned} \quad (25)$$

$$\text{Reformer} \quad \dot{E}_{d,ref} = \dot{E}_{in,ref} - \dot{E}_{out,ref} \quad (26)$$

$$\text{Heat exchanger} \quad \dot{E}_{HX} = (\dot{E}_{in,hot} + \dot{E}_{in,cold}) - (\dot{E}_{out,hot} + \dot{E}_{out,cold}) \quad (27)$$

$$\text{Burner} \quad \dot{E}_{burner} = \dot{E}_{in} - \dot{E}_{out} \quad (28)$$

In addition to the component exergy analysis, the exergy efficiency of the SOFC system is evaluated based on the second law of thermodynamics and is defined as the ratio of the electrical power output to the total exergy input, as expressed in Eq. (29):

$$\eta_{II} = \frac{P_{sys}}{Ex_{in}} \quad (29)$$

where Ex_{in} is the total exergy input to the system.

SOFC System Design and Operating Assumptions

The system configuration has a significant influence on the performance of an SOFC power generation system, particularly for the ammonia-fueled configuration, where the cracker directly affects the system efficiency and power output. Therefore, the system layout and operating strategy are carefully designed in this study. The major operating parameters of the SOFC system are summarized in Table 2.

To simplify the system analysis, the following

assumptions are adopted:

1. All gases are treated as ideal gases.
2. The ambient temperature and pressure are assumed to be 298 K and 1 atm, respectively.
3. Air consists of 21% O₂ and 79% N₂ by volume.
4. The stack operating temperature is equal to the outlet gas temperature.
5. The unreacted fuel is completely combusted in the burner.
6. For the hydrogen-fueled SOFC system, the inlet H₂/N₂ volumetric ratio is fixed at 3:1.

SOFC System Configuration

The performance of an SOFC system is strongly affected by the stack operating temperature and reactant flow rates. A burner is therefore used to combust the unreacted fuel and provide the heat required for stable system operation.

The hydrogen-fueled SOFC system is shown in Fig. 2. The inlet hydrogen and air are preheated by the heat exchangers before entering the SOFC stack. The exhaust gases are then used for heat recovery, while the remaining fuel is supplied to the burner for combustion.

The ammonia-fueled SOFC system is shown in Fig. 3. The inlet ammonia is preheated and supplied to the cracker, where it is decomposed into hydrogen and nitrogen before entering the SOFC stack. The exhaust heat is recovered to support ammonia cracking and preheat the inlet gases. Both systems were designed for a maximum power output of 10 kW. Because the cell performance differs between hydrogen and ammonia operation, the cell number and active area were adjusted to achieve the same target power output. The main operating parameters of both systems are summarized in Table 2. The thermal capacitance of each component was also considered in the transient simulation to predict the time required to reach steady-state operation.

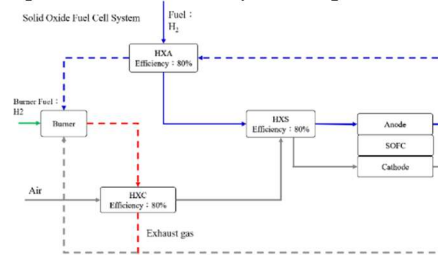


Figure 2. Schematic diagram of the hydrogen-fueled SOFC system configuration

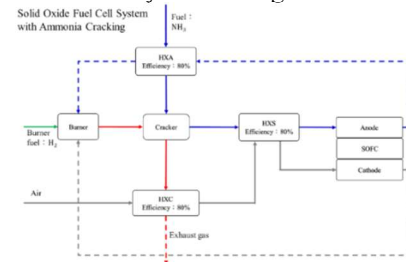


Figure 3. Schematic diagram of the ammonia-fueled SOFC system integrated with an ammonia cracker

Table 2. Operating parameters of the SOFC system

parameter	H2system	NH3system	unit
Number of cell	320	400	-
Cracker reaction rate	-	61.2%~99.6%	-
Fuel utilization rate	83%	83%	-
Heat transfer effectiveness	80%	80%	-
Operating temperature	750	750	°C
Stack area	0.014	0.008	m ²

Results and Discussion

Validation of the SOFC Stack Model and Performance Analysis

To validate the developed SOFC system model, an SOFC stack model was established based on the operating conditions listed in Table 1 and validated against the performance data of the SolydEra G8 Stack, as shown in Fig. 4. The predicted polarization curve shows good agreement with the reference data over the operating current range of 0–120 A, with the errors remaining below 10% throughout the comparison range. These results demonstrate that the developed SOFC stack model can reasonably predict the stack performance and can be used for subsequent system-level simulations.

Following the stack validation, the single-cell performance was evaluated at operating temperatures of 700°C, 750°C, and 800°C. The corresponding polarization and power density curves are shown in Fig. 5. As the operating temperature increased, both the operating voltage and power density improved because the higher temperature enhanced oxygen-ion conductivity and reduced activation and ohmic overpotentials. Moreover, the concentration overpotential became less significant at high current densities, resulting in improved cell performance. Based on these results, an operating temperature of 750°C was selected for the subsequent SOFC system simulations.

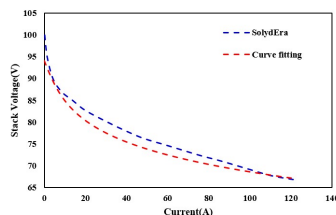


Figure 4. Validation of the developed SOFC stack model against a commercial SOFC stack

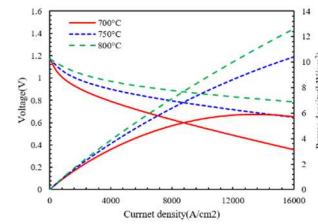


Figure 5. Polarization and power density curves of the SOFC single cell

Performance Analysis of the Hydrogen-Fueled SOFC System

The performance of the hydrogen-fueled SOFC system was evaluated under different operating power levels using the validated SOFC stack and system models. The stack operating temperature was maintained at 750°C, and the operating characteristics were analyzed in terms of stack current and voltage, reactant flow rates, component temperatures, heat exchanger temperatures, and system efficiency.

As shown in Fig. 6, the stack current increased from 0 to 149.75 A as the operating power increased from 0 to 10 kW, whereas the stack voltage decreased from 93.28 to 66.95 V. The higher current demand intensified the activation, ohmic, and concentration overpotentials, resulting in a gradual voltage drop. This trend agrees with the single-cell polarization curves shown in Fig. 5, indicating increased polarization losses at higher operating power.

The reactant flow rates are presented in Fig. 7. During the preheating stage (0 kW), additional fuel and air were supplied to the burner to provide sufficient heat for system start-up. As the operating power increased from 1 to 10 kW, the hydrogen flow rate increased from 21.24 to 109.96 LPM, while the air flow rate increased from 204.62 to 1584.66 LPM. The hydrogen flow supplied the required fuel for the electrochemical reaction, whereas the air flow was adjusted to regulate the stack temperature and maintain stable system operation.

Figures 8 and 9 show the temperatures of the system components and heat exchangers, respectively. As the operating power increased, the stack temperature rose from 727.58°C to the target operating temperature of 750°C and remained nearly constant above 3 kW, demonstrating effective thermal management. In contrast, the burner temperature gradually decreased because the increased cathode air flow cooled the combustion products. Meanwhile, the outlet temperatures of HXC and HXS decreased from 682.26°C and 670.60°C to 610.60°C and 610.13°C, respectively, whereas the HXA outlet temperature increased from 528.65°C to 657.06°C owing to enhanced heat recovery from the hotter anode exhaust.

The system efficiency is shown in Fig. 10. The efficiency increased with operating power, reached a

maximum at 6 kW, and then gradually decreased to 55.39% at 10 kW. At low operating power, part of the fuel energy was consumed to maintain the stack temperature. As the operating power increased, improved fuel utilization and heat recovery enhanced the system efficiency. However, once the fuel utilization reached its preset limit of 83%, additional cathode air was required for temperature control, increasing exhaust heat loss and reducing heat recovery, which led to a slight decrease in system efficiency at higher operating power.

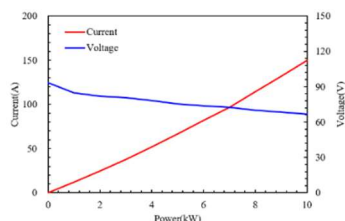


Figure 6. Stack current and voltage of the hydrogen-fueled SOFC system under different operating power

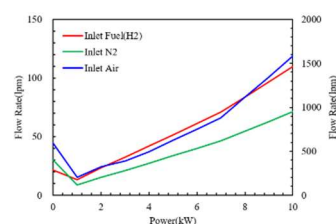


Figure 7. Reactant flow rates of the hydrogen-fueled SOFC system under different operating power

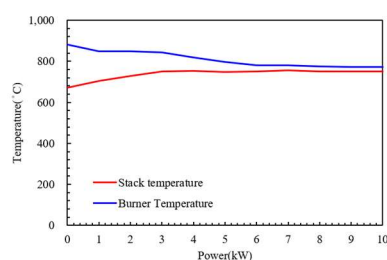


Figure 8. Component temperatures of the hydrogen-fueled SOFC system under different operating power

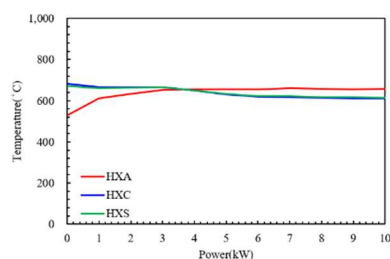


Figure 9. Heat exchanger temperatures of the hydrogen-fueled SOFC system under different operating power

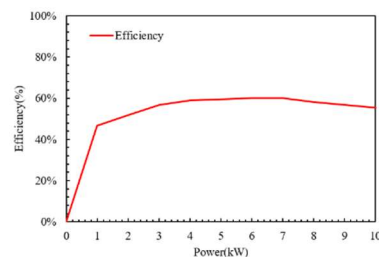


Figure 10. System efficiency of the hydrogen-fueled SOFC system under different operating power

Performance Analysis of the Ammonia-Fueled SOFC System

The performance of the ammonia-fueled SOFC system was further investigated under different operating power levels using the system configuration shown in Fig. 4. The stack operating temperature was maintained at 750°C, and the effects of ammonia cracking on thermal management and system performance were evaluated by comparison with the hydrogen-fueled SOFC system.

As shown in Fig. 11, the stack current increased from 10.4 to 130.24 A as the operating power increased from 1 to 10 kW, while the stack voltage decreased from 98.65 to 77.16 V. Similar to the hydrogen-fueled system, the increase in operating current intensified the activation, ohmic, and concentration overpotentials, resulting in a gradual voltage decrease. However, the endothermic ammonia cracking reaction improved the system thermal balance, allowing the stack to maintain a higher operating voltage under the same operating power.

The reactant flow rates are presented in Fig. 12. During the preheating stage (0 kW), the burner supplied 15.5 LPM of hydrogen and 50 LPM of nitrogen to establish the operating conditions required for system start-up and ammonia cracking. As the operating power increased from 1 to 10 kW, the ammonia flow rate increased from 15.95 to 80 LPM, while the air flow rate increased from 380 to 1600 LPM. A minimum air flow rate of 490 LPM was maintained between 1 and 3 kW to ensure sufficient heat for the burner and cracker. Compared with the hydrogen-fueled system, the endothermic cracking reaction reduced the burner thermal load and improved thermal management at low operating power.

Figures 13 and 14 show the temperatures of the system components and heat exchangers, respectively. As the operating power increased, the stack temperature increased from 650.94°C to 756.60°C, whereas the burner temperature decreased from 883.27°C to 811.56°C. Because a constant minimum air flow rate was maintained between 1 and 3 kW, the burner temperature first decreased to 796.48°C at 3 kW and then recovered to 841.16°C at 4 kW before gradually decreasing with increasing operating power. Meanwhile, the outlet temperatures of HXC and HXS

decreased from 604.58°C and 603.60°C to 584.93°C and 584.91°C, respectively, while the HXA outlet temperature increased from 508.79°C to 599.49°C owing to improved heat recovery from the anode exhaust.

The system efficiency is shown in Fig. 15. The efficiency increased rapidly with operating power, reached a maximum of 63.32% at 7 kW, and then decreased slightly to 58.38% at 10 kW. At low operating power, the fixed minimum air flow improved heat recovery, while the increase in fuel utilization further enhanced the system efficiency. Once the operating power exceeded 7 kW, additional cathode air was required to maintain the stack temperature, increasing exhaust heat loss and reducing heat recovery. Compared with the hydrogen-fueled SOFC system, the ammonia-fueled system achieved higher efficiency at medium and high operating power because the cracking reaction improved the thermal balance and reduced the burner thermal load. In addition, the cracking process altered the heat transfer characteristics of HXS, indicating different thermal management mechanisms between the two fuel systems.

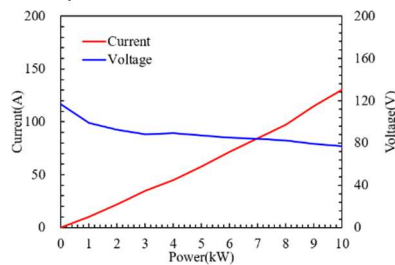


Figure 11. Stack current and voltage of the ammonia-fueled SOFC system under different operating power

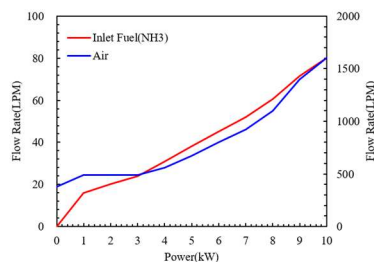


Figure 12. Reactant flow rates of the ammonia-fueled SOFC system under different operating

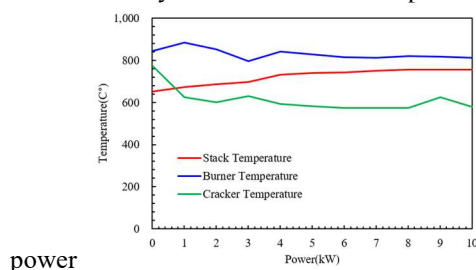


Figure 13. Component temperatures of the ammonia-fueled SOFC system under different operating power

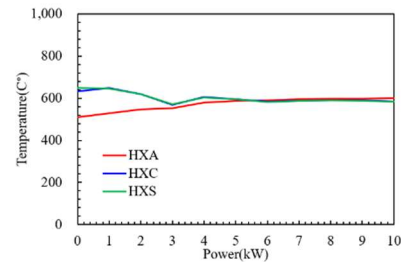


Figure 14. Heat exchanger temperatures of the ammonia-fueled SOFC system under different operating power

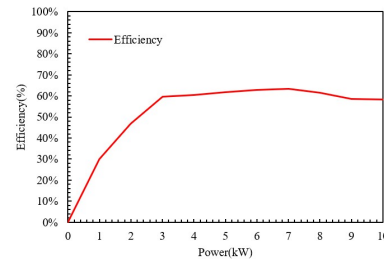


Figure 15. System efficiency of the ammonia-fueled SOFC system under different operating power

3.4 Exergy Sankey Diagram Analysis of Hydrogen- and Ammonia-Fueled SOFC Systems

To compare the exergy distribution of hydrogen- and ammonia-fueled SOFC systems, an exergy analysis was performed at an operating power of 10 kW. The corresponding exergy Sankey diagrams are shown in Figs. 16 and 17, illustrating the exergy flow and irreversible losses within each system.

Figure 16 shows the exergy Sankey diagram of the hydrogen-fueled SOFC system. The largest exergy destruction occurs in HXC (3.04 kW), followed by the burner (1.66 kW). The large temperature difference during heat exchange results in significant irreversibility in HXC, whereas the burner loss is mainly associated with fuel combustion. The SOFC stack, HXA, and HXS contribute relatively little to the total exergy destruction, resulting in an overall exergy destruction of 5.29 kW and an exergy efficiency of 69.90%.

Figure 17 presents the exergy Sankey diagram of the ammonia-fueled SOFC system. Although the exergy destruction in HXC decreases to 2.40 kW, the burner exergy destruction increases to 1.83 kW. The endothermic ammonia cracking reaction reduces the temperature difference across HXC, thereby lowering its exergy destruction. However, the additional cracking process increases system irreversibility, resulting in a total exergy destruction of 6.70 kW and an exergy efficiency of 63.66%.

Compared with the hydrogen-fueled SOFC system, the ammonia-fueled system achieves higher system efficiency because the cracking reaction improves the thermal balance. However, the additional irreversibility introduced by ammonia cracking leads to a lower exergy efficiency. For both

systems, most of the exergy destruction occurs in the heat exchanger and burner, indicating that these components dominate the overall exergy loss.

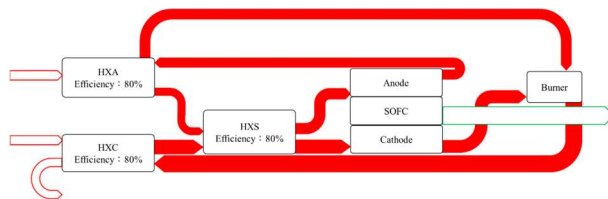


Figure 16. Exergy Sankey diagram of the hydrogen-fueled SOFC system at an operating power of 10 kW

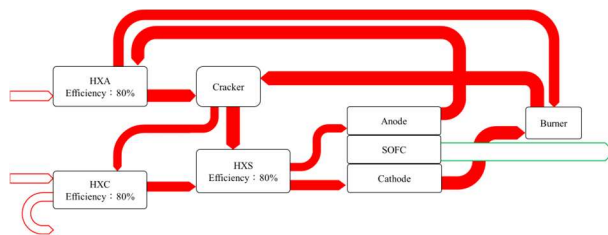


Figure 17. Exergy Sankey diagram of the ammonia-fueled SOFC system at an operating power of 10 kW

Conclusions

A thermodynamic model of hydrogen- and ammonia-fueled SOFC systems was developed and validated in this study. The operating characteristics, system efficiency, and exergy distribution of both systems were analyzed under different operating power levels. The main conclusions are summarized as follows:

1. The developed SOFC stack model was successfully validated against a commercial SOFC stack, with an average error of less than 10% over the operating current range of 0–120 A. Increasing the operating temperature from 700°C to 800°C improved the operating voltage and power density, indicating enhanced electrochemical performance at elevated temperatures.
2. The hydrogen-fueled SOFC system achieved a system efficiency of 55.39% at 10 kW and a maximum efficiency of approximately 60% at 6 kW. The ammonia-fueled SOFC system reached 58.38% at 10 kW and a maximum efficiency of 63.32% at 7 kW. The endothermic ammonia cracking reaction improved the system thermal balance, resulting in higher system efficiency under medium and high operating power.
3. As the operating power increased, the stack current increased while the operating voltage decreased because of polarization losses. Additional cathode air was required to maintain the stack temperature at 750°C, increasing exhaust heat loss and reducing system efficiency at high operating power.
4. Exergy analysis showed that the largest exergy destruction occurred in the HXC and burner for

both systems. Although the ammonia-fueled SOFC system achieved higher system efficiency, the additional irreversibility introduced by the ammonia cracking reaction resulted in a lower exergy efficiency than that of the hydrogen-fueled SOFC system.

Overall, ammonia is a promising hydrogen carrier for SOFC systems because its endothermic cracking reaction improves the system thermal balance and enhances system efficiency. The developed thermodynamic model provides a useful reference for the design and thermal management of hydrogen- and ammonia-fueled SOFC systems. In future work, the model can be further extended to larger-scale systems and transient operating conditions to investigate thermal management during load variations, providing practical guidance for the design and operation of SOFC power generation systems.

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