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Construction and Performance Analysis of an Atmospheric SOFC-Dual IBC Hybrid Power Generation System Based on CO_2 Recycling

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ABSTRACT

The Solid Oxide Fuel Cell-Inverted Brayton Cycle (SOFC-IBC) hybrid power generation system offers a solution to the challenge of directly coupling atmospheric pressure SOFC with the traditional Brayton cycle due to pressure mismatches. This study employs process simulation and theoretical analysis to establish a model of the atmospheric pressure SOFC-Double IBC hybrid power generation system based on CO_2 recycling, investigating the impact of fuel utilization on system performance and further exploring its internal energy conversion processes through exergy analysis. The results indicate that when the fuel utilization factor is 0.85, the system achieves a peak total efficiency of 76.74%, with an output power of 182.77 kW and an exergy efficiency of 63.46%.

Keywords: SOFC; IBC; hybrid power generation power; fuel utilization factor; exergy annalysis

1. INTRODUCTION

As environmental issues become increasingly severe, the public has gained a deeper understanding of the limitations of traditional energy utilization methods, prompting countries to invest in the development of new energy conversion devices[1,2]. Efficient and clean energy utilization has gradually become a strategic development goal for countries worldwide. Fuel cell technology, as a non-combustion high-efficiency energy conversion device, directly converts the chemical energy contained in fuel into electrical energy through electrochemical reactions, making it the fourth generation of power generation technology after hydropower, thermal power, and nuclear power. The Solid Oxide Fuel Cell (SOFC) is a fully solid-state chemical power generation device operating in a medium-high temperature environment[3]. The high-temperature exhaust gas it emits contains abundant waste heat resources, with temperatures reaching around 1000 ℃[4], providing significant reutilization value. It can meet the heat supply needed for natural gas reforming and can also form a combined cycle power generation system with gas turbines.

Among the various hybrid power generation system configurations, the SOFC-GT hybrid power generation system based on the Brayton Cycle (BC) has demonstrated significant competitive advantages. Diamantis et al.[5] conducted an optimized design of the compressor and turbine geometries for the SOFC-GT hybrid power generation system, aiming to ensure optimal performance under both design and overload conditions. Jamasb et al.[6] compared and analyzed SOFC-GT hybrid power generation systems with different connection modes, revealing that the direct hybrid power generation system exhibited the most superior performance, achieving power generation and overall efficiencies of 51% and 64%, respectively. In contrast, the combined hybrid power generation system achieved power generation and overall efficiencies of 43% and 59%, respectively, although its power output was 16% higher than that of the direct hybrid system. Oryshchy et al.[7] studied the impact of fuel utilization within the fuel cell on the performance of the direct-fired SOFC-GT hybrid power generation system, indicating that when the fuel utilization factor is 80%, the system efficiency reaches a peak of 75.6%, with the fuel cell contributing 66.2% of the total power and the gas turbine expansion work accounting for 33.8%.

However, for atmospheric pressure SOFC, due to its exhaust pressure mismatch with the traditional Brayton cycle, direct coupling is not possible, and integration can only be achieved indirectly using heat exchangers. Gandiglio et al.[8] conducted a comparative analysis of the thermodynamic characteristics and economic benefits of SOFC/GT hybrid power generation systems under atmospheric pressure and 20 bar pressure conditions, confirming that the pressurized hybrid power generation system outperforms the atmospheric system in performance, with SOFC operational losses reduced by approximately 20%. Furthermore, when considering the levelized cost of electricity (LCOE), the cost-effectiveness of both systems is comparable. In summary, although the pressurized SOFC-GT hybrid power generation system has an efficiency advantage over the indirectly coupled atmospheric SOFC-GT hybrid power generation system, the pressurized operation of fuel cells remains a significant technical bottleneck for the development of such systems. This is particularly true for compact and thin cell units, which undoubtedly limits the further application of SOFC-GT hybrid power generation systems.

This study focuses on solving the challenge of efficiently and directly utilizing the high-temperature exhaust heat of atmospheric pressure SOFCs while ensuring their safe operation, to maximize the utilization efficiency of exhaust heat when operating at atmospheric pressure. The research team led by Tsujikawa et al.[9] proposed the concept of using an Inverted Brayton Cycle (IBC), providing an effective means for direct coupling with atmospheric pressure SOFCs, and constructed an SOFC-IGT hybrid power generation system. Through this innovative solution, a total thermal efficiency exceeding 65% was achieved, significantly advancing the development of SOFC-GT hybrid power generation technology. Facchinetti et al.[10,11] integrated an SOFC module with two independent gas turbines (GT) in an atmospheric pressure inverted Brayton cycle and introduced an oxygen-enriched combustion unit. Their research results indicate that this system not only has higher energy conversion efficiency compared to existing pressurized hybrid power generation systems but also avoids the issues associated with pressurization technology. When the pressure ratio reaches 5, the system's first-law efficiency is expected to reach 80%. Wang et al.[12] used Aspen Plus to model a hybrid power generation system combining atmospheric pressure fuel cells and ambient pressure gas turbines (APGC). This hybrid power system achieved a power generation efficiency of 66.5%, an improvement of 14.5% compared to atmospheric pressure SOFCs and nearly 12% compared to pressurized SOFCs. Cardena et al.[13] proposed a novel SOFC-IBC hybrid power generation system using Aspen Plus, achieving a power generation efficiency of 63.5%. Although slightly lower than traditional pressurized SOFC-GT hybrid power generation systems, this system does not require pressure vessels, offering unique advantages.

Although efficient energy conversion devices such as SOFC and traditional Brayton cycle integrated systems have been extensively studied, the hybrid power generation system combining SOFC and IBC is still an emerging concept. Its system configuration, parameter design, cycle principles, and performance impacts are still in the early stages of development. Therefore, this paper employs process simulation and theoretical analysis to construct a hybrid power generation system configuration coupling Solid Oxide Fuel Cells (SOFC) with an Inverted Brayton Cycle (IBC) based on CO_2 recycling, and investigates the impact of fuel utilization on system performance.

2. MODELING

Fig 1 presents the flowchart of the proposed SOFC-IBC hybrid power generation system based on CO_2 recycling. This system integrates three core subsystems: the Solid Oxide Fuel Cell (SOFC), the Brayton cycle waste heat utilization system, and the fuel and air pre-treatment process. This integrated design aims to maximize energy conversion efficiency while optimizing overall system performance. The fuel/air pre-treatment system comprises six key components: the fuel/air preheaters (HE1 and HE2), the mixer, the pre-reformer, and the fuel/air pumps. The IBC waste heat utilization system consists of the afterburner, turbines (T1 and T2), the condensation process, and compressors (C1 and C2). The core components of the SOFC module include the anode, cathode, and DC-AC converter.

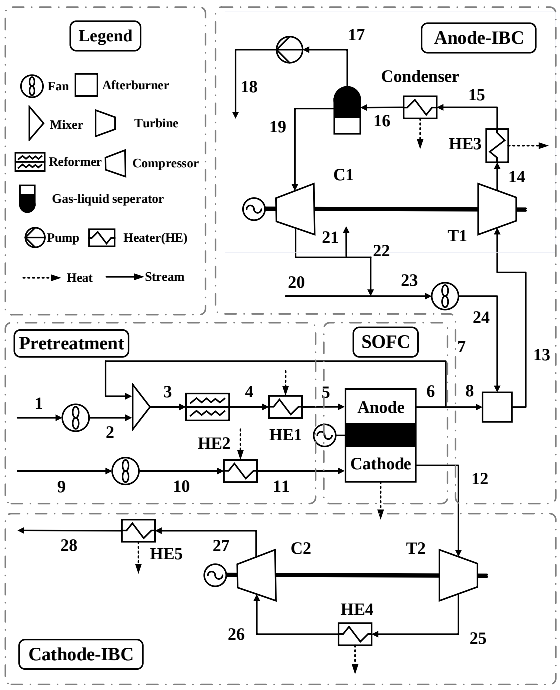

Fig 1: Flowchart of the SOFC-IBC Hybrid Power Generation System Based on CO_2 Recycling

In the specific workflow, the anode recirculated exhaust (stream 7) mixes with pure methane (stream 1) in the mixer, where the pure methane is at ambient temperature and pressure before entering the fuel pump for compression. The mixed gas is sent to the pre-reformer for the necessary external reforming treatment. The reformed gas (stream 4) exchanges heat with the turbine exhaust, reaching an appropriate temperature, and is then delivered to the SOFC anode. Meanwhile, the ambient air is pressurized by the compressor, exchanges heat with the exhaust from the turbine and compressor 2, reaches a temperature close to that of the anode inlet mixture, and is then delivered to the SOFC cathode to participate in the electrochemical reaction. The adiabatic electrochemical reactions within the SOFC provide the necessary heat for the internal reforming reactions, which mainly originate from the reforming reactions within the SOFC stack and the oxidation reactions of the fuel and oxygen. The DC-AC converter transforms the DC into AC to meet industrial or household power demands.

In this model, the SOFC cathode exhaust is not sent to the afterburner but to the cathode IBC system, where it undergoes expansion, condensation, and compression before being released into the environment. The anode exhaust undergoes complete adiabatic combustion in the afterburner with the introduced pure O_2 and the recycled CO_2 from the compressor 1 outlet. The resulting high-temperature flue gas is sent to the anode IBC system, where the turbine 1 flue gas (stream 14) exchanges heat with the intake air and fuel, providing a heat source for the IBC waste heat utilization system, thus effectively utilizing the high-temperature exhaust from the SOFC. When the anode turbine (T1) exhaust expands to a predetermined pressure ratio, the high-temperature exhaust (stream 14) is heat exchanged and then directed into the condenser to precipitate water, thereby reducing the working fluid flow entering the compressor. The precipitated water is pressurized to ambient pressure by the water pump and stored in a tank for subsequent use, a process referred to in this paper as the condensation process. After partial heat exchange with the inlet air, the compressed working fluid from the compressor is partially sent to the afterburner to reduce the excessively high temperature caused by pure oxygen combustion in the afterburner.

2.1 SOFC

As shown in Fig 1, the SOFC model directs the pre-reformed and heated fuel to the SOFC anode, where all the fuel is reformed into H_2 and CO. Additionally, under a fixed fuel utilization rate, a certain amount of fuel undergoes electrochemical reactions to produce CO_2 and H_2O, which, along with the unreacted H_2 and CO, are sent to the next stage as anode exhaust. The reforming and conversion reactions occurring within the SOFC are as follows[14]:

Methane reforming reaction:

$$\mathrm{CH_4 + H_2O \Leftrightarrow CO + 3H_2}$$

(1)

Water-gas shift reaction:

$$\mathrm{CO + H_2O \Leftrightarrow CO_2 + H_2}$$

(2)

Thus, the overall electrochemical reaction occurring within the SOFC is:

$$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

(3)

The calculation of current density is crucial for studying the performance of the cell system, given by:

$$i = \frac{I}{\mathrm{n_{cell}} \cdot \mathrm{A_{cell}}}$$

(4)

where I is the current (A); n_{cell} is the number of individual cells in the SOFC; A_{cell} is the effective area of a single cell (m^2).

The actual cell voltage is given by:

$$V_{\mathrm{SOFC}} = E_{\mathrm{N}} - V_{\mathrm{ohm}} - V_{\mathrm{act}} - V_{\mathrm{con}}$$

(5)

where E_N is the electromotive force of the cell reaction (V); V_{ohm} is the ohmic polarization (V); V_{act} is the activation polarization (V); V_{con} is the concentration polarization (V).

$$E_{\mathrm{N}} = 1.253 - 2.4516\times10^{-4}T + \frac{\mathrm{R}T}{2\mathrm{F}}\ln\left(\frac{p_{\mathrm{H_2}}\cdot p_{\mathrm{O_2}}{}^{0.5}}{p_{\mathrm{H_2O}}}\right)$$

(6)

where R is the universal gas constant (8.314 kJ/(kg·K)); T is the cell reaction temperature (K); p_j is the partial pressure of the gas at the electrode surface (bar); F is the Faraday constant (96485.33 C/mol).

Therefore, the AC power output of the SOFC is given by:

$$W_{\mathrm{SOFC}} = I \times V_{\mathrm{SOFC}} \times \eta_{\mathrm{DC\text{-}AC}} \times \mathrm{n_{cell}}$$

(7)

where $\eta_{DC\text{-}AC}$ is the DC-AC conversion coefficient.

The power generation efficiency is given by:

$$\eta_{\mathrm{SOFC}} = \frac{W_{\mathrm{SOFC}}}{m_{\mathrm{CH_4}} \cdot LHV}$$

(8)

where *m* is the mass flow rate (kg/s); *LHV* is the lower heating value of the input fuel (kJ/kg).

2.2 IBC

During the turbine expansion process, the ratio of the work done in the actual adiabatic process to the work done in the isentropic adiabatic process is given by the turbine isentropic efficiency calculation formula:

$$\eta_{\mathrm{st}} = \frac{h_l - h_{l+1}}{h_l - h_{(l+1)\mathrm{s}}}$$

(9)

where h is the specific enthalpy (kJ/kg).

Hence, the mechanical work done during the turbine expansion is:

$$W_{\mathrm{t}} = m_{\mathrm{t}} \cdot (h_l - h_{l+1})$$

(10)

The same applies to the compressor, thus:

$$\eta_{\mathrm{sc}} = \frac{h_{(l+1)\mathrm{s}} - h_l}{h_{l+1} - h_l}$$

(11)

$$W_{\mathrm{c}} = m_l \cdot (h_{l+1} - h_l)$$

(12)

the total output power of the IBC system is:

$$W_{\mathrm{IBC}} = \left(W_{\mathrm{t,total}} \cdot \eta_{\mathrm{m}} - W_{\mathrm{c,total}} / \eta_{\mathrm{m}}\right) \cdot \eta_{\mathrm{g}}$$

(13)

where η_{m} is the mechanical efficiency; η_{g} is the power generation efficiency.

2.3 Performance Evaluation Indicators

2.3.1 Thermodynamic Analysis

The output power and thermodynamic efficiency of the hybrid power generation system serve as the primary performance evaluation indicators, which can be determined by the following formulas:

$$W_{\mathrm{total}} = W_{\mathrm{SOFC}} + W_{\mathrm{IBC}}$$

(14)

$$\eta_{\mathrm{total}} = \frac{W_{\mathrm{total}}}{m_{\mathrm{CH_4}} \cdot LHV}$$

(15)

2.3.2 Exergy Analysis

Exergy represents the maximum available energy when the working fluid returns to the environmental state, reflecting the proportion of any form of energy that can theoretically be converted into useful work in a given environmental state. The exergy values of various streams in the hybrid power generation system can be obtained using the following formulas[15]:

$$E = E_{\mathrm{ph}} + E_{\mathrm{ch}}$$

(16)

$$E_{\mathrm{ph}} = \sum_j m_j \cdot \left[\left(h_j - h_0\right) - T_0\left(s_j - s_0\right)\right]$$

(17)

$$E_{\mathrm{ch}} = n_j \cdot \left(\sum_j x_j \bar{e}_{0i} + \mathrm{R}T_0 \sum_j x_j \ln x_j\right)$$

(18)

where E_{ph} is the physical exergy value (kW); E_{ch} is the chemical exergy value (kW); T_0 is the environmental reference temperature (℃); s is the specific entropy value (kJ/(kg·K)); x is the mole fraction; $\bar{e}_0$ is the standard molar chemical exergy (kJ/kmol)[11].

Exergy destruction refers to the loss of available energy due to irreversible processes during energy conversion and transfer. The exergy destruction in the energy conversion process is the difference between the system's input exergy and output exergy, directly reflecting the efficiency of energy conversion. According to the literature, the balance equations for the system components can be expressed by the following formulas:

$$\sum_{l=1}^{n} E_{\mathrm{in}} + Q_{\mathrm{in}} + W_{\mathrm{in}} = \sum_{l=1}^{n} E_{\mathrm{out}} + Q_{\mathrm{out}} + W_{\mathrm{out}} + E_{\mathrm{D}}$$

(19)

where Q is the heat (kW); W is the work (kW); E_{D} is the exergy destruction (kW);

The exergy efficiency of the entire hybrid power generation system is:

$$\eta_E = \frac{W_{\mathrm{SOFC}} + W_{\mathrm{IBC}}}{E_{\mathrm{in,total}}}$$

(20)

2.4 Simulation Assumptions

(1) Methane is used as the fuel, and air is used as the SOFC cathode input material. Air, fuel, and water are considered to enter the system under environmental conditions.

(2) It is assumed that unreacted gases in the afterburner undergo complete adiabatic combustion.

(3) In the hybrid system, only the pressure losses in the SOFC and condenser are considered, while the pressure losses in other components are negligible.

2.5 SOFC Model Validation

In this section, the previously constructed Solid Oxide Fuel Cell (SOFC) model will be further validated for accuracy and reliability. We used the simulation data provided in reference[14] as a benchmark. In the comparative analysis, the results of various output parameters of the SOFC have been organized and listed in Table 4. Additionally, to provide more detailed information, the detailed output results of various streams in the SOFC are listed in Table 2. Through these data comparisons, we can observe that the SOFC model established in this paper shows good consistency with the data in reference[14], with all parameter differences within acceptable error ranges.

Table 1. Performance Parameters Comparison of Simulation Output Results[14]

Parameter	Reference	Validation	Error (%)
DC output power (kW)	120.00	121.75	1.46
Current density (A/m2)	1790.00	1790.80	0.04
Voltage (V)	0.70	0.71	1.43
Reformer output temperature (℃)	533.00	535.29	0.43
Exhaust temperature (℃)	834.00	835.97	0.24
Exhaust composition (%)	77N_2,16O_2, 5H_2O,2CO_2	77.28N_2,15.86O_2, 4.52H_2O,2.34 CO_2	/
SOFC AC efficiency (%)	50.00	50.73	1.46

Table 2. Physical Properties Comparison Results[14]

Stream	T (℃)			p (atm)			ṅ (kmol/h)		
	Ref	Validation	Error (%)	Ref	Validation	Error (%)	Ref	Validation	Error (%)
2	200.00	200	0.00	3.24	3.24	0.00	1.07	1.07	0.00
3	744.03	743.92	0.01	1.08	1.08	0.00	5.77	5.74	0.52
4	621.35	621.35	0.00	1.08	1.08	0.00	6.39	6.32	1.10
6	910.00	910	0.00	1.08	1.08	0.00	7.68	7.65	0.39
7	910.00	910	0.00	1.08	1.08	0.00	4.69	4.67	0.43
8	910.00	910	0.00	1.08	1.08	0.00	2.99	2.98	0.33
10	630.00	630	0.00	1.08	1.08	0.00	40.10	40.10	0.00
11	821.32	821.32	0.00	1.08	1.08	0.00	40.10	40.10	0.00
12	910.00	910	0.00	1.08	1.08	0.00	38.50	38.49	0.03
13	1012.35	1012.33	0.00	1.08	1.08	0.00	41.20	41.19	0.02

3. RESULTS AND DISCUSSION

3.1 Basic Operating Conditions

To conduct a comprehensive and precise evaluation, the thermodynamic performance of the proposed SOFC-IBC hybrid power generation system was thoroughly investigated under a series of standard operating conditions. Table 3 lists the basic operating conditions of the constructed hybrid system, while Table 4 presents the main output results under these conditions.

Table 3. Simulation Calculation Conditions[14]

Parameter	**Value**	**Parameter**	**Value**
Ambient temperature (℃)	25	Air utilization factor (%)	35.40
Ambient pressure (bar)	1.01	Steam to carbon ratio	2.55
SOFC operating pressure (bar)	1.02	DC-AC conversion coefficient (%)	92
Anode and cathode inlet temperature (℃)	700	Afterburner efficiency (%)	100
Active surface area of the SOFC (m2)	96.1	Anode exhaust gas recycle ratio (%)	61.07

Number of cells	1152	Pressure ratio	4
Fuel mole flows (kmol/h)	1.07	Turbine isentropic efficiency (%)	85
Air inlet temperature (℃)	25	Compressor isentropic efficiency (%)	85
Fuel inlet temperature (℃)	25	Turbine mechanical efficiency (%)	99
Air inlet pressure (bar)	1.01	Compressor mechanical efficiency (%)	99
Fuel inlet pressure (bar)	1.01	Pump efficiency (%)	80
Air inlet composition (%)	$21O_2;79N_2;$	Pump driver efficiency (%)	95
Fuel inlet composition (%)	$100CH_4$	Condenser pressure loss coefficient	0.0037
Pure oxygen inlet temperature (℃)	25	Compressor outlet pressure (bar)	1.01
Fuel utilization factor (%)	85	IGT generator efficiency (%)	99

Table 4. Performance Comparison of the Proposed Hybrid Power Generation System under Rated Conditions

Parameter	Value
SOFC voltage (V)	0.78
SOFC current density (A/m2)	2029.22
SOFC electricity generation (kW)	139.79
Amount of condensed water (kg/h)	25.39
Turbine 1 expansion power (kW)	18.02
Turbine 2 expansion power (kW)	64.65
Compressor 1 power consumption (kW)	4.12
Compressor 2 power consumption (kW)	35.14
Pump power (W)	0.72
System gross output power of the IGT(s) (kW)	42.98
SOFC AC efficiency (%)	58.70
System gross efficiency (%)	76.74
System total exergy destruction (kW)	47.44
System total exergy efficiency (%)	63.46

3.2 Impact of Fuel Utilization on System Performance

Fig 2 vividly and intuitively illustrates the close relationship between the dynamic characteristics of the turbine inlet and outlet temperatures and fuel utilization. The study found that as fuel utilization increases, the turbine inlet and outlet temperatures exhibit a corresponding decreasing trend. This phenomenon is due to the increased oxygen supply to the SOFC anode, which enhances the reforming and conversion reactions within the electrochemical system and accelerates the electrochemical reaction rate. Consequently, the amount of unreacted fuel supplied to the afterburner decreases, directly leading to a reduction in turbine inlet temperature. Under constant heat transfer conditions and expansion ratios, the change in turbine outlet temperature corresponds to the decrease in inlet temperature.

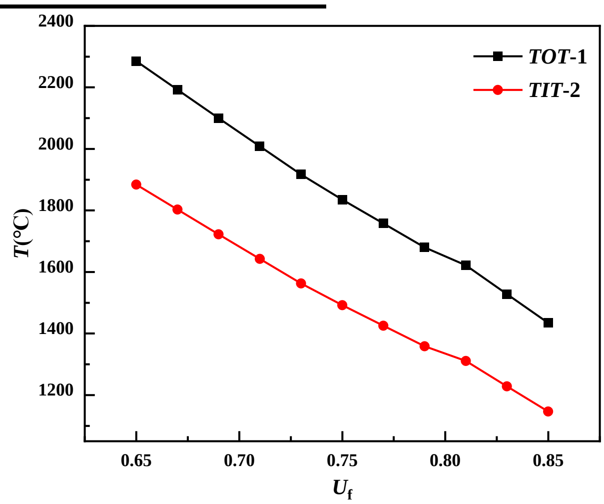

Fig 2 Impact of Fuel Utilization on Turbine 1 Inlet and Outlet Temperatures in the Hybrid System

Fig 3 clearly demonstrates the impact of fuel utilization on turbine expansion work and compressor energy consumption in the IBC system. Specifically, within this hybrid system framework, turbine expansion work generally has a positive correlation with fuel utilization. The effective recovery of waste heat from the cathode and anode is reflected in their respective turbine expansion power and compressor power consumption. As the total turbine expansion power and total compressor power consumption of the system increase, the total output power of the IBC also increases.

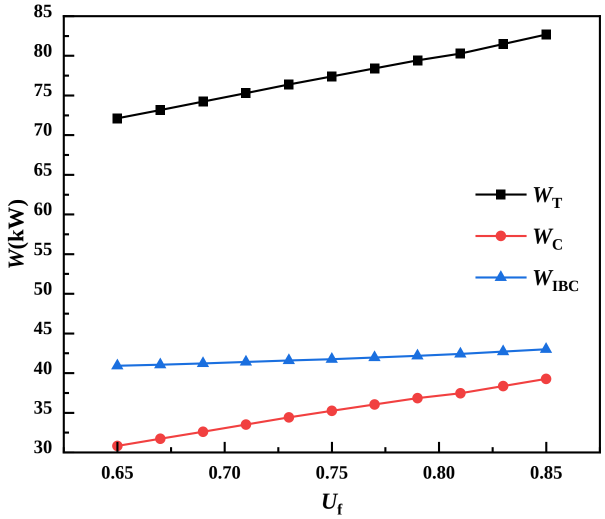

Fig 3 Impact of Fuel Utilization on Turbine, Compressor, and Total Output Power of the IBC in the Hybrid System

Fig 4 analyzes the direct impact of fuel utilization on the electrochemical reaction mechanism within the Solid Oxide Fuel Cell (SOFC), particularly in the context of a hybrid power system. The results indicate that as fuel utilization continues to increase, the consumption rates of the key reactants, carbon monoxide (CO) and hydrogen (H_2), in the electrochemical process accelerate significantly. This change directly enhances electrochemical reaction activity, manifested as a substantial increase in current density, indicating that more charge carriers pass through the electrodes per unit time, participating in the energy conversion process. Meanwhile, the output voltage initially increases and then gradually decreases. When the fuel utilization reaches 0.79, the SOFC achieves a maximum output voltage of 0.78V, and with the increase in power generation, its efficiency also improves.

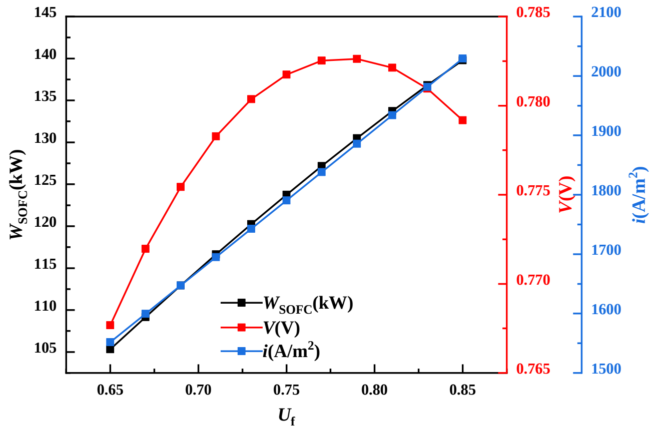

Fig 4 Impact of Fuel Utilization on the Electrochemical Reaction Mechanism within the SOFC

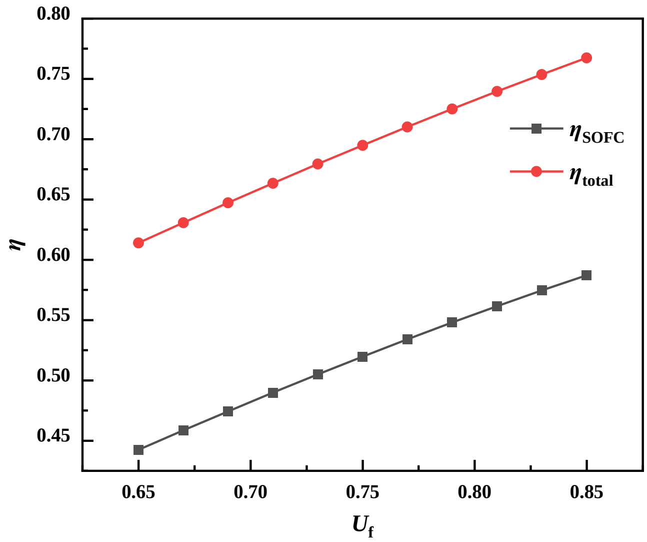

Fig 5 Impact of Fuel Utilization on SOFC Power Generation Efficiency and Total Efficiency of the Hybrid System

Fig 5 further deepens the understanding of the impact of fuel utilization on the power generation performance of the SOFC-IBC system. The research data clearly show that with the continuous increase in fuel utilization, the system achieves significant growth in power generation efficiency and a positive upward trend in overall efficiency. This finding reveals that optimizing fuel utilization enables the system to more efficiently convert chemical energy into electrical and usable thermal energy, demonstrating dual optimization of energy conversion and utilization efficiency. It is worth noting that although the total output power of the system increases with higher fuel utilization, the growth rate gradually slows. This phenomenon suggests that while pursuing higher fuel utilization, there is a diminishing efficiency gain effect.

3.3 Exergy Analysis

Under the discussed system operating conditions, we can accurately calculate the exergy values distribution at various key nodes within the system based on the thermodynamic property parameters of each stream, such as molar flow rate and pressure. Table 5 summarizes the exergy balance equations of the hybrid power generation system established in this paper. These equations quantify the exergy destructions in various subcomponents and the entire hybrid power generation system, based on which the exergy efficiency of each system is calculated. The table shows that the heat exchanger, afterburner, and SOFC are the primary sources of total exergy destruction in the system.

Table 5. Exergy Output Results of System D

Component	$\dot{E}_{F,k}$ (kW)	$\dot{E}_{P,k}$ (kW)	$\dot{E}_{D}$ (kW)	$\eta_{\dot{E},k}$ (%)
Fuel fan	247.19	247.19	0.00	100.00
Mixer	359.22	354.45	4.76	98.67
Reformer	354.45	351.79	2.67	99.25
HE1	401.72	400.21	1.49	99.63
SOFC	430.45	421.89	8.56	98.01
Air fan	0.95	0.94	0.01	98.75
HE2	78.59	66.81	11.78	85.02
T2	96.26	93.07	3.19	96.68
C2	14.62	9.97	4.65	68.17
Afterburner	76.63	68.81	7.82	89.80
T1	68.81	67.94	0.87	98.74
C1	13.54	13.08	0.46	96.59
Condensation process	14.11	13.15	0.96	93.22
CO_2 treatment process +Blower	13.70	13.47	0.23	98.34
Total	288.02	182.77	47.44	63.46

Specifically, the chemical reactions occurring within the afterburner, the significant temperature difference across the heat exchanger causing heat transfer efficiency losses, and the complex chemical reactions within the SOFC unit coupled with non-ideal electrical energy conversion mechanisms collectively result in significant exergy destructions within the system. Furthermore, Fig 6 visually presents the distribution of exergy destructions in various components of the hybrid system. It can be seen that the air preheater in the hybrid system shows the highest exergy destruction proportion, reaching 24.83%. The exergy efficiency of the hybrid system is 63.46%, while the total exergy destruction is as high as 47.44 kW. Significant exergy destructions are generally present in the heat exchangers of the hybrid system during heat exchange. This is because heat exchangers rely on temperature differences for heat transfer. Although high temperature differences can lead to higher heat exchange efficiency, according to the second law of thermodynamics, the heat transfer process driven by temperature differences is inherently irreversible, resulting in significant exergy destructions.

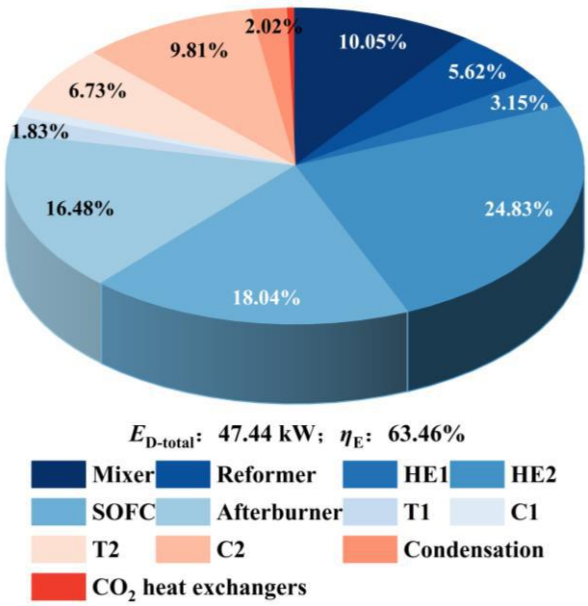

Fig 6 Exergy destruction Distribution of Each Component in the Hybrid System

The exergy destructions in the SOFC can be attributed to the following aspects: 1) the irreversibility of electrochemical reactions, which is a direct result of the second law of thermodynamics; 2) polarization effects caused by the resistance of electrolyte and electrode materials, leading to overpotentials or polarization losses when current flows; 3) incomplete chemical reactions leading to incomplete conversion of fuel and oxidant into electrical energy; 4) inadequate waste heat management, i.e., the heat generated during fuel cell operation is not effectively recovered, leading to exergy destructions; 5) heat conduction and radiation within the SOFC also cause exergy destructions. The afterburner's exergy destruction is due to the irreversibility of internal chemical reactions and the significant temperature difference between the inlet and outlet fluids.

Such in-depth analysis not only deepens our understanding of the mechanisms of exergy transfer and conversion within each system but also provides critical data support and theoretical guidance for optimizing system performance, thereby aiding in the design and implementation of targeted improvement measures to enhance the energy conversion efficiency of the entire hybrid power generation system.

4. CONCLUSION

This study fully utilized the characteristics of the IBC system operating under atmospheric conditions, aiming to recover the high-temperature waste heat resources generated by atmospheric Solid Oxide Fuel Cells (SOFC). By comprehensively applying process simulation techniques and in-depth theoretical analysis methods, an accurate SOFC-IBC hybrid power generation system model based on CO_2 recycling was constructed, and the modulation effect of fuel utilization rate changes on the overall system performance was thoroughly investigated. On this basis, further exergy analysis tools were used to meticulously analyze the energy conversion and transfer mechanisms within the system to fully reveal its efficient operation's physical nature.

The research results highlight that when the fuel utilization factor is set to 0.85, the SOFC-IBC hybrid power generation system achieves optimal performance, reaching a peak total efficiency of 76.74%, while the system output power reaches 182.77 kW. Additionally, from an exergy perspective, the system's exergy efficiency also reached an impressive 63.46%, further validating its efficiency and rationality in the energy conversion process.

These research findings not only validate the effectiveness of the constructed model but also provide important reference and theoretical support for developing efficient and environmentally friendly energy conversion systems, having profound significance in promoting the development of future clean energy technologies.

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