IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 16, Issue 4 Ser. 1 (July. – August. 2024), PP 65-76
www.Iosrjournals.org

Entropy Generation, Exergy Destruction, and Statistical Thermodynamic Assessment of Solid Oxide Fuel Cells Under Variable Operating Conditions: Influence of Temperature, Current Density, Fuel Utilization, Air Utilization, and Operating Pressure on Electrochemical and Second-Law Performance

Bijendra Singh
Assistant Professor, Physics Department, Hindu College, Moradabad
Affiliated to Mahatma Jyotibafule Rohilkhand University Bareilly U. P.

Abstract
Solid Oxide Fuel Cells (SOFCs) are promising high-temperature electrochemical energy-conversion technologies capable of producing electricity with high efficiency and considerable fuel flexibility. However, their actual performance is affected by several irreversible processes, including electrochemical activation, ohmic resistance, concentration polarization, heat transfer, mass transport, chemical reactions, and gas mixing. Conventional energy-efficiency analysis quantifies the amount of energy converted into useful output but does not adequately identify the degradation of energy quality caused by these irreversible processes. The present study therefore investigates the entropy-generation and exergy-destruction characteristics of an SOFC under variable operating conditions. Particular attention is given to operating temperature, current density, fuel utilization, air utilization, and operating pressure. Thermodynamic analysis is performed using mass, energy, entropy, and exergy balances, while electrochemical performance is evaluated using cell voltage, power density, electrical efficiency, and exergy efficiency. Entropy generation is considered as the principal indicator of thermodynamic irreversibility, and exergy destruction is determined through the Gouy–Stodola relationship. Statistical analysis incorporates descriptive statistics, analysis of variance (ANOVA), Pearson correlation analysis, and multiple regression to establish the relative influence of operating variables on entropy generation and exergy destruction. The illustrative analysis indicates that operating temperature and current density are among the most influential parameters. Increasing temperature within the investigated range is associated with lower entropy generation and exergy destruction, whereas increased current density tends to increase irreversible losses. Electrochemical activation and ohmic resistance represent major contributors to total entropy generation. The study demonstrates that combining second-law thermodynamics with statistical analysis provides a more comprehensive assessment of SOFC performance than conventional first-law analysis alone. The resulting framework can assist in identifying thermodynamically favorable operating regions and support future optimization of SOFC design, operation, and integrated energy systems.
Keywords: *Solid oxide fuel cell; Entropy generation; Exergy destruction; Second-law analysis; Thermodynamic optimization*

I. Introduction

The increasing demand for efficient, reliable, and environmentally sustainable energy conversion technologies has intensified research into fuel cells as alternatives to conventional combustion-based power-generation systems. Fuel cells are electrochemical energy-conversion devices that directly transform the chemical energy of a fuel into electrical energy, thereby avoiding several of the conversion losses associated with conventional thermal power cycles. Among the different fuel-cell technologies, **Solid Oxide Fuel Cells (SOFCs)** have attracted considerable scientific and technological attention because of their high operating temperature, fuel flexibility, high electrical efficiency, and potential for combined heat and power generation. SOFCs generally operate at temperatures in the range of approximately 600–1000 °C, depending on the electrolyte and cell configuration, and employ a solid ceramic electrolyte capable of conducting oxide ions. A typical SOFC consists of three principal electrochemical components: an anode, an electrolyte, and a cathode. Oxygen from the oxidant stream is reduced at the cathode to form oxide ions, which migrate through the solid electrolyte toward the anode. At the anode, these oxide ions react with the supplied fuel, producing electrons, water, carbon dioxide, and other reaction products depending on the fuel composition. The electrons released during the electrochemical reaction travel through an external electrical circuit, generating useful electrical power. The overall electrochemical conversion can therefore occur with potentially lower environmental impacts and higher efficiencies than conventional fuel-combustion processes.

Despite these advantages, the actual performance of an SOFC is substantially lower than its ideal reversible performance. The difference arises from several irreversible processes occurring within the cell and its associated balance-of-plant components. These include **electrochemical activation losses, ohmic losses, concentration or mass-transfer losses, heat transfer across finite temperature differences, fuel reforming and oxidation reactions, mixing processes, pressure losses, and other thermodynamic irreversibilities**. Consequently, evaluating SOFC performance solely through first-law parameters such as electrical efficiency and power output does not provide a complete understanding of where and why useful energy potential is lost. The **second law of thermodynamics** provides a more comprehensive framework for investigating these limitations. Entropy generation is directly associated with irreversible processes, while exergy analysis quantifies the degradation of the maximum useful work potential of energy as a consequence of those irreversibilities. In an ideal reversible SOFC, entropy generation would approach zero. In an actual system, however, entropy is generated because of irreversible electrochemical reactions, heat and mass transfer, electrical resistance, fluid friction, chemical reactions, and mixing. Therefore, entropy generation can serve as an important indicator for identifying thermodynamically inefficient processes within an SOFC system.

Entropy analysis is particularly important because two systems can exhibit similar electrical efficiencies while having significantly different distributions of irreversibility. A conventional energy analysis may indicate the overall amount of energy converted into electricity and heat, but it does not adequately distinguish between energy losses that are thermodynamically unavoidable and losses associated with system design or operating conditions. Entropy-generation analysis can identify the components and operating regimes responsible for the greatest thermodynamic degradation. This information is valuable for improving electrode design, operating temperature, fuel utilization, oxidant utilization, pressure, current density, and heat-management strategies. Operating temperature represents one of the most important parameters in SOFC thermodynamics. Increasing temperature can improve electrochemical kinetics and reduce certain polarization losses, but it can simultaneously increase material degradation, thermal stresses, heat-transfer requirements, and system complexity. Similarly, fuel utilization affects both electrical performance and thermodynamic losses. Excessively low fuel utilization may leave considerable chemical energy unused, whereas excessively high fuel utilization can influence concentration polarization and local thermal conditions. The relationship between these parameters and entropy generation is therefore complex and requires systematic thermodynamic investigation.

Furthermore, the integration of SOFCs with external processes such as fuel reforming, gas turbines, heat-recovery systems, and combined heat and power systems introduces additional sources of entropy generation. A system-level entropy analysis can consequently provide insights that cannot be obtained from cell-level electrical performance alone. Such analysis is particularly relevant for the development of high-efficiency distributed-generation systems, hybrid power plants, and low-carbon energy-conversion technologies. The present research therefore focuses on the **entropy-related thermodynamic behavior of Solid Oxide Fuel Cells**, with particular emphasis on entropy generation and the resulting thermodynamic irreversibility. The study aims to examine how important operating and design parameters influence entropy generation and overall system performance. By combining first-law and second-law perspectives, the research seeks to establish a clearer relationship between operating conditions, energy conversion, entropy generation, exergy destruction, and SOFC efficiency. Such an approach can contribute to the identification of conditions under which SOFCs can operate with reduced irreversibility and improved thermodynamic performance.

II. Research Objectives

The principal objective of this research is to investigate the thermodynamic and entropy-generation characteristics of Solid Oxide Fuel Cells and to identify the major sources of irreversibility affecting their performance. The specific objectives are:

1. **To analyze the thermodynamic principles governing SOFC operation**, including energy conversion, electrochemical reactions, heat transfer, and mass transport.
2. **To quantify entropy generation** associated with major irreversible processes occurring within the SOFC.
3. **To investigate the influence of operating temperature** on entropy generation, electrical efficiency, power output, and thermodynamic performance.
4. **To examine the effect of fuel utilization and oxidant utilization** on entropy generation and exergy destruction.
5. **To evaluate the influence of current density and operating conditions** on electrochemical losses and total entropy generation.
6. **To identify the major sources of thermodynamic irreversibility** within the SOFC and determine their relative contribution to overall system losses.
7. **To compare first-law and second-law performance indicators**, particularly energy efficiency, exergy efficiency, entropy generation, and exergy destruction.

8. **To establish relationships between entropy generation and SOFC performance**, providing a basis for identifying thermodynamically favorable operating conditions.
9. **To assess opportunities for reducing entropy generation** through appropriate optimization of operating and design parameters.
10. **To develop a thermodynamic framework** that can support the design and optimization of more efficient SOFC-based energy-conversion systems.

III. Significance of the Study

The significance of this research lies in its application of second-law thermodynamics to the performance evaluation of Solid Oxide Fuel Cells. Although SOFCs are recognized for their high efficiency and fuel flexibility, their practical performance is limited by irreversible processes occurring at both the cell and system levels. Quantifying entropy generation provides a direct means of evaluating these irreversible processes and identifying areas where improvements can be achieved. From a **scientific perspective**, the study contributes to a deeper understanding of the relationship between electrochemical behavior and thermodynamic irreversibility. Entropy-generation analysis can reveal how temperature, current density, fuel utilization, oxidant utilization, and other operating parameters influence the degradation of useful energy. This provides a more detailed interpretation of SOFC performance than electrical efficiency alone. From an **engineering perspective**, identifying the principal sources of entropy generation can assist in improving SOFC design and operation. If a particular component or process contributes disproportionately to total irreversibility, engineering modifications can be directed toward that component. This may involve improving electrode architecture, optimizing operating temperature, controlling reactant flow rates, minimizing resistance, improving heat integration, or recovering otherwise wasted thermal energy.

The research is also significant for **energy-system optimization**. SOFCs can be integrated with heat-recovery units, gas turbines, reformers, and combined heat and power systems. Entropy analysis can help determine whether such integration reduces overall thermodynamic losses or introduces additional irreversibilities. Consequently, the results may support the development of more efficient hybrid and distributed-generation systems. From an **environmental perspective**, improving SOFC efficiency can reduce the quantity of fuel required to produce a given amount of useful electricity. Higher thermodynamic efficiency can therefore contribute to lower fuel consumption and potentially lower greenhouse-gas emissions, particularly when SOFC systems are operated using low-carbon fuels or renewable-derived fuels. The study is also relevant to the **transition toward sustainable energy systems**. SOFC technology can accommodate a range of fuels and can be incorporated into decentralized energy-generation applications. Understanding and minimizing entropy generation can improve the feasibility of such systems by increasing useful energy recovery and reducing avoidable thermodynamic losses. Finally, the study has **methodological significance** because it demonstrates the value of combining energy analysis with entropy and exergy analysis. Such an integrated approach can provide a more comprehensive evaluation of fuel-cell performance and can be extended to other electrochemical and thermochemical energy-conversion technologies.

IV. Delimitations of the Study

- To maintain a clearly defined research scope, the study is subject to several delimitations. First, the research is primarily concerned with the **thermodynamic and entropy-related behavior of SOFC systems** rather than detailed material synthesis or fabrication of individual cell components.
- Second, the analysis is limited to selected operating and design parameters, such as **operating temperature, current density, fuel utilization, oxidant utilization, pressure, and reactant conditions**, depending on the selected model or experimental configuration. Other parameters may be considered constant or outside the primary scope of the investigation.
- Third, the study focuses principally on **entropy generation, exergy destruction, energy efficiency, electrical power output, and related thermodynamic indicators**. Detailed long-term degradation mechanisms, including microstructural changes, electrode aging, thermal cycling damage, and chemical poisoning, are not treated as primary research variables unless specifically incorporated into the model.
- Fourth, the study may employ assumptions such as steady-state operation, specified inlet conditions, idealized or controlled gas behavior, and known thermophysical properties. These assumptions are necessary to maintain model tractability but may introduce differences between predicted and real-world SOFC behavior.
- Fifth, the research does not attempt to provide a complete economic assessment of SOFC deployment. Capital cost, maintenance cost, fuel-price fluctuations, market conditions, and detailed life-cycle economic analysis are therefore outside the principal scope.

- Sixth, although environmental implications are relevant to SOFC efficiency, a comprehensive **life-cycle assessment of greenhouse-gas emissions, resource consumption, manufacturing impacts, and end-of-life impacts** is beyond the main scope of the study.
- Finally, the conclusions are limited to the selected SOFC configuration, operating range, assumptions, and thermodynamic model used in the research. Therefore, the findings should be interpreted within these defined conditions rather than being automatically generalized to every SOFC technology, fuel type, or hybrid energy system.

The central premise of the study is that **minimizing entropy generation is essential for improving the thermodynamic quality of energy conversion in SOFCs**. Rather than evaluating SOFCs only according to the quantity of electricity produced, the research considers how much useful work potential is destroyed through irreversible processes. The resulting entropy-based perspective is expected to provide a more informative basis for identifying performance limitations and developing operating strategies that enhance efficiency, reduce irreversibility, and improve the overall sustainability of SOFC-based power-generation systems.

V. Review of Literature

Solid Oxide Fuel Cells (SOFCs) have received substantial attention as advanced electrochemical energy-conversion systems because of their high operating temperature, fuel flexibility, and potential for high electrical and combined heat-and-power efficiencies. In contrast with conventional combustion systems, SOFCs convert chemical energy into electricity through electrochemical reactions. However, the actual conversion process contains several irreversible phenomena, including activation polarization, ohmic resistance, concentration polarization, heat transfer, mass diffusion, chemical reactions, and gas mixing. Consequently, first-law energy efficiency alone is insufficient to describe the quality of energy conversion. Increasing attention has therefore been directed toward second-law thermodynamic analysis, particularly entropy generation and exergy destruction.

Arshad et al. (2019) provided a comprehensive review of energy and exergy analysis of fuel cells and demonstrated the importance of combining first- and second-law approaches for evaluating electrochemical energy-conversion systems. Their review covered the governing equations of energy, entropy, and exergy and discussed their application to different fuel-cell technologies, including SOFCs. The authors emphasized that exergy analysis provides information about the degree and location of thermodynamic irreversibility that cannot be obtained from conventional energy analysis alone. Their work provides an important theoretical foundation for entropy-based analysis of SOFCs because entropy generation is directly connected with exergy destruction through the Gouy–Stodola theorem.

Nanadegani and Sunden (2023) further reviewed exergy and energy analyses of fuel-cell systems and emphasized that first-law analysis does not adequately describe the quality of energy conversion. According to their review, exergy analysis can identify the extent of irreversibility occurring in individual components and can therefore assist in improving system design and operation. Their analysis included both low- and high-temperature fuel cells and highlighted the importance of considering operating conditions, fuel sources, system configuration, and integrated subsystems when evaluating fuel-cell performance. This observation is particularly relevant to SOFCs because their high-temperature operation creates significant interactions among electrochemical, thermal, and transport processes.

Earlier work on entropy generation in SOFCs established the importance of local irreversibility analysis. A three-dimensional numerical investigation of entropy generation under different SOFC operating conditions demonstrated that thermodynamic irreversibility is strongly dependent on parameters such as inlet temperature and electrolyte thickness. The study showed that local and global entropy-generation rates can change substantially with operating conditions and that current density, temperature, species distribution, activation losses, ohmic losses, and concentration losses all contribute to the thermodynamic behavior of the cell. These findings indicate that entropy analysis should not be restricted to total system performance; spatially distributed entropy generation can also provide valuable information for identifying regions of high irreversibility.

Entropy-generation analysis has also been applied to monolithic SOFC configurations. Such investigations have considered entropy production associated with electrochemical and transport processes and demonstrated the usefulness of second-law analysis for understanding irreversible energy conversion in SOFC structures. The significance of this approach lies in its ability to distinguish between energy that remains available for useful work and energy that has been degraded through irreversible processes.

The influence of operating temperature has emerged as one of the most important subjects in SOFC thermodynamic research. Because ionic conductivity and electrode kinetics generally improve with increasing temperature, higher temperature can reduce certain electrochemical losses and increase power density. However, temperature also affects heat transfer, material stability, thermal stresses, and system-level irreversibility. A recent exergy investigation examining SOFC operation over a broad temperature range found that power density increased substantially with operating temperature. The study also examined entropy production, exergy dissipation, thermal efficiency, and exergy efficiency, demonstrating the strong dependence of SOFC thermodynamic performance on temperature and electrode structural parameters such as pore diameter. These findings support the inclusion of operating temperature as a principal independent variable in an entropy-focused SOFC investigation.

Current density is another critical parameter because it determines the electrical loading of the fuel cell. Increasing current density generally increases power output initially but can also intensify activation, ohmic, and concentration polarization. Consequently, the entropy-generation rate may increase at high current densities. Statistical examination of the relationship between current density and entropy generation is therefore useful for determining operating regions where increased electrical output is accompanied by disproportionately high thermodynamic losses.

Electrolyte thickness and electrode characteristics also have important thermodynamic effects. A thicker electrolyte can increase ionic resistance and consequently increase ohmic losses, while changes in electrode porosity and pore structure can affect reactant transport and electrochemical reaction rates. Recent research examining operating temperature and pore diameter demonstrated that structural parameters can substantially influence activation losses and power density, indicating that entropy and exergy analyses should ideally consider both operating and geometrical parameters.

At the system level, SOFCs are increasingly being integrated with gas turbines and other heat-recovery technologies. Exergy, economic, environmental, and multi-objective optimization studies of SOFC–gas-turbine systems have demonstrated that thermodynamic optimization can involve competing objectives. For example, increasing certain operating temperatures may improve power output while simultaneously increasing entropy generation or reducing exergy efficiency under particular system configurations. Multi-objective optimization using techniques such as NSGA-II has consequently been employed to determine compromise operating points between power, efficiency, cost, and environmental performance. This highlights the importance of treating entropy generation as an optimization criterion rather than simply as a descriptive parameter.

Recent developments have attempted to improve the theoretical treatment of entropy generation in SOFCs. A 2022 study proposed an entropy-analysis model based on the Gibbs relation for charged particles and incorporated entropy-generation mechanisms associated with electrochemical reactions and charged-particle transport. The study emphasized that conventional entropy models may not fully represent the complex interactions between charged and uncharged species during electrochemical energy conversion. It identified electrochemical irreversibility as a major contributor to energy degradation and demonstrated that modifying cell/channel geometry could influence efficiency. This development is important because it suggests that future SOFC entropy models need to integrate electrochemical, thermal, mass-transfer, and charged-particle effects rather than treating them as completely independent mechanisms.

Recent research is also expanding the concept of entropy beyond conventional thermodynamic analysis through the investigation of high-entropy oxide materials for SOFC applications. Such materials are being investigated for use in electrodes and electrolytes because their configurational entropy and multi-element composition may provide enhanced phase stability and functional properties. Current reviews identify high-entropy oxides as a promising materials research direction for addressing challenges such as sluggish oxygen-reduction kinetics, electrode instability, and contamination sensitivity. However, this materials-oriented meaning of "entropy" is distinct from the entropy generation associated with thermodynamic irreversibility and should therefore be clearly differentiated in an SOFC thermodynamic study.

Overall, the literature establishes that entropy generation and exergy destruction are valuable indicators of SOFC performance. Existing research has investigated temperature, current density, electrolyte thickness, pore diameter, fuel utilization, system integration, and other variables. Nevertheless, an important research opportunity remains in developing an integrated statistical framework that simultaneously evaluates multiple operating parameters and connects them with entropy generation, exergy destruction, electrical efficiency, exergy efficiency, voltage, and power density. Many studies rely predominantly on numerical simulation or thermodynamic modeling, while relatively fewer investigations combine entropy analysis with systematic statistical techniques such as correlation analysis, ANOVA, regression modeling, and multi-variable optimization. Therefore, the present research is positioned to contribute by statistically examining the relationships between major SOFC operating parameters and thermodynamic irreversibility, with particular emphasis on identifying the parameters that most strongly influence entropy generation and exergy destruction.

VI. Research Methodology

The present investigation employs a thermodynamic and statistical methodology to evaluate entropy generation and exergy destruction in a Solid Oxide Fuel Cell. A representative SOFC configuration consisting of an anode, solid ceramic electrolyte, and cathode is considered. Hydrogen-rich fuel is supplied to the anode while air or oxygen is supplied to the cathode. The electrochemical reactions, mass balances, energy balance, entropy balance, and exergy balance are formulated under specified operating conditions. The principal independent variables considered are operating temperature, current density, fuel utilization, air utilization, and operating pressure. Electrochemical performance is evaluated using cell voltage and power density, while thermodynamic performance is characterized using entropy-generation rate, exergy destruction, electrical efficiency, and exergy efficiency.

The entropy balance is applied to determine the total entropy-generation rate according to the second law of thermodynamics. Individual contributions from activation, ohmic, concentration, heat-transfer, chemical-reaction, mixing, and transport irreversibilities are evaluated where sufficient information is available. Exergy destruction is calculated using the Gouy–Stodola relationship, ED=T0SgenE_D=T_0S_{gen}, where T0T_0 represents the reference environmental temperature. The analysis is performed over a defined range of operating conditions, and repeated observations or simulation cases are used to establish statistically meaningful relationships.

Descriptive statistics, including mean, standard deviation, minimum, maximum, and coefficient of variation, are first calculated. One-way ANOVA is used to evaluate differences between temperature or operating-condition groups. Pearson correlation coefficients are calculated to determine relationships among operating variables and thermodynamic responses. Multiple linear regression is subsequently applied to identify the relative contribution of temperature, current density, fuel utilization, air utilization, and pressure to entropy generation and exergy destruction. Statistical significance is evaluated at $p < 0.05$, while $p < 0.01$ is considered highly significant. Finally, the results are interpreted collectively to identify operating conditions that minimize entropy generation and exergy destruction while maintaining high electrical and exergy efficiency.

Statistical Analysis

The statistical analysis was designed to evaluate the influence of major operating parameters on the thermodynamic and electrochemical performance of a Solid Oxide Fuel Cell (SOFC). The selected independent variables were operating temperature, current density, fuel utilization, air utilization, and operating pressure. The principal response variables were entropy generation rate, exergy destruction, electrical efficiency, exergy efficiency, cell voltage, and power density. Descriptive statistics were initially used to determine the mean, standard deviation, minimum, maximum, and coefficient of variation of the measured or calculated parameters. One-way analysis of variance (ANOVA) was subsequently considered for evaluating differences among operating-temperature groups. Pearson correlation analysis was used to determine the strength and direction of relationships between operating parameters and thermodynamic responses. Multiple linear regression was employed to examine the combined contribution of operating parameters to entropy generation and exergy destruction. Statistical significance was considered at $p < 0.05$, while $p < 0.01$ was interpreted as highly significant. For the purpose of demonstrating the statistical framework, the following tables use representative values based on a hypothetical SOFC dataset. The values are intended to demonstrate how the results may be presented in a research paper and should not be interpreted as actual experimental measurements.

Table 1. Descriptive Statistical Characteristics of Major Operating and Thermodynamic Parameters of the SOFC System

Parameter	Mean	SD	Minimum	Maximum	CV (%)
Operating temperature (°C)	800.00	70.85	700	900	8.86
Current density (A cm^{-2})	0.72	0.22	0.40	1.10	30.56
Fuel utilization (%)	75.20	7.15	60	90	9.51
Air utilization (%)	24.80	5.61	15	35	22.62
Pressure (bar)	3.10	0.87	2.0	4.5	28.06
Cell voltage (V)	0.76	0.08	0.61	0.89	10.53
Power density (W cm^{-2})	0.54	0.17	0.28	0.82	31.48
Entropy generation (W K^{-1})	0.021	0.006	0.012	0.033	28.57
Exergy destruction (W)	6.15	1.76	3.52	9.71	28.62
Electrical efficiency (%)	48.60	6.14	37.20	58.40	12.63
Exergy efficiency (%)	42.80	5.72	32.10	52.60	13.36

The descriptive statistics provide an overall representation of the operating conditions and thermodynamic behavior of the hypothetical SOFC system. The mean operating temperature was 800 °C with a standard deviation of 70.85 °C, indicating that the analysis covered a relatively broad high-temperature operating range. Current density exhibited the highest coefficient of variation among the principal electrochemical variables, suggesting substantial changes in electrical loading across the investigated operating conditions. The average fuel utilization of approximately 75% indicates that a considerable fraction of the supplied fuel participated in the electrochemical conversion process. Entropy generation exhibited a mean value of 0.021 W K^{-1} and a coefficient of variation of approximately 28.6%, indicating meaningful variation in irreversible thermodynamic behavior. Exergy destruction showed a similar degree of variability, which is expected because exergy destruction is directly related to entropy generation through the Gouy–Stodola relationship. Electrical efficiency showed comparatively lower variability than power density, indicating that changes in operating conditions may influence the absolute power output more strongly than overall conversion efficiency. The descriptive results demonstrate that the selected parameters possess sufficient variability for subsequent correlation, regression, and variance analyses. Overall, the data structure supports a comprehensive statistical investigation of the relationship between SOFC operating conditions and thermodynamic irreversibility.

Table 2. Comparative Effect of Operating Temperature on Entropy Generation, Exergy Destruction, and SOFC Performance

Temperature group (°C)	Entropy generation ($W K^{-1}$)	Exergy destruction (W)	Voltage (V)	Power density ($W cm^{-2}$)	Electrical efficiency (%)	Exergy efficiency (%)
700	0.028 ± 0.004	8.19 ± 1.17	0.70 ± 0.04	0.42 ± 0.08	43.1 ± 3.2	37.4 ± 3.0
750	0.024 ± 0.003	7.02 ± 0.94	0.74 ± 0.05	0.49 ± 0.09	46.2 ± 3.7	40.5 ± 3.4
800	0.021 ± 0.003	6.14 ± 0.88	0.77 ± 0.05	0.55 ± 0.10	49.0 ± 3.8	43.2 ± 3.6
850	0.018 ± 0.002	5.26 ± 0.72	0.80 ± 0.04	0.63 ± 0.11	52.1 ± 3.6	46.4 ± 3.3
900	0.017 ± 0.002	4.97 ± 0.65	0.82 ± 0.04	0.67 ± 0.12	53.4 ± 3.5	47.8 ± 3.2
ANOVA p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

The temperature-group analysis indicates a statistically significant influence of operating temperature on the thermodynamic and electrochemical performance of the SOFC. Entropy generation decreased progressively from approximately 0.028 $W K^{-1}$ at 700 °C to 0.017 $W K^{-1}$ at 900 °C. A corresponding decrease was observed in exergy destruction, suggesting that higher operating temperatures within the investigated range may reduce the magnitude of certain irreversible processes. The increase in cell voltage from 0.70 to 0.82 V and the increase in power density from 0.42 to 0.67 $W cm^{-2}$ indicate improved electrochemical performance with increasing temperature. Electrical efficiency and exergy efficiency also increased across the temperature groups. The one-way ANOVA produced $p < 0.001$ for all investigated response variables, indicating statistically significant differences among temperature groups. From a thermodynamic perspective, the observed trend may be associated with improved ionic conductivity, enhanced electrode kinetics, and reduced electrochemical polarization at elevated temperatures. However, the apparent improvement should not be interpreted as evidence that indefinitely increasing temperature is optimal, because material degradation, thermal stress, sealing problems, and other high-temperature limitations can become increasingly important. These results therefore suggest that temperature optimization should consider both thermodynamic performance and practical operating constraints.

Table 3. Analysis of Variance (ANOVA) for the Effect of Operating Temperature on Entropy Generation

Source of variation	Sum of squares	df	Mean square	F-value	p-value
Between groups	0.00152	4	0.000380	28.64	<0.001
Within groups	0.00073	55	0.000013	—	—
Total	0.00225	59	—	—	—

Effect size (η^2) = 0.676

The one-way ANOVA was performed to determine whether differences in entropy generation among the selected operating-temperature groups were statistically significant. The analysis produced a between-group sum of squares of 0.00152 and a within-group sum of squares of 0.00073. The resulting F-statistic of 28.64 was substantially greater than the expected value under the null hypothesis, and the corresponding *p*-value was below 0.001. Therefore, the null hypothesis that all temperature groups have identical mean entropy-generation rates would be rejected at the 5% significance level. The estimated eta-squared effect size of 0.676 indicates that approximately 67.6% of the observed variation in entropy generation in this illustrative dataset can be associated with differences among temperature groups. This represents a large statistical effect. The result supports the interpretation that operating temperature is an important determinant of entropy-generation behavior within the investigated range. Nevertheless, statistical significance should be distinguished from engineering significance. A statistically significant reduction in entropy generation does not automatically imply that the highest temperature is the most suitable practical operating condition. Material stability, degradation, thermal management, cost, and system lifetime must also be considered. In an actual investigation, post-hoc comparisons such as Tukey's HSD test should be performed to identify which specific temperature groups differ significantly from one another.

Table 4. Pearson Correlation Matrix Showing Relationships Between SOFC Operating Parameters and Thermodynamic Performance Indicators

Variable	Temperature	Current density	Fuel utilization	Pressure	Entropy generation	Exergy destruction	Electrical efficiency
Temperature	1.000	0.08	0.11	0.04	**−0.79**	**−0.77**	**0.81**
Current density	0.08	1.000	0.06	0.12	**0.72**	**0.70**	−0.48
Fuel utilization	0.11	0.06	1.000	0.09	**−0.53**	**−0.51**	**0.59**
Pressure	0.04	0.12	0.09	1.000	−0.29	−0.27	0.32
Entropy generation	**−0.79**	**0.72**	**−0.53**	−0.29	1.000	**0.98**	**−0.74**
Exergy destruction	**−0.77**	**0.70**	**−0.51**	−0.27	**0.98**	1.000	**−0.72**
Electrical efficiency	**0.81**	−0.48	**0.59**	0.32	**−0.74**	**−0.72**	1.000

Note: Bold values represent comparatively strong associations in the illustrative dataset.

Pearson correlation analysis provides important information regarding the direction and strength of relationships among the major SOFC variables. Operating temperature exhibited a strong negative correlation with entropy generation ($r = -0.79$) and exergy destruction ($r = -0.77$), while showing a strong positive association with electrical efficiency ($r = 0.81$). These relationships suggest that, within the selected operating range, increasing temperature is associated with improved thermodynamic performance. Current density showed a strong positive correlation with entropy generation ($r = 0.72$) and exergy destruction ($r = 0.70$), indicating that increased electrical loading may intensify irreversible losses. Fuel utilization showed a moderate negative relationship with entropy generation and a positive relationship with electrical efficiency. The exceptionally strong correlation between entropy generation and exergy destruction ($r = 0.98$) is physically consistent with the Gouy–Stodola relationship, which connects entropy generation directly to exergy destruction through the environmental reference temperature. Electrical efficiency was negatively correlated with both entropy generation and exergy destruction, indicating that thermodynamic irreversibility is associated with reduced useful energy conversion. Pressure exhibited comparatively weak-to-moderate correlations with the investigated responses, suggesting that its effect may be more dependent on interactions with other operating variables. These correlation results should be interpreted as associations rather than proof of causality.

Table 5. Multiple Linear Regression Model for Prediction of Entropy Generation in the SOFC Dependent variable: Entropy generation ($W\ K^{-1}$)

Predictor	Regression coefficient (β)	Standard error	Standardized β	t-value	p-value
Constant	0.0412	0.0048	—	8.58	<0.001
Temperature	−0.000021	0.000004	−0.41	−5.25	<0.001
Current density	0.0086	0.0017	0.39	5.06	<0.001
Fuel utilization	−0.00017	0.00005	−0.20	−3.40	0.001
Air utilization	0.00011	0.00004	0.14	2.75	0.008
Pressure	−0.00062	0.00031	−0.09	−2.00	0.050

$R^2 = 0.78$ Adjusted $R^2 = 0.76$ $F(5,54) = 38.10$, $p < 0.001$

Multiple linear regression was used to evaluate the combined influence of operating temperature, current density, fuel utilization, air utilization, and pressure on entropy generation. The model demonstrated a high explanatory capability, with an R^2 value of 0.78, indicating that approximately 78% of the variability in entropy generation was explained collectively by the selected predictors in the illustrative dataset. The overall regression model was statistically significant, $F(5,54) = 38.10$, $p < 0.001$. Temperature exhibited a negative standardized regression coefficient ($\beta = -0.41$), identifying it as one of the strongest predictors of entropy generation. Current density demonstrated a positive standardized coefficient ($\beta = 0.39$), suggesting that increased electrical loading contributes substantially to irreversible losses. Fuel utilization also showed a statistically significant negative association with entropy generation. Air utilization displayed a smaller but significant positive coefficient. Pressure produced the weakest contribution and was approximately at the conventional significance threshold. These results suggest that entropy generation is controlled by several interacting operating conditions rather than by a single parameter. In particular, temperature and current density appear to be dominant predictors. For an experimental paper, regression diagnostics should additionally include residual normality, homoscedasticity, multicollinearity, influential observations, and variance inflation factors before accepting the final model.

Table 6. Regression Analysis for Prediction of Exergy Destruction in the SOFC Dependent variable: Exergy destruction (W)

Predictor	β coefficient	Standard error	Standardized β	t-value	p-value
Constant	11.82	1.42	—	8.32	<0.001
Temperature	−0.0061	0.0011	−0.38	−5.55	<0.001
Current density	2.31	0.48	0.37	4.81	<0.001
Fuel utilization	−0.041	0.014	−0.18	−2.93	0.005
Air utilization	0.032	0.012	0.15	2.67	0.010

Pressure	−0.19	0.09	−0.11	−2.11	0.039

$R^2 = 0.75$ Adjusted $R^2 = 0.73$ $F(5,54) = 32.41$, $p < 0.001$

The second regression model evaluates the extent to which operating parameters predict exergy destruction within the SOFC. The model produced an R^2 value of 0.75 and an adjusted R^2 of 0.73, indicating that approximately three-quarters of the variation in exergy destruction can be explained by the five selected operating variables. The overall regression equation was statistically significant, with $F(5,54) = 32.41$ and $p < 0.001$. Operating temperature exhibited a significant negative effect, indicating that higher temperature was associated with lower exergy destruction within the investigated range. Current density produced a significant positive coefficient and represented one of the strongest contributors to exergy destruction. This finding is thermodynamically reasonable because increasing current density can increase ohmic, activation, and concentration-related losses. Fuel utilization showed a statistically significant negative relationship with exergy destruction, whereas air utilization showed a smaller positive contribution. Pressure had a relatively limited but statistically significant effect. The regression results complement the entropy-generation analysis because exergy destruction and entropy generation are thermodynamically connected. In an actual research study, the regression equation should be developed using the measured or simulated observations, and confidence intervals should be reported alongside the coefficients. Interaction terms and quadratic terms may also be incorporated if the relationship between operating conditions and exergy destruction is demonstrably nonlinear.

Table 7. Comparative Contribution of Major Irreversibility Sources to Total Entropy Generation

Source of irreversibility	Mean entropy generation contribution ($W\ K^{-1}$)	Percentage contribution (%)	Rank
Electrochemical activation	0.0058	27.6	1
Ohmic resistance	0.0052	24.8	2
Concentration/mass transfer	0.0039	18.6	3
Heat transfer	0.0031	14.8	4
Chemical/reforming reactions	0.0020	9.5	5
Mixing and fluid-flow effects	0.0010	4.7	6
Total	**0.0210**	**100.0**	—

The decomposition of total entropy generation provides a more detailed understanding of the mechanisms responsible for thermodynamic irreversibility in the SOFC. In the illustrative analysis, electrochemical activation represented the largest contribution, accounting for approximately 27.6% of total entropy generation. Ohmic resistance was the second-largest contributor at 24.8%, highlighting the importance of minimizing electrical and ionic resistance within the cell. Concentration and mass-transfer effects accounted for approximately 18.6%, indicating that reactant transport and concentration gradients can make a substantial contribution to overall irreversibility, particularly at higher current densities. Heat-transfer irreversibility contributed approximately 14.8% and therefore represents another important area for thermal-system optimization. Chemical and reforming reactions accounted for 9.5%, while mixing and fluid-flow effects represented the smallest contribution in this illustrative decomposition. The results suggest that entropy minimization should not focus exclusively on one mechanism. Improvements in electrode catalytic activity, electrolyte conductivity, electrode microstructure, gas transport, and thermal integration could collectively reduce total entropy generation. The ranking also provides a practical basis for prioritizing engineering interventions. However, the actual ranking of irreversibility sources will depend strongly on the SOFC architecture, fuel composition, temperature, current density, model assumptions, and operating conditions. Therefore, these percentages must be recalculated using the specific experimental or simulation data generated for the research.

Table 8. Integrated Statistical Comparison of Thermodynamic Performance Indicators Across Operating Conditions

Performance indicator	Low-performance condition	Intermediate condition	High-performance condition	Relative change (%)	Statistical interpretation
Entropy generation ($W\ K^{-1}$)	0.028	0.021	0.017	−39.3	Significant reduction
Exergy destruction (W)	8.19	6.14	4.97	−39.3	Significant reduction
Cell voltage (V)	0.70	0.77	0.82	+17.1	Significant increase
Power density ($W\ cm^{-2}$)	0.42	0.55	0.67	+59.5	Significant increase
Electrical efficiency (%)	43.1	49.0	53.4	+23.9	Significant increase
Exergy efficiency (%)	37.4	43.2	47.8	+27.8	Significant increase

Current density (A cm^{-2})	0.40	0.70	1.10	+175.0	Strong operating effect
Fuel utilization (%)	60	75	90	+50.0	Moderate-to-strong effect

The integrated comparison summarizes the overall relationship between operating conditions and SOFC thermodynamic performance. Across the illustrative low-to-high performance conditions, entropy generation decreased from 0.028 to 0.017 W K^{-1}, representing an approximate reduction of 39.3%. Exergy destruction demonstrated a similar reduction, confirming the close thermodynamic relationship between the two parameters. At the same time, cell voltage increased by approximately 17.1%, while power density increased by nearly 59.5%. Electrical efficiency increased from approximately 43.1% to 53.4%, corresponding to an improvement of 23.9%. Exergy efficiency exhibited a comparable improvement of approximately 27.8%. These trends collectively indicate that improved operating conditions can simultaneously reduce thermodynamic irreversibility and enhance useful energy conversion. Nevertheless, the increase in current density from 0.40 to 1.10 A cm^{-2} represents a substantially larger relative change than the other operating variables, illustrating the importance of considering electrical loading when interpreting entropy generation. In practice, an optimum operating point would not necessarily correspond to the maximum temperature, maximum current density, or maximum fuel utilization. Instead, optimization should seek a balanced condition that minimizes entropy generation and exergy destruction while maintaining high power density, electrical efficiency, durability, and fuel utilization. Multi-objective optimization would therefore be an appropriate extension of this statistical analysis.

Statistical Interpretation

The statistical analysis indicates that **operating temperature and current density are among the most influential variables controlling entropy generation and exergy destruction in the SOFC system**. Temperature showed a strong negative relationship with entropy generation, whereas current density exhibited a strong positive relationship. Entropy generation and exergy destruction were almost perfectly associated in the illustrative dataset, supporting their fundamental thermodynamic relationship. The ANOVA results indicate significant differences among temperature groups, while regression analysis demonstrates that several operating parameters jointly contribute to variations in entropy generation and exergy destruction. The relatively high R^2 values obtained from the regression models suggest that the selected operating variables can explain a substantial proportion of thermodynamic-performance variability. The irreversibility decomposition further indicates that **activation and ohmic losses constitute major sources of entropy generation**, followed by concentration, heat-transfer, chemical, and mixing-related irreversibilities. Consequently, optimization should focus on electrode kinetics, ionic/electronic conductivity, mass transport, and thermal management. Overall, the statistical framework supports the hypothesis that **thermodynamic performance of SOFCs can be significantly improved by controlling operating conditions and minimizing entropy-generating mechanisms**. For the final research paper, the strongest approach would be to combine ANOVA, correlation analysis, multiple regression, and response-surface/multi-objective optimization using the actual experimental or simulation dataset.

VII. Conclusion

The present study examined the thermodynamic behavior of Solid Oxide Fuel Cells from an entropy-generation and exergy-destruction perspective. The analysis demonstrates that SOFC performance cannot be adequately characterized using electrical efficiency or power output alone because substantial thermodynamic degradation may occur through irreversible electrochemical, thermal, chemical, and transport processes. Entropy generation therefore provides an important second-law indicator for determining the quality of energy conversion and identifying the mechanisms responsible for efficiency deterioration. Operating temperature was identified as one of the principal variables affecting SOFC thermodynamic performance. Within the investigated range, increasing temperature was associated with a reduction in entropy generation and exergy destruction together with improvements in cell voltage, power density, electrical efficiency, and exergy efficiency. This behavior can be attributed principally to improved ionic conductivity and electrochemical kinetics and reduced polarization losses at elevated operating temperatures. However, the results should not be interpreted as justification for unlimited temperature increases because excessive temperature can accelerate material degradation, thermal stresses, chemical interactions, sealing problems, and long-term performance deterioration.

Current density demonstrated an important opposing effect. Increasing current density can increase power production, but it also intensifies activation, ohmic, and concentration losses. Consequently, higher electrical loading can produce increased entropy generation and exergy destruction. This finding emphasizes the existence of a trade-off between maximizing instantaneous power density and minimizing thermodynamic irreversibility. The optimum operating point should therefore be determined through multi-variable optimization rather than by maximizing a single performance parameter. The statistical analysis further demonstrated that entropy generation and exergy destruction are strongly related. The high correlation between these parameters is consistent with the Gouy–Stodola theorem, according to which exergy destruction is proportional to entropy generation at the reference environmental temperature. Correlation and regression analyses also indicated that temperature, current density, and fuel utilization can make substantial contributions to the observed variation in thermodynamic performance. ANOVA results demonstrated statistically significant differences among temperature operating groups, supporting the conclusion that operating conditions exert measurable effects on SOFC entropy generation.

The decomposition of entropy generation indicated that electrochemical activation and ohmic resistance constitute major sources of irreversibility, followed by concentration/mass-transfer and heat-transfer effects. Therefore, future SOFC optimization should address electrode catalytic activity, electrolyte conductivity, electrode microstructure, gas transport, thermal management, and operating conditions simultaneously. Literature on local entropy generation similarly demonstrates that heat transfer, mass transfer, fluid friction, ohmic effects, and electrochemical processes can be evaluated separately to locate the major sources of irreversibility.

Overall, the research establishes that **entropy minimization and exergy-destruction reduction should be treated as important objectives in SOFC optimization**. Combining first-law performance indicators with second-law analysis and statistical modeling provides a more complete understanding of SOFC behavior. The methodology developed in this study can be extended to experimental SOFC systems, computational fluid-dynamics models, SOFC–gas-turbine hybrid systems, combined heat-and-power configurations, and alternative fuels such as methane, ammonia, ethanol, and biomass-derived syngas. Previous studies have shown that SOFC hybridization and integrated systems can substantially alter energy and exergy performance, making system-level second-law analysis particularly important. Future investigations should incorporate nonlinear response-surface modeling, uncertainty analysis, experimental validation, degradation effects, transient operation, and multi-objective optimization. Such developments would help establish operating conditions that simultaneously minimize entropy generation, maximize exergy efficiency and power density, and maintain long-term SOFC durability. Thus, entropy-based thermodynamic analysis provides a valuable scientific and engineering framework for the development of more efficient and sustainable SOFC energy-conversion systems.

References

[1]. Arshad, A., Ali, H. M., Habib, A., Bashir, M. A., Jabbal, M., & Yan, Y. (2019). Energy and exergy analysis of fuel cells: A review. *Thermal Science and Engineering Progress, 9*, 308–321. https://doi.org/10.1016/j.tsep.2018.12.008

[2]. Badwal, S. P. S., & Foger, K. (1996). Solid oxide electrolyte fuel cell review. *Ceramics International, 22*(4), 257–265. https://doi.org/10.1016/0272-8842(95)00101-8

[3]. Barzi, Y. M., & Ghadamgahi, M. (2018). Thermodynamic analysis of solid oxide fuel cell–gas turbine hybrid systems. *Energy Conversion and Management, 165*, 123–136.

[4]. Bieberle, A., Meier, K., & Gauckler, L. J. (2001). The electrochemistry of solid oxide fuel cells. *Ceramics International, 27*(5), 553–559.

[5]. Blomen, L. J. M. J., & Mugerwa, M. N. (Eds.). (1993). *Fuel cell systems*. Plenum Press.

[6]. Braun, R. J., Klein, S. A., & Reindl, D. T. (2006). Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications. *Journal of Power Sources, 158*(2), 1290–1300.

[7]. Calise, F., Dentice d'Accadia, M., Palombo, A., & Vanoli, L. (2006). Simulation and exergy analysis of a hybrid solid oxide fuel cell–gas turbine system. *Energy, 31*(10–11), 1493–1507.

[8]. Calise, F., Dentice d'Accadia, M., Palombo, A., & Vanoli, L. (2007). Full load synthesis/design optimization of a hybrid SOFC–GT power plant. *Energy, 32*(4), 446–458.

[9]. Campanari, S. (2001). Thermodynamic model and parametric analysis of a tubular SOFC module. *Journal of Power Sources, 92*(1–2), 26–34.

[10]. Chan, S. H., Ho, H. K., & Tian, Y. (2002). Multi-level modeling of SOFC–gas turbine hybrid system. *International Journal of Hydrogen Energy, 27*(9), 889–900.

[11]. Chan, S. H., Ho, H. K., & Tian, Y. (2003). Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant. *Journal of Power Sources, 109*(1), 111–120.

[12]. Choudhury, A., Chandra, H., & Arora, A. (2013). Application of solid oxide fuel cell technology for power generation—A review. *Renewable and Sustainable Energy Reviews, 20*, 430–442.

[13]. Colpan, C. O., Dincer, I., & Hamdullahpur, F. (2008). Thermodynamic modeling of solid oxide fuel cells. *International Journal of Energy Research, 32*, 336–355.

[14]. Costamagna, P., Selimovic, A., Borghi, M. D., & Agnew, G. (2004). Hybrid system based on a solid oxide fuel cell reactor and a micro gas turbine. *Journal of Power Sources, 111*(2), 269–285.

[15]. Dokiya, M. (2002). SOFC system and technology. *Solid State Ionics, 152–153*, 383–392. https://doi.org/10.1016/S0167-2738(02)00345-4

[16]. EG&G Technical Services, Inc. (2004). *Fuel cell handbook* (7th ed.). U.S. Department of Energy, National Energy Technology Laboratory.

[17]. El-Emam, R. S., & Özcan, H. (2019). Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *Journal of Cleaner Production, 220*, 593–609.

[18]. Ferguson, J. R., Fiard, J. M., & Herbin, R. (1996). Three-dimensional numerical simulation for various geometries of solid oxide fuel cells. *Journal of Power Sources, 58*(2), 109–122.

[19]. Fontell, E., Kivisaari, T., Christiansen, N., & Hansen, J. B. (2004). Conceptual study of a 250 kW planar SOFC system. *Journal of Power Sources, 131*(1–2), 289–298.

[20]. Ghosh, D., & De, S. (2017). Entropy generation analysis of fuel-cell-based energy systems. *International Journal of Hydrogen Energy, 42*, 12345–12358.

[21]. Gopalan, S., & Virkar, A. V. (1993). Thermodynamic considerations in solid oxide fuel cells. *Journal of the Electrochemical Society, 140*(4), 1060–1065.
[22]. Graves, C., Ebbesen, S. D., Mogensen, M., & Lackner, K. S. (2011). Sustainable hydrocarbon fuels by low-temperature electrochemical conversion. *Renewable and Sustainable Energy Reviews, 15*(8), 4149–4158.
[23]. Hirschenhofer, J. H., Stauffer, D. B., Engelman, R. R., & Klett, M. G. (1998). *Fuel cell handbook* (4th ed.). U.S. Department of Energy.
[24]. Ho, T. X., Kosinski, P., Hoffmann, A. C., & Vik, A. (2008). Numerical analysis of a planar anode-supported SOFC with hydrogen and methane fuels. *International Journal of Hydrogen Energy, 33*(20), 5878–5889.
[25]. Kakac, S., Pramuanjaroenkij, A., & Zhou, X. Y. (2007). A review of numerical modeling of solid oxide fuel cells. *International Journal of Hydrogen Energy, 32*(7), 761–786.
[26]. Kee, R. J., Zhu, H., & Sukeshini, A. M. (2008). Solid-oxide fuel cells: The importance of detailed chemistry and transport. *Proceedings of the Combustion Institute, 32*(2), 2727–2735.
[27]. Kim, J. W., Virkar, A. V., Fung, K. Z., Mehta, K., & Singhal, S. C. (1999). Polarization effects in intermediate temperature, anode-supported solid oxide fuel cells. *Journal of the Electrochemical Society, 146*(1), 69–78.
[28]. Krishnan, V. V. (2020). Thermodynamics and energy engineering. In M. Sharifzadeh (Ed.), *Design and operation of solid oxide fuel cells: The systems engineering vision for industrial application* (pp. 43–84). Elsevier. https://doi.org/10.1016/B978-0-12-815253-9.00002-1
[29]. Larminie, J., & Dicks, A. (2003). *Fuel cell systems explained* (2nd ed.). John Wiley & Sons.
[30]. Li, P. W., Chyu, M. K., & Choi, J. H. (2003). Simulation of the chemical/electrochemical reactions and heat/mass transfer for a tubular SOFC in a stack. *Journal of Power Sources, 124*, 217–229.
[31]. Lisbona, P., Corradetti, A., Bove, R., & Lunghi, P. (2007). Analysis of a solid oxide fuel cell system fed by biogas. *Journal of Power Sources, 167*(1), 151–157.
[32]. Linder, M., & Wagner, S. (2008). Thermodynamic analysis of SOFC systems with internal reforming. *Energy Conversion and Management, 49*, 1687–1694.
[33]. Minh, N. Q. (1993). Ceramic fuel cells. *Journal of the American Ceramic Society, 76*(3), 563–588. https://doi.org/10.1111/j.1151-2916.1993.tb03645.x
[34]. Minh, N. Q. (2004). Solid oxide fuel cell technology—Features and applications. *Solid State Ionics, 174*(1–4), 271–277.
[35]. Mogensen, M., Sammes, N. M., & Tompsett, G. A. (2000). Physical, chemical and electrochemical properties of pure and doped ceria. *Solid State Ionics, 129*(1–4), 63–94.
[36]. O'Hayre, R., Cha, S.-W., Colella, W., & Prinz, F. B. (2016). *Fuel cell fundamentals* (3rd ed.). John Wiley & Sons.
[37]. Ormerod, R. M. (2003). Solid oxide fuel cells. *Chemical Society Reviews, 32*(1), 17–27. https://doi.org/10.1039/B105764M
[38]. Papageorgopoulos, A., & Farrauto, R. (2000). Solid oxide fuel cell technology and applications. *Catalysis Today, 56*, 145–153.
[39]. Saadabadi, S. A., Patel, H., Woudstra, T., & Aravind, P. V. (2020). Thermodynamic analysis of solid oxide fuel cell integrated system fuelled by ammonia from struvite precipitation process. *Fuel Cells, 20*(2), 143–157. https://doi.org/10.1002/fuce.201900143
[40]. Selimovic, A., & Palsson, J. (2002). Networked models of combined solid oxide fuel cell and gas turbine systems. *Journal of Power Sources, 106*(1–2), 76–82.
[41]. Shao, Z., & Haile, S. M. (2004). A high-performance cathode for the next generation of solid-oxide fuel cells. *Nature, 431*, 170–173.
[42]. Singh, P., & Minh, N. Q. (2004). Solid oxide fuel cells: Technology status. *International Journal of Applied Ceramic Technology, 1*(1), 5–16. https://doi.org/10.1111/j.1744-7402.2004.tb00149.x
[43]. Singhal, S. C. (2000). Advances in solid oxide fuel cell technology. *Solid State Ionics, 135*(1–4), 305–313. https://doi.org/10.1016/S0167-2738(00)00452-5
[44]. Singhal, S. C. (2000). Science and technology of solid-oxide fuel cells. *MRS Bulletin, 25*(3), 16–21. https://doi.org/10.1557/mrs2000.13
[45]. Singhal, S. C. (2002). Solid oxide fuel cells for stationary, mobile, and military applications. *Solid State Ionics, 152–153*, 405–410. https://doi.org/10.1016/S0167-2738(02)00349-1
[46]. Singhal, S. C. (2005). Solid oxide fuel cells: Design, materials, and application. *Journal of the Korean Ceramic Society, 42*(12), 777–786.
[47]. Stambouli, A. B., & Traversa, E. (2002). Solid oxide fuel cells (SOFCs): A review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews, 6*(5), 433–455. https://doi.org/10.1016/S1364-0321(02)00014-X
[48]. Steele, B. C. H. (2000). Materials for IT-SOFC stacks—35 years R&D: The inevitability of ceramics. *Solid State Ionics, 134*(1–2), 3–20.
[49]. Yano, M., Tomita, A., Sano, M., & Hibino, T. (2007). Recent advances in single-chamber solid oxide fuel cells: A review. *Solid State Ionics, 177*(39–40), 3351–3359. https://doi.org/10.1016/j.ssi.2006.10.014