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Impact of Channel Geometry and Operating Temperature on the Performance of Solid Oxide Electrolyzer Cells: A Study of Uniform and Non-Uniform Temperature Effects

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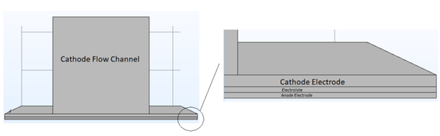
Anahtar Kelimeler

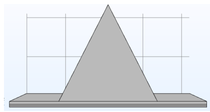
Katı oksit elektrolizör hücreleri
Kanal geometrisi
Düzenli sıcaklık dağılımı
Düzensiz sıcaklık dağılımı

Graphical/Tabular Abstract (Grafik Özet)

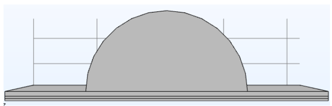
This study examines the impact of channel geometry and operating temperature on the performance of Solid Oxide Electrolyzer Cells (SOECs), a promising technology for efficient hydrogen production, both in uniform and non-uniform conditions. / Bu çalışma, verimli hidrojen üretimi için umut verici bir teknoloji olan Katı Oksit Elektroliz Hücrelerinin (SOEC) performansı üzerindeki kanal geometrisi ve işletme sıcaklığının etkilerini, hem uniform hem de non-uniform koşullarda incelemektedir.



(a)Rectangular Flow Channel



(b)Triangular Flow Channel



(c)Semicircular Flow Channel

***Figure A**: SOECs geometry /**Şekil A:**.SOEC geometrisi*

Highlights (Önemli noktalar)

- *Rectangular channels improve performance by 10%. Increasing the temperature from 1073 K to 1273 K boosts efficiency by 15%. / Dikdörtgen kanallar %10 verimlilik artışı sağlar. Sıcaklık 1073 K'dan 1273 K'ya çıkarsa %15 verimlilik artar.*
- *Rectangular channels improve mass transport, while serpentine designs enhance gas residence time. / Dikdörtgen kanallar kütle taşımasını artırırken, serpantin tasarımları gazın ikamet süresini uzatır.*
- *Non-uniform temperature distribution has little effect on performance in small-scale SOECs. / Düzensiz sıcaklık dağılımı, küçük ölçekli SOEC'lerde performansı çok etkilemez.*

Aim (Amaç): *This study aims to numerically investigate the effects of flow channel geometry and temperature on the performance of solid oxide electrolyzers. / Bu çalışma, akış kanalı geometrisi ve sıcaklığın katı oksit elektrolizörlerinin performansı üzerindeki etkilerini sayısal olarak incelemeyi amaçlamaktadır.*

Originality (Özgünlük): *The originality of this study lies in its comprehensive numerical analysis of the effects of different flow channel geometries and temperature variations on the performance of SOECs. / Farklı akış kanalı geometrilerinin ve sıcaklık değişimlerinin SOEC performansı üzerindeki etkilerinin kapsamlı bir sayısal analizine dayanmasıdır.*

Results (Bulgular): *The results demonstrate that rectangular flow channels enhance performance by 10%, and increasing the temperature from 1073 K to 1273 K improves efficiency by 15%, with minimal impact from non-uniform temperature distribution. / Sonuçlar, dikdörtgen akış kanallarının performansı %10 oranında artırdığını ve sıcaklığın 1073 K'dan 1273 K'ya çıkmasının verimliliği %15 oranında iyileştirdiğini, düzensiz sıcaklık dağılımının ise minimal etkisi olduğunu göstermektedir.*

Conclusion (Sonuç): *In conclusion, optimizing flow channel geometry and temperature significantly improves the performance of solid oxide electrolyzers, with rectangular channels and higher temperatures offering the best results./ Sonuç olarak, akış kanalı geometrisi ve sıcaklık optimizasyonu, solid oxide elektrolizörlerinin performansını önemli ölçüde artırmakta olup, dikdörtgen kanallar ve daha yüksek sıcaklıklar en iyi sonuçları sunmaktadır.*

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Abstract

This study investigates the effects of channel geometry and operating temperature on the performance of Solid Oxide Electrolyzer Cells (SOECs), a promising technology for efficient hydrogen production. Through computational simulations and experimental analysis, we explore the impact of different channel designs—rectangular, triangular, and semicircular—on system efficiency. Among the geometries, rectangular channels deliver the highest performance, with a 10% efficiency improvement over the others. Additionally, increasing the operating temperature from 1073 K to 1273 K accelerates reaction kinetics, yielding a 15% efficiency gain. The study identifies the optimization of both channel design and temperature as crucial for maximizing hydrogen production. Furthermore, the research finds that non-uniform temperature distribution has minimal impact on performance for the small-scale fuel cell configuration used. These findings emphasize the importance of understanding the interplay between geometry and operating conditions in SOEC design and contribute to the advancement of sustainable hydrogen production technologies.

Katı Oksit Elektrolizör Hücrelerinin Performansı Üzerindeki Kanal Geometrisi ve Çalışma Sıcaklığının Etkisi: Düzgün ve Düzgün Olmayan Sıcaklık Etkilerinin İncelenmesi

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Öz

Bu çalışma, verimli hidrojen üretimi için umut verici bir teknoloji olan Katı Oksit Elektrolizör Hücrelerinin (SOEC) performansı üzerindeki kanal geometrisi ve çalışma sıcaklığının etkilerini incelemektedir. Hesaplamalı simülasyonlar ve deneysel analizler yoluyla, farklı kanal tasarımlarının — dikdörtgen, üçgen ve yarım daire — sistem performansı üzerindeki etkisi araştırılmaktadır. Geometriler arasında dikdörtgen kanallar, diğerlerine kıyasla %10 oranında daha yüksek bir performans sergileyerek en yüksek verimliliği elde etmektedir. Ayrıca, çalışma sıcaklığının 1073 K'den 1273 K'ye yükseltilmesi, reaksiyon kinetiğini hızlandırarak %15 oranında bir verimlilik artışı sağlamaktadır. Çalışma, hem kanal tasarımının hem de sıcaklık optimizasyonunun, hidrojen üretiminin maksimize edilmesi açısından kritik öneme sahip olduğunu belirlemektedir. Ayrıca, araştırma, kullanılan küçük ölçekli yakıt hücresi yapılandırmasında düzensiz sıcaklık dağılımının performans üzerinde minimal bir etkisi olduğunu ortaya koymaktadır. Bu bulgular, SOEC tasarımında geometri ve işletme koşulları arasındaki etkileşimin anlaşılmasının önemini vurgulamakta ve sürdürülebilir hidrojen üretim teknolojilerinin gelişimine katkı sağlamaktadır.

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1. INTRODUCTION (GİRİŞ)

Solid oxide electrolyzers (SOECs) have garnered increasing attention as key components in the development of advanced energy conversion technologies. These electrolyzers utilize high-temperature solid oxide electrolytes to facilitate electrochemical reactions, positioning them as a promising approach for the efficient and sustainable production of hydrogen and other important electrochemical processes [1]. The inherent characteristics of SOECs, including their high operational efficiency, rapid response times, and adaptability to a range of applications, have driven substantial research and development efforts within the field of electrochemical engineering.

SOECs operate at elevated temperatures, typically exceeding 600°C, which enhances the ion conductivity of the solid oxide electrolyte. This reduction in electrical resistance leads to improved efficiency, enabling SOECs to achieve higher current densities with lower energy input when compared to other types of electrolyzers, such as proton exchange membrane (PEM) electrolyzers or alkaline electrolyzers [2]. This high-temperature operation is a key factor in the performance advantages of SOECs.

Hydrogen production plays a central role in various industrial and energy sectors, particularly in the context of its integration with gas turbine technology. Gas turbines, widely utilized in power generation and aviation, stand to benefit significantly from hydrogen as a clean and sustainable fuel. Hydrogen can serve as a carbon-neutral or low-carbon fuel, which has the potential to drastically reduce greenhouse gas emissions in gas turbine operations. By integrating hydrogen production and storage systems, gas turbines can transition from reliance on fossil fuels to hydrogen, contributing to cleaner, more environmentally friendly power generation and propulsion systems. Additionally, hydrogen's high energy density and efficient combustion properties make it an ideal candidate for enhancing the performance and reducing the environmental footprint of gas turbines, ultimately supporting the broader goal of a sustainable energy future [3,4].

The growing interest in SOECs is largely driven by their potential to address critical challenges in the transition toward a cleaner, more sustainable energy landscape. As global efforts intensify to reduce greenhouse gas emissions and achieve energy independence, SOECs present a viable solution for harnessing renewable energy sources to produce green hydrogen. This hydrogen plays an essential role in the decarbonization of sectors such as transportation, industry, and energy storage. This paper aims to explore the influence of channel geometry and temperature on the performance of SOECs.

Existing literature includes both numerical and experimental studies that investigate the performance of solid oxide electrolyzers under various parameters [5–10]. For instance, Ni et al. [11] examined the effects of component thickness on an anode-supported solid oxide electrolysis configuration. Their findings indicated that increasing electrode porosity and pore size could reduce voltage losses. Additionally, both elevated temperature and higher steam molar fractions were found to enhance the electrical efficiency of solid oxide electrolysis. Chen et al. [12] developed a numerical cell model that integrates electrochemical, flow, and thermal aspects, validating the model through comparisons with current-voltage curves and electrochemical impedance spectroscopy. Their study demonstrated significant performance improvements as operating temperature increased and uniformity of temperature distribution enhanced by higher steam partial pressures. However, it resulted in a reduction in steam conversion rates. Similarly, Wang et al. [13] investigated the performance of intermediate-temperature solid oxide electrolysis cells at 650°C, finding that higher steam concentrations reduced the cell voltage, primarily by diminishing steam electrode polarization. Srinivas et al. [14] explored the impact of various electrolytes, such as scandium-doped zirconia (SCGZ), yttrium-stabilized zirconia (YSZ), and gadolinium-doped ceria (GDC), under different temperature and pressure conditions. Their simulation models, incorporating convection, diffusion, and the Butler–Volmer equation, demonstrated a high R^2 value of over 0.996 in predicting polarization curves and electrochemical behavior. Notably, the impedance of SCGZ was significantly lower compared to YSZ and GDC, suggesting its superior electrochemical performance.

Furthermore, several studies have investigated the effects of material properties on the performance of SOECs [15–19]. Biswas et al. [20] examined the electrochemical performance of three distinct cathode configurations made from copper and gadolinia-doped ceria (Cu-GDC) cermets for steam electrolysis at 800°C in a tubular SOEC. Their research achieved an impressive polarization resistance of 0.42 Ωcm^2 at 1.60 V and a Faradaic efficiency exceeding 95%. They also noted that the optimal steam flow rate for maximizing current density at a given operating temperature was influenced by the concentration of electrocatalytically active sites. Xing et al. [21] conducted experimental research on $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_{3-\delta}$ (LSCM)-YSZ cathode-supported SOECs, reporting a hydrogen production rate of 561 mL cm^{-2} h^{-1} at 850°C with 80% absolute humidity at 1.6 V. Bercero et al. [22] investigated the performance of Ni-YSZ/10Sc1CeSZ/Pt single cells, obtaining current densities of −450 mA cm^{-2} at 1.5 V at 900°C with an ASR of 0.99 Ω cm².

Additionally, numerous studies have examined hydrogen production from seawater electrolysis, both experimentally and numerically [23–28]. Liu et al. [29] demonstrated the outstanding performance of solid oxide electrolysis cells in seawater splitting, highlighting their potential for large-scale hydrogen production.

A review of the literature reveals that while solid oxide electrolyzers with different flow channel geometries offer various advantages and disadvantages, no comprehensive numerical or experimental study explicitly addressing the impact of flow channel geometry on SOEC performance has been found [30,31].

In this study, the numerical effects of flow channel geometry on the performance of solid oxide electrolyzers are investigated. Additionally, the influence of temperature on the performance of different channel geometries is examined numerically. It is well-established that numerical studies are a vital first step in advancing experimental research [32]. The results of this study are expected to fill a critical gap in the literature and provide valuable insights for researchers intending to conduct experimental investigations into flow channel geometry in SOECs.

2. MATERIALS AND METHODS (MATERYAL VE METHOD)

2.1. Mathematical Model (Matematiksel Model)

Solid oxide electrolyzers (SOECs) are a specialized category of electrochemical devices that hold significant importance in the field of energy conversion and storage. These devices are predominantly utilized for the production of hydrogen and syngas through the electrolysis of water and carbon dioxide. The development of a precise and reliable mathematical model for SOECs is crucial for optimizing their performance, as well as for gaining a deeper understanding of the complex physical and chemical processes involved in their operation. A robust mathematical model of a solid oxide electrolyzer generally incorporates several key components that are essential for simulating the electrochemical behavior, heat transfer, fluid dynamics, and material properties that influence the overall efficiency and effectiveness of the system.

The fundamental electrochemical processes occurring within the SOEC, including oxygen and hydrogen ion transport across the solid oxide electrolyte, electrochemical reactions at the electrodes, and charge transfer kinetics.

The electrochemical reactions that occur in a solid oxide electrolyzer (SOEC) during the electrolysis of water involve the splitting of water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) gases. SOECs are high-temperature electrochemical devices that use a solid oxide electrolyte to facilitate this reaction. Eq.1 and Eq.2 are the two main electrochemical reactions that take place in a solid oxide electrolyzer:

Anode Reaction (Oxygen Evolution Reaction):

At the anode (the positive electrode), oxygen ions (O2-) are generated from oxygen molecules in the air. The electrochemical reaction at the anode can be represented as follows:

$$2H_2O\ (g) \rightarrow O_2\ (g) + 4e^- + 4O^{2-} \quad (1)$$

In this reaction, water molecules are ionized, and oxygen gas is evolved while releasing electrons. These electrons then flow through the external circuit to the cathode.

Cathode Reaction (Hydrogen Evolution Reaction):

At the cathode (the negative electrode), hydrogen gas (H2) is produced by the reduction of water molecules. The electrochemical reaction at the cathode can be represented as follows:

$$4H_2O + 4e^- \rightarrow 2H_2\ (g) + 4OH^- \quad (2)$$

In this reaction, water molecules gain electrons to form hydrogen gas, and hydroxide ions (OH^-) are produced.

The overall electrochemical reaction for a solid oxide electrolyzer is the combination of these two half-reactions, which can be written as Equation 3:

$$2H_2O\ (g) \rightarrow 2H_2\ (g) + O_2\ (g) \quad (3)$$

It's important to note that SOECs operate at elevated temperatures, typically above 600°C, which is necessary for the solid oxide electrolyte to be sufficiently conductive to facilitate the ion transport and electrochemical reactions. Additionally, the exact reaction mechanisms and kinetics may vary depending on the specific materials and design of the SOEC.

The physical geometry of the SOEC, as well as the boundary conditions, including temperature profiles, gas flow rates, and electrical current densities at the electrodes.

No-Slip Conditions on Walls: Non-slip conditions were assumed for velocity at the impermeable walls, where the velocity at the wall contact point is zero.

Negligible Boundary Layers: Boundary layers for gas flow were neglected since they are insignificant compared to the corresponding radius.

Zero Flux at Electrode and Electrolyte Ends: It was assumed that the flux is zero at the ends of both the electrode and the electrolyte.

Uniform Potential and Species Concentrations at Electrode-Gas Channel Interface: It was presumed that the electrical potential and species concentrations are uniform at the interface between the electrode and gas channel.

Boundary Treated as Well-Insulated: The boundary was considered well-insulated, implying that there is no change in variables at the boundary.

Zero Electric Potential at Fuel and Air-Side Interconnects: The electric potential was assumed to be zero at the fuel and air-side interconnects.

Constant Current Density at Interconnect Base: At the base of the interconnect, the current density was considered constant.

The main assumptions made in this study were as follows [33]:

•The distribution of temperature within each subsystem is assumed to be constant due to its tiny size.

•The velocities of the fluid and partial pressures are assumed to be uniformly uniform in each subsystem and in every direction.

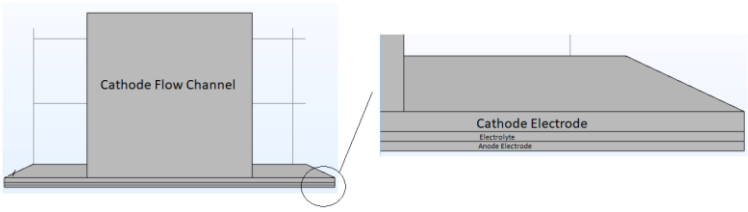
•The viscosity of the fluid in each subsystem is the same.

Table 1 shows the governing equations for the SOEC model [12,35].

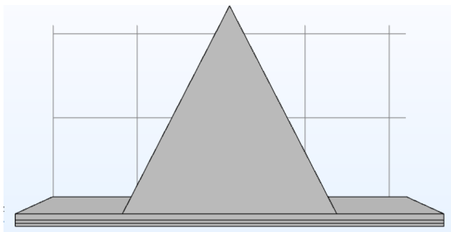
Table 1. Governing equations (Genel denklemler)

Description	Governing equaiton
Mass	$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = Q_{mass}$$
Momentum	$$\nabla \left\{ -pI + \frac{\mu}{\varepsilon}[\nabla \vec{u} + (\nabla \vec{u})^T] - \frac{2\mu}{3\varepsilon} \nabla \vec{u} \right\} - \left(\frac{\mu}{B_0} + Q_{mom} \right) \vec{u} = \frac{\rho}{\varepsilon} \left(\frac{\partial \vec{u}}{\partial t} + \frac{\vec{u}}{\varepsilon} \nabla \vec{u} \right)$$
Conservation of species	$$\varepsilon \rho \frac{\partial \omega_i}{\partial t} + \nabla \cdot \vec{J_i} + \rho (\vec{u} \cdot \nabla) \omega_i = R_i$$
Conservation of charge	$$\nabla \cdot (-\sigma_{ion} \varphi_{ion}) = Q_{ion}; \nabla \cdot (-\sigma_e \varphi_e) = Q_e$$
Energy	$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \vec{u} \cdot \nabla T = \nabla \cdot \left(\kappa^{eff} \nabla T \right) + Q$$

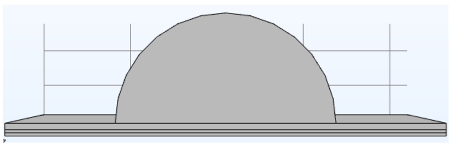
To further enhance the understanding of mass transport within the SOEC, this study employs a set of well-established mathematical models. These models account for the primary transport phenomena, including diffusion, convection, and electrochemical fluxes, which govern the movement of reactants and products in the cell. However, it is essential to recognize that the transport behavior in SOECs is highly influenced by the intricate interplay between flow dynamics and thermal gradients. In recent years, SOECs have garnered significant attention as promising devices for sustainable hydrogen production and energy conversion due to their high efficiency and versatility. The accurate modeling of SOEs plays a crucial role in optimizing their performance and understanding fundamental processes. In this study, we employ COMSOL Multiphysics, a powerful finite element analysis software, to develop a comprehensive numerical model for the simulation of SOEC operation. This model aims to provide valuable insights into the complex electrochemical and transport phenomena occurring within the SOEC, enabling the design and improvement of these vital components in various energy conversion applications. The (a) rectangular flow channel, (b) triangular flow channel and (c) semicurcilar flow channel geometry used in the SOEC analyses are shown in Figure 1 and the model parameters are given in Table 2.



(a)Rectangular Flow Channel



(b) Triangular Flow Channel



(c) Semicircular Flow Channel

Figure 1. SOECs geometry [35] (Katı oksit elektrolizör hücreleri geometrisi)

Table 2. Processing parameters (İşleme parametreleri)

Cell Structure Parameters		
Anode thickness	$15x10^{-6}$	[m]
Electrolyte thickness	$15x10^{-6}$	[m]
Cathode thickness	$31x10^{-6}$	[m]
Cell length	40	[mm]
Channel height	1.05	[mm]
Channel weight	1.05	[mm]

Cell Physics Parameters	
Electrode permeability	10^{-13} [m^2]
Gas pore volume fraction	0.475
Electrolyte volume fraction	0.4
Electrode specific surface area	$1.025x10^5$ [1/m]
Cell voltage	1.4 [V]

3. RESULTS (BULGULAR)

The use of COMSOL Multiphysics, enhanced by the specialized Fuel Cell & Electrolyzer Module for numerical simulations, facilitated a thorough investigation of cathode-supported, rectangular flow channel SOECs. This approach allowed for detailed analysis of various operational parameters, leading to a deeper insight into the behavior of SOECs and the optimization of their performance under different conditions.

3.1 Model Validation (Model Doğrulaması)

In this study, the results effectively validated our numerical analysis through comprehensive experimental investigations, demonstrating a high level of consistency and agreement. As shown in Figure 2, the outcomes from both numerical simulations and experimental measurements were in remarkable alignment, thereby confirming the accuracy and reliability of our computational models. Building on this strong correlation between numerical and experimental data, we have proceeded with further analyses, using these validated parameters as a solid foundation. This not only highlights the robustness of our numerical approach but also strengthens our confidence in the predictive capabilities of the model for future research and practical applications. The numerical model utilized in this study was validated against experimental data, ensuring the reliability of the results.

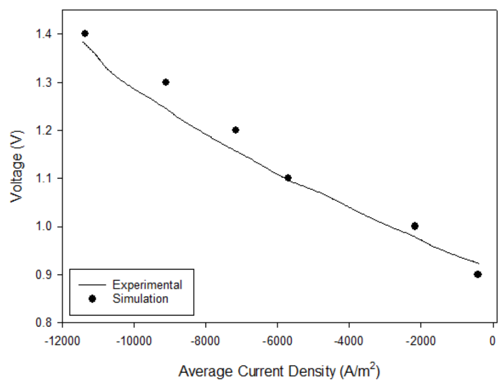
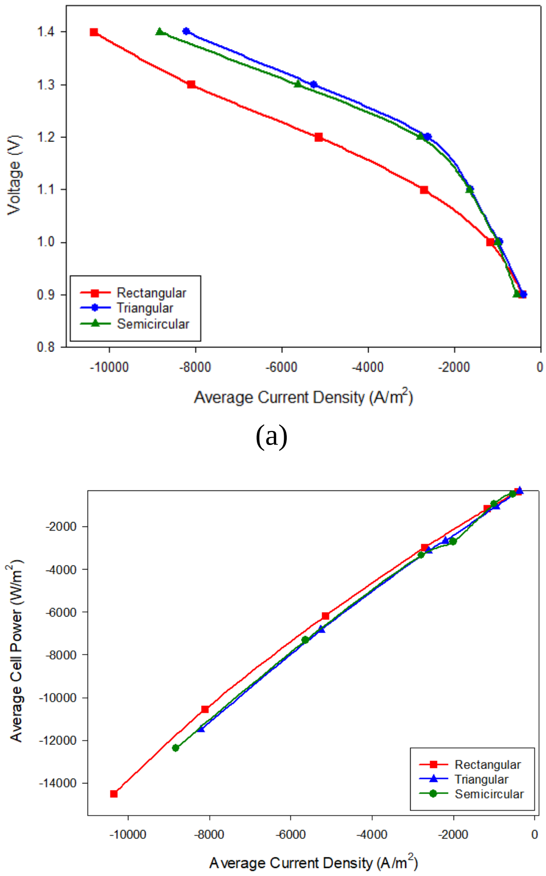


Figure 2. Model validation with experimental results [12,35] (Deneysel sonuçlarla model doğrulaması)

3.2 Effect of flow channel geometry (Akış kanalı geometrisinin etkisi)

Polarization losses refer to the resistive losses that occur at the electrode surfaces within an electrochemical cell when an electrical current passes through. These losses are caused by the buildup of charged species at the electrode-electrolyte interface, which impedes the effective transfer of charge and reduces the overall efficiency of the cell. In this study, we performed an extensive comparison of polarization and performance outcomes across rectangular, triangular, and semicircular flow channels at an operating temperature of 1073 K. The results of this analysis are presented visually in Figure 3. Through this comparison, we were able to identify the unique advantages and trade-offs associated with each channel geometry, particularly regarding their influence on polarization and overall performance. These findings offer crucial insights into the optimization of flow channel designs for high-temperature applications, emphasizing the importance of selecting the most appropriate geometry to improve the efficiency and effectiveness of the system. Flow channel geometry plays a significant role in mass transport within SOECs. This study demonstrates the impact of geometric factors, such as channel width and length, on the overall electrochemical performance.



(a)

(b)

Figure 3. Flow channel geometry effect on (a) polarization curve and (b) performance curve [35] (Akış kanalı geometrisinin etkisi a) Polarizasyon eğrisi b) Performans eğrisi)

As shown in Figure 3, the rectangular flow channel SOEC demonstrated superior performance based on the conducted analysis. Due to its four equal sides, the rectangular geometry offers a larger internal surface area compared to other flow channel shapes of similar dimensions. This expanded surface area allows for a more excellent distribution of electrocatalysts, thereby facilitating a higher volume of simultaneous electrochemical reactions. Consequently, this improves the overall performance of the system by promoting more efficient reactant conversion.

In addition, rectangular flow channels typically provide a more uniform distribution of reactants across the electrode surfaces. The consistent flow of gases and electrolytes minimizes the formation of localized concentration gradients, thereby reducing polarization losses. This enhancement in mass transport contributes to improved cell performance. Furthermore, rectangular flow channels generally exhibit lower pressure drop characteristics compared to triangular or semicircular geometries. Reduced pressure drops indicate that the system requires less energy to maintain the desired flow rates, resulting in better overall energy efficiency.

The rectangular geometry also promotes efficient heat transfer. Heat generated during the electrochemical reactions is more effectively dissipated within square channels, helping maintain a consistent temperature throughout the cell. This thermal stability is critical for ensuring optimal electrolyte conductivity and, consequently, for maximizing overall performance.

The mole fraction of water can be seen in Figure 4 and the mole fraction of hydrogen can be seen in Figure 5 (A) rectangular flow channel, (B) triangular flow channel and, (C) semicircular flow channel respectively.

(a)Rectangular flow channel

(b) Triangular flow channel

(c) Semicircular flow channel

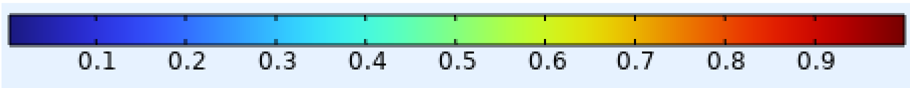


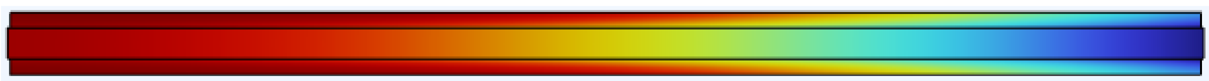
Figure 4. Mole fraction of the water. (Suyun mol dağılımı)

The mole fraction of water in rectangular, triangular, and semicircular flow channels can be understood by considering the geometry of each channel and its influence on the distribution and concentration of water vapor within the system. In rectangular channels, the relatively larger cross-sectional area provides more space for water vapor to accumulate. This increased surface area facilitates efficient diffusion and mixing of the water vapor, resulting in a more uniform distribution of water molecules along the length and width of the channel. Due to the rectangular shape, water molecules exhibit greater mobility, promoting a homogeneous mole fraction of water across the entire channel.

In contrast, triangular channels present a more constrained geometry, with a narrower base compared to a rectangular channel of the same width. This limitation in available space leads to variations in water vapor distribution, with higher concentrations typically observed at the center of the channel and lower concentrations near the edges. The more confined environment in triangular channels may also hinder the diffusion and mixing of water vapor, further impacting the uniformity of the mole fraction.

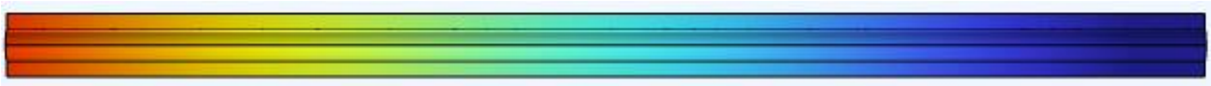
Semicircular channels, characterized by their curved shape, introduce additional complexities in the distribution of water vapor. Water vapor tends to accumulate near the center of the channel, where the curvature is most pronounced, resulting in higher mole fractions of water at the core and lower concentrations at the edges. The curvature of the channel may limit the lateral movement of water vapor molecules, exacerbating concentration gradients across the channel.

Overall, the mole fraction of water in these different geometries is heavily influenced by the specific flow patterns, diffusion characteristics, and available space within each channel. Rectangular channels generally offer a more uniform distribution of water vapor, while triangular and semicircular channels exhibit concentration variations due to their geometric constraints and the impact of curvature on diffusion dynamics.



(a)Rectangular flow channel

(b) Triangular flow channel



(c) Semicircular flow channel

Figure 5. Mole fraction of the hydrogen. (Hidrojen mol dağılımı)

As illustrated in Figure 5, rectangular flow channels, with their relatively spacious cross-sectional area, provide ample space for the presence of hydrogen molecules. The large surface area facilitates efficient diffusion and thorough mixing of hydrogen gas, resulting in a relatively uniform distribution of hydrogen throughout the channel. The rectangular geometry promotes a consistent mole fraction of hydrogen, extending across both the width and length of the channel, assuming that other factors, such as flow rate and operating conditions, are kept constant.

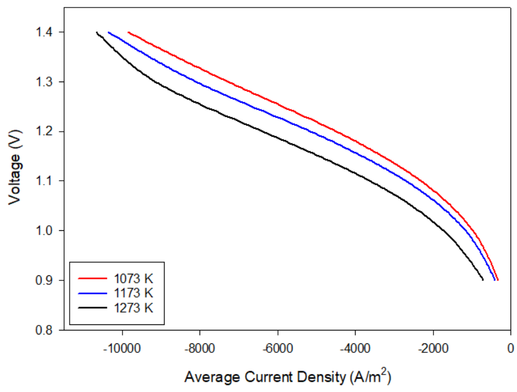
In contrast, triangular flow channels present a more constrained geometry, characterized by a narrower base than a rectangular channel of the same width. This limitation in space can lead to variations in hydrogen distribution, with higher concentrations near the center of the channel and lower concentrations at the edges. The confined geometry of triangular channels may also slow down the diffusion and mixing of hydrogen, which negatively impacts the uniformity of the hydrogen mole fraction.

Semicircular channels, due to their curved shape, result in distinct hydrogen distribution patterns. Hydrogen gas tends to accumulate in the central region of the semicircular channel, where the curvature is most pronounced. This causes the mole fraction of hydrogen to be higher at the center, gradually decreasing toward the edges of the channel. The curved structure of these channels restricts the lateral movement of hydrogen molecules, which further exacerbates the concentration variations.

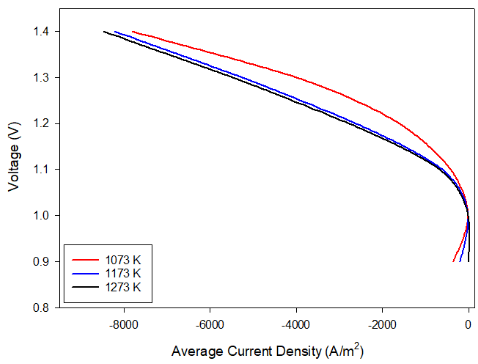
Overall, rectangular channels tend to produce a more consistent distribution of hydrogen, while triangular and semicircular channels experience more significant variations in hydrogen concentration. These differences are primarily due to the geometric constraints and the confined environments inherent to each channel type, which influence the diffusion and mixing characteristics of hydrogen gas within the flow channels.

3.3 Effect of temperature (Sıcaklığın etkisi)

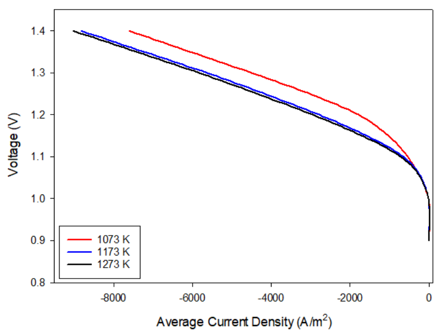
Temperature plays a crucial role in shaping the polarization curve of a SOEC, primarily due to its profound effects on electrochemical kinetics and ionic conductivity within the cell. As the temperature increases, the kinetic energy of particles rises, which in turn accelerates reaction rates at the electrode-electrolyte interfaces. This enhancement in reaction rates leads to a reduction in activation overpotential, allowing for faster electrochemical reactions. As a result, the cell's resistance decreases, and current densities at a given voltage increase. Furthermore, higher temperatures improve the ionic conductivity of the solid oxide electrolyte, which supports more efficient ion transport within the cell. This enhanced ionic conductivity further reduces ohmic overpotentials, contributing to better overall cell performance. Consequently, the operation of an SOEC system at elevated temperatures generally results in lower polarization losses, increased current output, and higher energy efficiency. Such improvements underscore the importance of temperature control in optimizing SOEC operation, particularly for applications such as hydrogen production and energy storage. Temperature gradients have a profound effect on mass transport within SOECs. As the temperature increases, the diffusivity of the species involved in the electrolysis process also changes, which in turn affects the efficiency of the system. Figure 6 illustrates the impact of temperature on the polarization curve, showing (a) rectangular, (b) triangular, and (c) semicircular flow channel configurations.



a) Rectangular Flow Channel



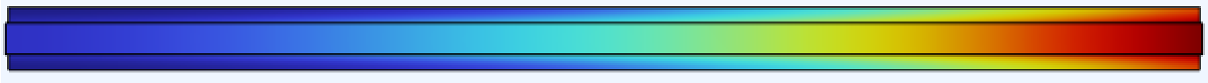
b) Triangular flow channel



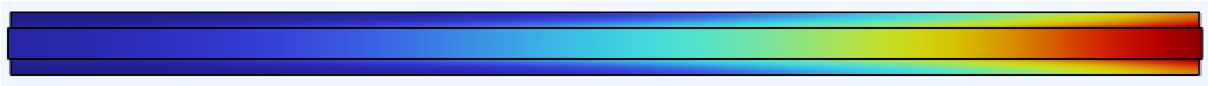
c) Semicircular flow channel

Figure 6. The effect of temperature on polarization curve [35] (Sıcaklığın polarizasyon eğrisi üzerine etkisi)

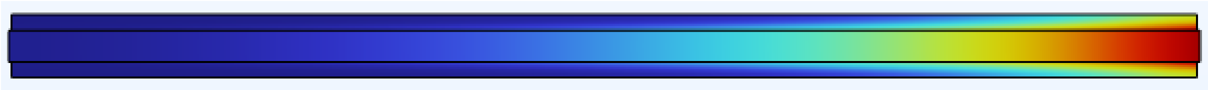
As depicted in Figure 6, the influence of temperature on SOEC performance varies across different flow channel geometries. In rectangular flow channels, higher temperatures typically accelerate electrochemical reactions at the electrodes due to an increase in kinetic energy, which leads to a reduction in activation overpotentials and lower resistive losses. This results in improved efficiency at elevated temperatures. In triangular flow channels, temperature significantly affects the flow dynamics, influencing both mass transport and the local temperature distribution. Elevated temperatures can enhance convective heat and mass transfer, which may reduce overpotentials and further enhance the overall system efficiency. Similarly, in semicircular flow channels, temperature influences the flow patterns and thermal gradients, which in turn affect mass transfer and electrochemical kinetics. Regardless of the flow channel configuration, temperature control remains a critical factor in optimizing SOEC performance, as it governs the complex interactions between electrochemical reactions and transport processes within each distinct channel geometry.



a) 1073 K



b) 1173 K

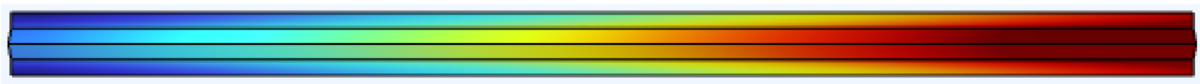


c) 1273 K

Figure 7. The effect of temperature on mole fraction of the water at rectangular flow channel. (Dikdörtgen akış kanalında sıcaklığın suyun mol dağılımı üzerindeki etkisi)

a) 1073 K

b) 1173 K

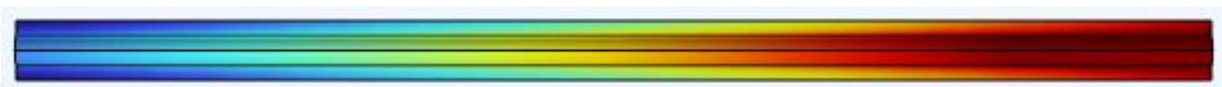


c) 1273 K

Figure 8. The effect of temperature on mole fraction of the water at triangular flow channel. (Üçgen akış kanalında sıcaklığın suyun mol dağılımı üzerindeki etkisi)

a) 1073 K

b) 1173 K



c) 1273 K

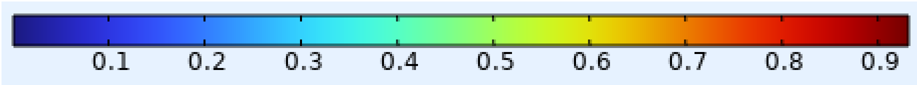
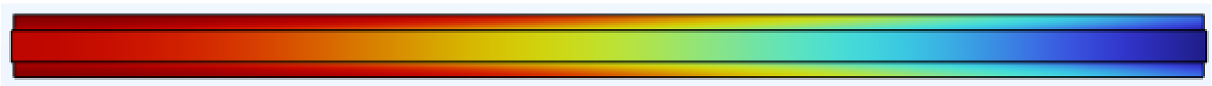
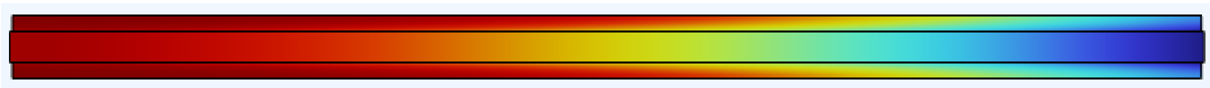


Figure 9. The effect of temperature on mole fraction of the water at semicircular flow channel. (Yarımdaire akış kanalında sıcaklığın suyun mol dağılımı üzerindeki etkisi)

Figures 7, 8, and 9 illustrate the influence of temperature on the mole fraction of water in rectangular, triangular, and semicircular flow channels, respectively. In rectangular flow channels, an increase in temperature generally results in a decrease in the mole fraction of water. This is attributed to the enhancement of water vapor dissociation into hydrogen and oxygen at the electrode-electrolyte interface, which accelerates electrochemical reactions. As more water molecules are consumed in the electrolysis process, their concentration within the channel diminishes. In triangular flow channels, the effect of temperature on the mole fraction of water follows a similar trend to that observed in rectangular channels. However, the temperature-induced changes in convective heat and mass transfer patterns within the channel also play a significant role. Elevated temperatures can enhance convective transport, promoting improved mixing of the reactant gases and potentially maintaining a more stable mole fraction of water compared to rectangular channels. In semicircular flow channels, temperature impacts the mole fraction of water through its influence on flow patterns and thermal gradients. Higher temperatures increase the kinetic energy of gas molecules, which may enhance their diffusion rates and lead to a more uniform distribution of water along the channel. However, the exact effect of temperature in semicircular channels may vary depending on the specific design and operational conditions, making it essential to consider these factors when optimizing SOEC performance.



a) 1073 K



b) 1173 K

c) 1273 K

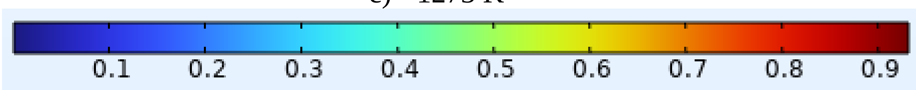
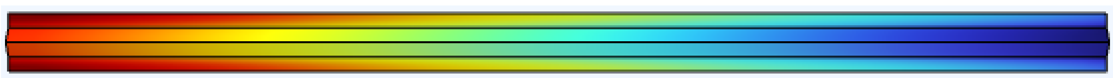


Figure 10. The effect of temperature on mole fraction of the hydrogen at rectangular flow channel. (Dikdörtgen akış kanalında sıcaklığın hidrojen mol dağılımı üzerindeki etkisi)

a) 1073 K



b) 1173 K

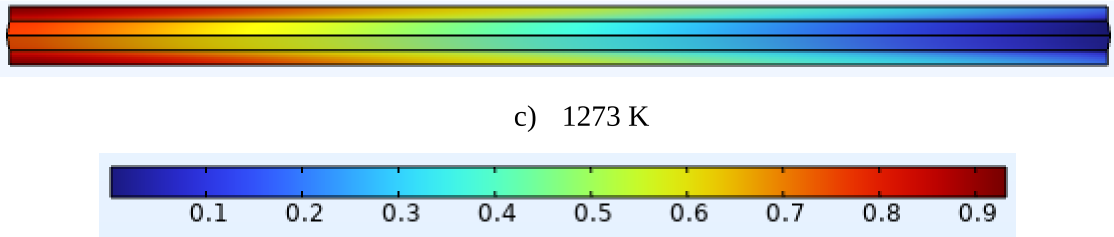


Figure 11. The effect of temperature on mole fraction of the hydrogen at triangular flow channel. (Üçgen akış kanalında sıcaklığın hidrojen mol dağılımı üzerindeki etkisi)

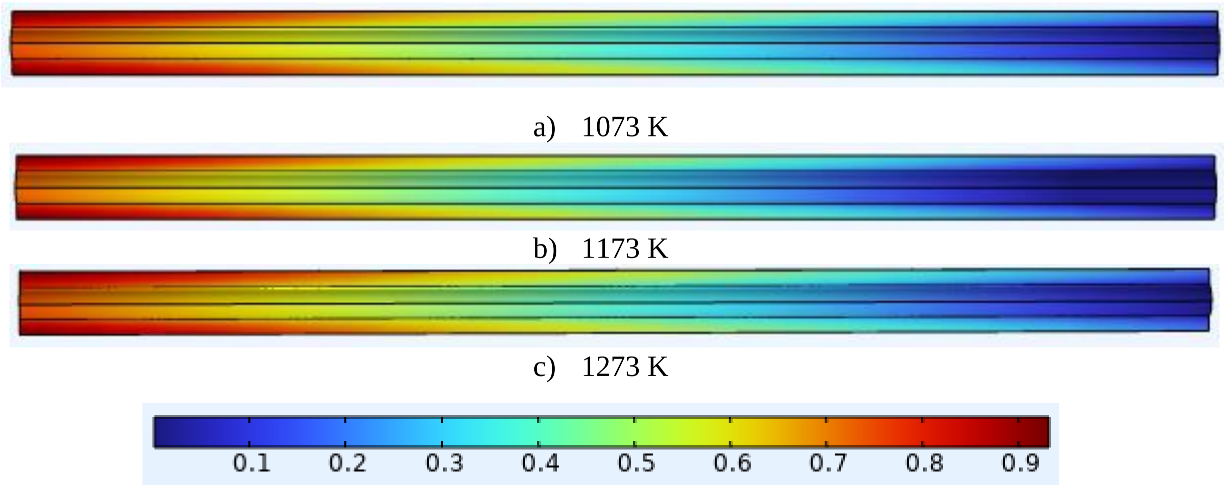


Figure 12. The effect of temperature on mole fraction of the hydrogen at semicircular flow channel. (Yarımdaire akış kanalında sıcaklığın hidrojen mol dağılımı üzerindeki etkisi)

Figures 10, 11, and 12 demonstrate the effect of temperature on the mole fraction of hydrogen in rectangular, triangular, and semicircular flow channels, respectively. In rectangular flow channels, increasing the temperature typically results in a rise in the mole fraction of hydrogen. This is primarily due to the enhanced hydrogen evolution reactions at the electrode-electrolyte interface, driven by the increased thermal energy. The elevated temperature accelerates the dissociation of water into hydrogen and oxygen, leading to higher hydrogen production rates and consequently a higher mole fraction of hydrogen within the channel. In triangular flow channels, the effect of temperature on the mole fraction of hydrogen follows a similar pattern as observed in rectangular channels. Higher temperatures promote more efficient hydrogen production by accelerating the electrochemical reactions, thereby increasing the mole fraction of hydrogen. In semicircular flow channels, the impact of temperature on the mole fraction of hydrogen is influenced by the flow patterns and thermal gradients within the channel. Elevated temperatures can enhance the kinetics of hydrogen evolution, which may lead to a higher mole fraction of hydrogen. However, the exact effect is dependent on the specific design of the channel and the complex interactions between temperature, flow dynamics, and reaction kinetics, making it essential to consider these factors in optimizing system performance.

3.4 Effect of non-uniform operating temperature conditions

SOECs, when operated at high temperatures, often encounter significant challenges in sustaining optimal conditions. Combustion chambers and furnaces are commonly utilized to generate the requisite elevated temperatures. However, an analysis of combustion systems highlights that ensuring a uniform temperature distribution remains a persistent challenge [34]. In the concluding phase of the study, the influence of this temperature imbalance on the operational efficiency of SOECs was systematically examined.

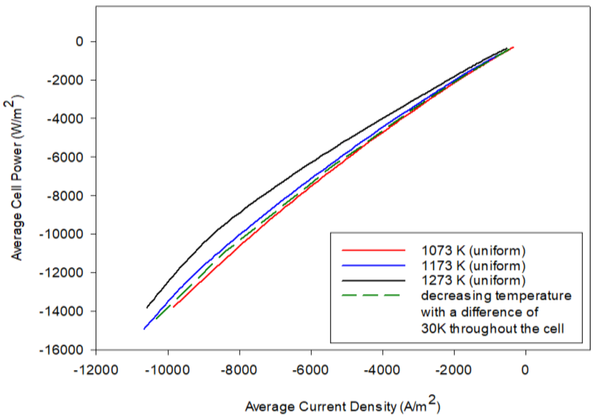


Figure 13. Power curves of rectangular flow channel geometry SOEC under uniform and non-uniform (decreasing) temperature condition. (Dikdörtgen akış kanalının düzenli ve düzensiz (azalan) sıcaklık dağılımlarında güç eğrisi)

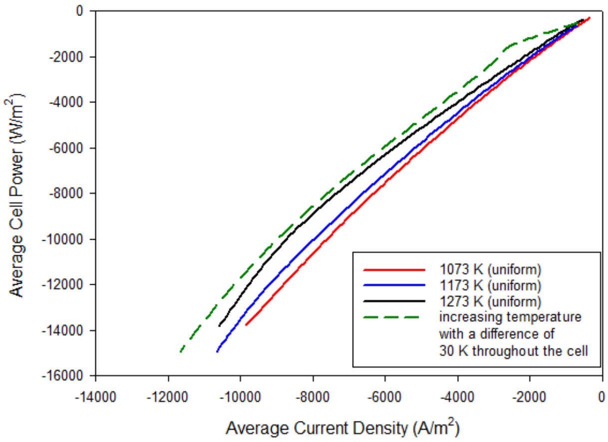


Figure 14. Power curves of rectangular flow channel geometry SOEC under uniform and non-uniform (increasing) temperature condition. (Dikdörtgen akış kanalının düzenli ve düzensiz (artan) sıcaklık dağılımlarında güç eğrisi)

Figure 13 presents the power curve of the rectangular flow channel geometry SOEC under varying operating temperature conditions, highlighting a 30 K decrease in temperature from the cell inlet when compared to power curves obtained at different temperatures. A closer analysis of the graph reveals that the cell power, especially at lower current densities, is reduced relative to the reference curve. This effect is attributed to the characteristics of the rectangular flow channel. In contrast, Figure 14 displays the power curve of the fuel cell under the condition of a 30 K increase in operating temperature from the cell inlet, compared to the curves at other temperature conditions. The graph demonstrates an improvement in cell performance as the temperature rises from the cell entrance, with the influence of the rectangular flow channel considered as a significant factor.

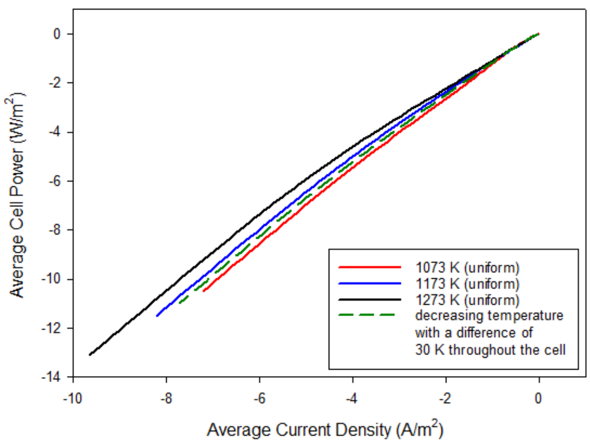


Figure 15. Power curves of triangular flow channel geometry SOEC under uniform and non-uniform (decreasing) temperature condition. (Üçgen akış kanalının düzenli ve düzensiz (azalan) sıcaklık dağılımlarında güç eğrisi)

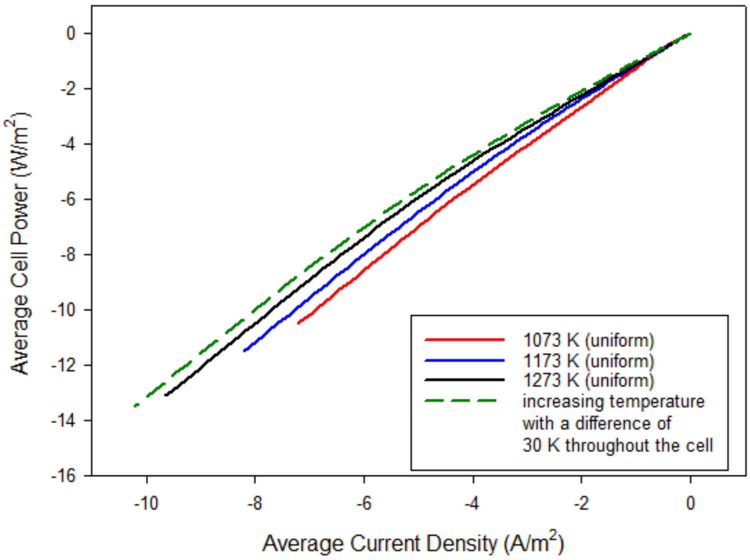


Figure 16. Power curves of triangular flow channel geometry SOEC under uniform and non-uniform (increasing) temperature condition. (Üçgen akış kanalının düzenli ve düzensiz (artan) sıcaklık dağılımlarında güç eğrisi)

Figure 15 illustrates the power curve of the SOEC with a triangular flow channel geometry under varying operating temperature conditions, highlighting a 30 K decrease in temperature from the cell inlet when compared to power curves at different operating temperatures. Upon analyzing the graph, it is evident that the cell power is lower than that of the reference curve. This reduction in power is attributed to the specific characteristics of the triangular flow channel. In Figure 16, the power curve of the fuel cell is shown under a condition where the operating temperature increases by 30 K from the cell inlet, compared to curves at other temperature settings. The graph indicates a noticeable improvement in cell performance as the temperature rises from the cell entrance, with particular emphasis on the impact of the triangular flow channel.

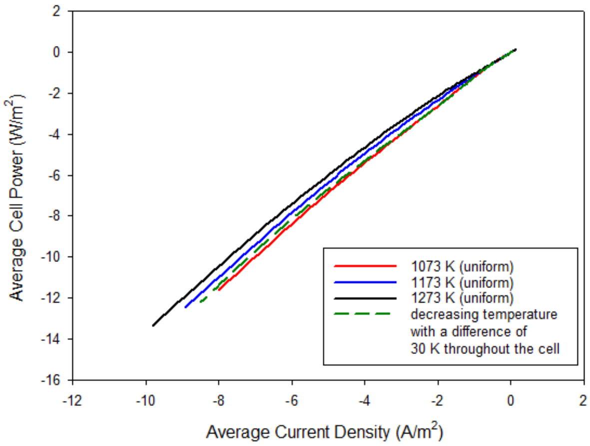


Figure 17. Power curves of semicircular flow channel geometry SOEC under uniform and non-uniform (decreasing) temperature condition. (Yarımdaire akış kanalının düzenli ve düzensiz (azalan) sıcaklık dağılımlarında güç eğrisi)

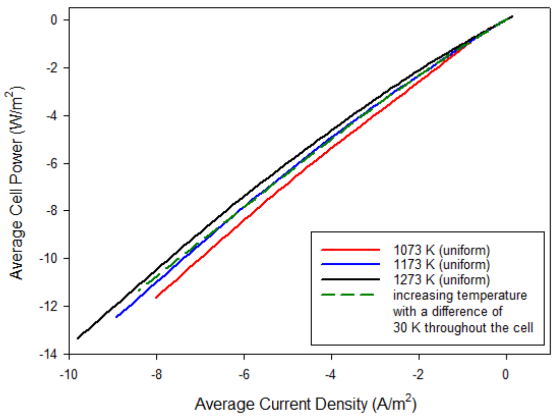


Figure 18. Power curves of semicircular flow channel geometry SOEC under uniform and non-uniform (increasing) temperature condition. (Yarımdaire akış kanalının düzenli ve düzensiz (artan) sıcaklık dağılımlarında güç eğrisi)

Figure 17 depicts the power curve of the SOEC featuring a semicircular flow channel geometry under varying operating temperature conditions, highlighting a 30 K reduction in temperature from the cell inlet compared to power curves at different operating temperatures. Upon examining the graph, it becomes clear that the cell power is lower than the reference curve. This reduction is primarily influenced by the characteristics of the semicircular flow channel. In Figure 18, the power curve of the fuel cell is shown under the condition of a 30 K increase in operating temperature from the cell inlet, in comparison to curves at different temperature conditions. The graph demonstrates a positive correlation between the rise in temperature from the cell entrance and improved cell performance, with the semicircular flow channel's influence taken into account.

In fluid dynamics, the heat distribution across various flow geometries is pivotal in determining temperature variations within the medium. Among the commonly studied geometries—rectangular, triangular, and semicircular—the semicircular flow geometry exhibits the least degree of non-uniform temperature distribution. This can be attributed to the symmetrical design of the semicircular flow, where the curvature facilitates a more uniform heat distribution. In contrast, rectangular and triangular geometries, with their sharp corners and edges, often result in localized temperature variations due to the abrupt changes in fluid direction. The smooth, continuous curvature of the semicircular geometry helps minimize these abrupt transitions, thereby fostering a more even and stable temperature distribution.

4. CONCLUSIONS (SONUÇLAR)

In this study, the integration of COMSOL Multiphysics, specifically the Fuel Cell & Electrolyzer Module, enabled a thorough analysis of cathode-supported, rectangular flow channel Solid Oxide Electrolyzer Cells (SOECs). The findings were rigorously validated through experimental investigations, with numerical simulations showing a strong correlation with the experimental data. The use of rectangular flow channels, with their increased internal surface area, enhanced performance by facilitating more efficient electrochemical reactions, promoting a more uniform distribution of reactants, reducing pressure drops, and optimizing heat transfer. Temperature was found to significantly influence the mole fractions of water and hydrogen within the channels, with higher temperatures generally improving distribution patterns and overall performance. This study underscores the advantages of rectangular flow channels in SOEC applications and highlights the critical role of temperature management in optimizing performance across various flow channel configurations.

In conclusion, this research provides important insights into the operational behavior and performance optimization of SOECs, particularly in the context of rectangular flow channel designs. The strong agreement between numerical simulations and experimental results reinforces the reliability of the computational model and enhances its predictive capability for future research and practical applications. The study highlights the benefits of rectangular flow channels, especially in terms of improved reactant distribution and enhanced electrochemical performance, while also emphasizing the significant influence of temperature on mole fraction profiles. Additionally, a notable observation was made regarding the effect of non-uniform temperature distributions—commonly observed in experimental settings—on SOEC performance. This finding contributes to a deeper understanding of SOEC behavior and sets the stage for future advancements in the development and optimization of such systems.

Overall, this study offers a unique contribution by providing a comprehensive analysis of cathode-supported, rectangular flow channel designs in SOECs, utilizing COMSOL Multiphysics simulations validated against experimental data. The research emphasizes the significant role of rectangular flow channels in enhancing electrochemical performance, optimizing heat transfer, and reducing pressure drops. Furthermore, it underscores the critical influence of temperature management on mole fraction profiles, offering valuable insights into SOEC behavior and laying a solid foundation for future advancements in system optimization.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Berre KÜMÜK*:** She developed the numerical model, conducted the analysis and wrote the manuscript.

Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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