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Improvement in Current Density Distribution of Solid Oxide Fuel Cell

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Abstract**—** Solid oxide fuel cells (SOFCs) are a promising technology for clean and efficient electricity generation. However, their performance is intricately linked to various physical and chemical processes. This study employs COMSOL Multiphysics 6.3 simulation software to examine the impact of electrode kinetics on SOFC performance. The simulation covers electrode kinetics, activation overpotential, ohmic losses, and mass transport, offering key insights into SOFC behavior. Critical parameters, including electrode potential, electrolyte potential, and current density, are analyzed to identify optimization opportunities, particularly in controlling current density distribution and enhancing the H2 mole fraction on the anode surface. The findings underscore the significant influence of electrode kinetics and activation overpotential on SOFC performance, guiding the design and optimization of these fuel cells for sustainable energy solutions.

Keywords**—** Solid Oxide Fuel Cells, COMSOL Multiphysics, Simulation, Optimization, Performance Analysis.

I. INTRODUCTION

In Solid oxide fuel cells (SOFCs) are widely recognized for their potential to generate electricity with high efficiency and low emissions, making them a vital component of future sustainable energy systems. Despite their advantages, SOFCs are influenced by complex interrelated processes, including electrode kinetics, activation overpotential, and mass transport. Understanding these processes is crucial for optimizing SOFC performance and longevity. This study seeks to explore the impact of these factors on SOFC behavior using advanced simulation techniques, with the ultimate goal of informing the design and development of more efficient fuel cells [1].

Solid oxide fuel cells (SOFCs) have garnered significant attention as a promising technology for clean and efficient electricity generation. With rising global energy demands and the urgent need to reduce carbon emissions, SOFCs offer a sustainable solution that can operate on various fuels, including hydrogen, natural gas, and biogas. Their high efficiency, fuel flexibility, and low environmental impact make them an attractive option for a wide range of applications, from stationary power generation to transportation [3].

Scientific and industrial progress has increased during the past few decades. Due to the rising energy consumption caused by these developments, clean, secure, economical, and sustainable energy sources are sought for. However, fossil fuels have a negative impact on climate change and they are not sustainable due to their continuous depletion in a given region [1]. Fossil fuel consumption is responsible for environmental problems that negatively affect people's health and way of life, such as air pollution and global warming. The ambition of entirely decarbonizing the power system by 2030 has been recognized major step towards attaining the decrease in CO2 emissions required in order to be on schedule to meet this goal. This can be done by substituting The generation capacity of wind farms, geothermal power plants, nuclear power, and other solar- based technologies are examples of renewable energy sources, can be used to replace older power facilities with large gigawatt-hour (GWh) carbon emissions, such as those from coal-fired plants. The generation of renewable energy is sometimes unreliable, which is a significant obstacle to their widespread adoption [2]. For instance, intermittent wind patterns allow for the generation of power during periods low demand times, like the middle of the night, whereas intermittent wind patterns during periods of high demand may result in low levels of power production.

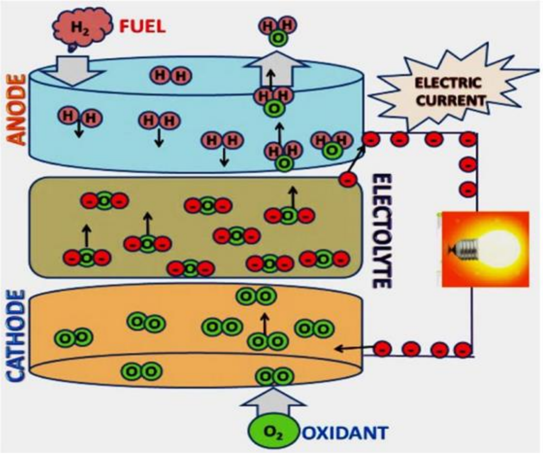
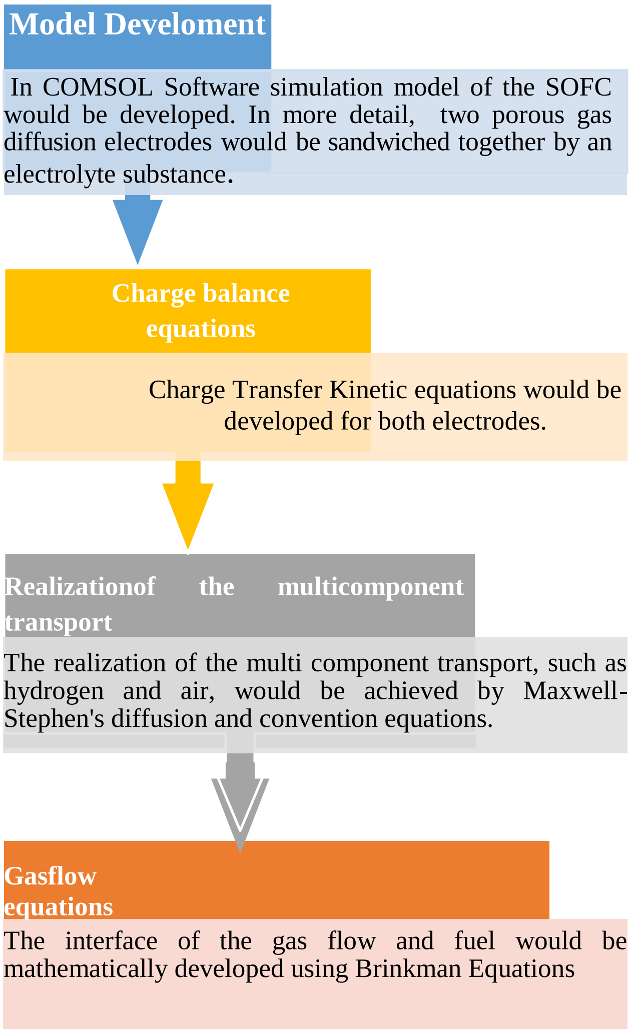


Figure 1. The fuel cell's operation [3]

This complicates the task of real-time grid balancing, which is necessary to ensure that the grid's electricity demands are met by the combined output of all linked units. This is seen as a major

hurdle that needs to be overcome before renewable generating can contribute significantly to the energy mix. In fact, it has been estimated that until renewables account for 30% of the entire grid capacity, the stability of the system will be jeopardised without a substantial quantity of energy storage [2]. Therefore, research over the last few decades has centred on discovering clean, affordable, highly efficient, and sustainable alternative energy sources. The fuel cell (FC), depicted in Fig.1 above, is one example of such a source because it possesses all of the aforementioned qualities and has been commercially available since around the middle of the 1960s [4].

In the research methodology, our first step is model development in model development we are using a software named COMSOL in Fig. 2 detail given. this software is basically are digital platform in which we can build all types of objects related to geometry electrical architecture and all other types of object in which we also can perform tests and get results of different aspects of the test like potential test and voltage test we are using COMSOL software to build a simulation solid oxide fuel cell design in more details to porous gas diffusion electrodes would be sandwich together by electrolyte substance the most important thing of this software that we can perform all type of test and get there results without providing any cost of the software, because this software is fully free we don't want to purchase any object without taking test of it firstly we should develop all the model on console then we should buy all the objects and instruments regarding to our project is the best platform for electrical students in the second step which is named as charge balance equation would be developed for both electrodes which is very important for our experiment equation balancing is the main topic when we are dealing with the experiment which is based on chemicals and also related to chemistry [13]. So, in this field the main thing to balance the equation when we get fully able to understand what we are mixing and what we will get then it will be very easier to understand that how our thing will perform so we develop both electrodes equation which is named as charge balanced equation charges are important to balance in all the experiments related with solid oxide fuel cells because in electrical we only want to create electricity with different methods and in electricity this field is all to all based on the movement of charges so the charge balancing is very important in this aspect so in our third step the realization of multi component transport in this tab the realization of multi component transport such as hydrogen and air would be achieved by Maxwell and Stephen's diffusion and convention equation and in our four step which is named as gas flow equation the interface of the gas flow and fuel would be mathematically developed using brinkman's equation so this is our whole summary that how we can perform our task and achievements this is the methodology of our project which will we implement in the heart to achieve that solid oxide fuel cell working.



In COMSOL Software simulation model of the SOFC would be developed. In more detail, two porous gas diffusion electrodes would be sandwiched together by an electrolyte substance.

Charge Transfer Kinetic equations would be developed for both electrodes.

The realization of the multi component transport, such as hydrogen and air, would be achieved by Maxwell-Stephen's diffusion and convention equations.

The interface of the gas flow and fuel would be mathematically developed using Brinkman Equations

Figure 2. Simulation model of the SOFC

II. LITERATURE REVIEW

Extensive research has been conducted on the development and optimization of SOFCs, with studies focusing on various aspects such as electrode materials, electrolyte composition, and operating conditions. These studies have demonstrated SOFCs' potential in various sectors, including power generation, industrial processes, and distributed energy systems. For instance, the integration of SOFCs into combined heat and power (CHP) systems has been explored, offering both electrical and thermal energy with high efficiency. Additionally, the use of SOFCs in microgrids and as auxiliary power units in transportation has shown significant promise. Previous research has extensively covered the principles of SOFC operation, focusing on the role of electrode materials, electrolyte composition, and operating conditions in determining performance. Studies have highlighted the importance of electrode kinetics and activation overpotential in influencing current density and overall efficiency. However, there is a gap in the literature regarding the comprehensive simulation of these processes using advanced tools like COMSOL Multiphysics. This study aims to fill this gap by providing a detailed analysis of SOFC performance through simulation, contributing to a deeper understanding of the factors affecting fuel cell efficiency.

i. Overview of SOFC Technology

SOFCs operate at high temperatures (typically between 600°C and 1000°C), using a solid oxide or ceramic electrolyte to conduct oxygen ions from the cathode to the anode. The high operating temperature enables internal reforming of fuels and the use of non-precious metal catalysts, contributing to the overall efficiency and cost-effectiveness of the technology. SOFCs are composed of three primary components: the anode, cathode, and electrolyte. The anode facilitates the oxidation of the fuel, the cathode reduces oxygen, and the electrolyte allows the transport of oxygen ions while preventing electronic conduction.

ii. Challenges and Limitations of SOFCs

Despite their advantages, SOFCs face several challenges that hinder their widespread commercialization. High operating temperatures can lead to material degradation, thermal stresses, and longer startup times, affecting the durability and reliability of the fuel cells. Additionally, the development of cost-effective materials that can withstand these temperatures while maintaining high ionic conductivity is a significant challenge. The efficiency of SOFCs [5] is also influenced by complex interactions between electrochemical processes, mass transport, and heat management, making optimization difficult. Addressing these challenges requires a deep understanding of the underlying physical and chemical processes that govern SOFC performance.

iii. Research Objectives, Hypotheses, and Questions

This study aims to investigate the impact of electrode kinetics, activation overpotential, ohmic losses, and mass transport on the performance of SOFCs. The primary objective is to understand how these factors influence current density distribution and overall fuel cell efficiency. The hypothesis is that optimizing electrode kinetics and reducing activation overpotential can significantly enhance SOFC performance. The research questions guiding this study include:

- How do electrode kinetics affect the current density distribution in SOFCs?
- What role does activation overpotential play in determining SOFC efficiency?
- How can the H2 mole fraction on the anode surface be optimized to improve SOFC performance?

The literature review highlights the importance of SOFC research and its potential for revolutionizing the energy industry. Further research is needed to address the remaining challenges and optimize SOFC technology for widespread adoption.

III. METHODOLOGY PATH

The The performance and efficiency of solid oxide fuel cells (SOFCs) are significantly influenced by the current density distribution. The cell's current density distribution can be be affected by a range of factors, including electrode design, fuel composition, and operating conditions. The following steps must be taken in order to maximize the performance of SOFCs accurately measure and analyze the current density distribution using advanced techniques and to test the kinetics parameters that affect the distribution.

One advanced technique for measuring current density distribution in SOFCs is EIS stands for spectroscopy of electrochemical impedance. EIS measures the impedance of the cell at different frequencies and can be applied to figure out the present density distribution within the cell. EIS can also be used to test the kinetics characteristics include the density of the impedance to charge transfer and the exchange current, which affect the current density distribution. Another advanced technique for measuring current density distribution in SOFCs is infrared thermography (IRT). IRT measures the temperature distribution across the cell and can be used to infer the current density distribution. By combining IRT with EIS, It is feasible to achieve a measurement that is more precise of the current density distribution. In addition to these techniques, it is also important to test the kinetics parameters that affect the distribution of current density, such as fuel oxidation kinetics and the oxygen reduction kinetics. This can be done using techniques such as cyclic voltammetry and chronoamperometry, which measure the current response of the cell to changes in voltage and time, respectively.

By considering and analyzing the current density distribution in SOFCs using advanced and optimal techniques and testing the kinetics parameters that affect the distribution, it is possible to optimize the performance and efficiency of the cell. This can lead to improvements in the design and operation of SOFCs, Additionally, new materials and technologies are being developed for these devices [6].

i. Equation:

There are several mathematical equations used in COMSOL for simulating the behavior of (SOFCs) for solid oxide fuel cells. Here are some of the key equations used in COMSOL for modeling SOFCs:

a) Nernst equation

The voltage of the SOFC is determined using the Nernst equation depending on the oxygen partial pressures and fuel at the electrodes. The equation is given by:

$$E = E0 - (RT/nF)\ln(pO2/pF)$$

where pO2 and pF are the partial pressures of oxygen and fuel, respectively, at the cathode and anode, and E is the SOFC's voltage, E0 is the reaction's standard potential, R is the gas constant, T is the reaction's temperature, n is the number of electrons transferred, F is the Faraday constant.

b) Butler-Volmer equation

One can use the Butler-Volmer formula to compute the current density at the electrodes of the SOFC. The equation is given by:

i = i0 [exp(-alpha_aFeta_a/RT) – exp (-(1-alpha_a) Feta_c/RT)]

where eta_a is the overpotential at the anode, alpha_a is the anodic transfer coefficient, alpha_c is the cathodic coefficient of transfer, and i is the density of current while i0 is the density of exchange current.

c) Poisson's equation

Poisson's equation is used to calculate the electrostatic potential within the SOFC. The equation is given by:

$$\nabla \cdot (\varepsilon \nabla \varphi) = -\rho$$

where ρ is the charge density, φ is the electrostatic potential, and ε is the material's permittivity.

d) Navier-Stokes equation

The Navier-Stokes formula is used as a simulator flow of gases within the SOFC. The equation is given by:

$$\rho\,(\partial u/\partial t + u \cdot \nabla u) = -\nabla p + \nabla \cdot (\mu(\nabla u + (\nabla u)^T)) + f$$

where the fluid's density is ρ, its viscosity is μ, its velocity is u, its pressure is p, and its force on the body is f.

Along with additional equations like the conservation of mass, these equations and species transport equations, are used in COMSOL to model the behavior of SOFCs [7] and predict their performance under different operating conditions.

IV. RESULTS AND DISCUSSION

The simulations conducted in this study reveal several critical insights into SOFC performance. Electrode kinetics and activation overpotential emerge as key factors influencing current density distribution within the fuel cell. The analysis shows that by optimizing these parameters, significant improvements in SOFC performance can be achieved. Additionally, the study identifies the distribution of current density and the H2 mole fraction on the anode surface as areas for potential optimization. The medium impact of mass transport on SOFC performance is also noted, indicating that while it is important, other factors like electrode potential and activation overpotential have a more pronounced effect.

Before we progress to the performance evaluation results, the selected parameters for SOFC meshing are important to discuss in Table 1. And Table 2. because they affect the overall performance.

Table 1 : Detail values of SOFC MESHING

Description	**Value**
Calibrate for	Fluid dynamics
The largest element size	3.15E-4
The smallest element size	7.87E-5
Curvature factor	0.9
Resolution of constrained areas	0.4
Maximum growth rate for elements	1.3
Predefined size	Extra coarse

Table 2: Main parameters that affect the performance of SOFC current density using COMSOL Multiphysics

Parameter	Impact on Current Density	**Range of Value**
Electrode kinetics	High	0.1-0.5 s-1
Activation overpotential	High	
Ohmic losses	Low	0.5-0.8 V
Mass transport	Medium	
Electrode potential	High	0.01-0.1 Ωcm2
Ohmic losses	Low	Medium Impact
Mass transport	Medium	-0.8 to -0.9 V
Electrolyte potential	High	
Electrolyte potential	High	0.5-0.7 V
Mole fraction of H2	High	0.8-0.9
Mole fraction of O2	Low	0.1-0.2
Mole fraction of H2O	Medium	0.2-0.3
Temperature	High	800-1000°C

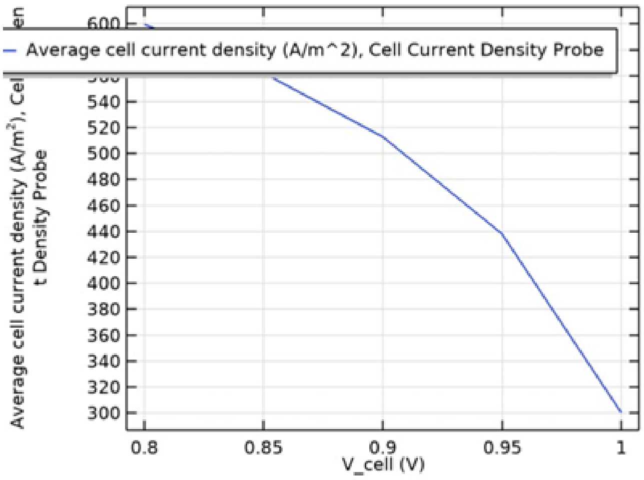


Figure 3. Probe Plot Group

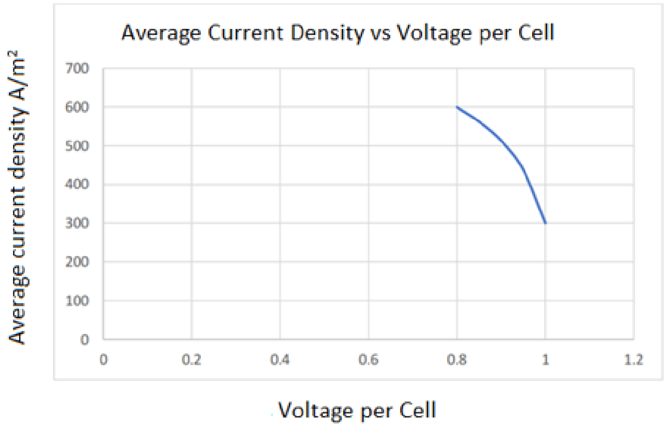


Figure 4. Current Denisty Distribution Peak (A/m^2) of SOFC

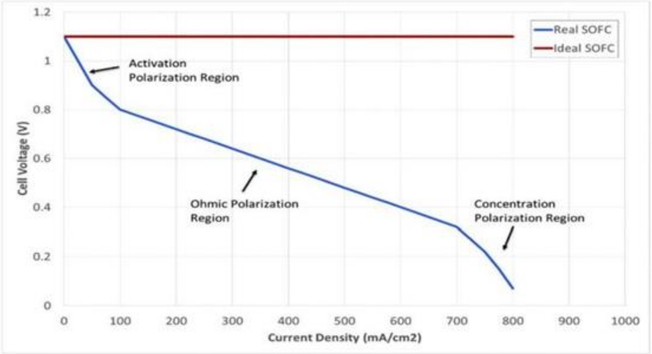


Figure 5. Solid Oxide Fuel Cell V-1 Curve in its deal (red) and typical (Blue) State.

Overall Performance Metrics

Considering the reference performance values of [8] and to map the performance analysis, we define the normalized performance of our proposed SOFC as:

$$Normalized\ Performance\ Improvment\ (\%) = \frac{\text{Actual Value} - \text{Reference Value}}{Actual\ Value}$$

Considering the reference current density distribution in [8], 200mA/cm2 at 0.5V and 700oC, we define the performance indicator of our SOFC as:

Table 3. performance indicator of SOFC

Value	**Current Density A/cm²**	**Voltage(V)**	**Temperature (°C)**	**Fuel Utilization (%)**	**Gas Flow Rate (cm³/s)**	**Normalized Performance (%)**	
Reference Value	200	0.5	700	-	-	**0**	**Reference Cell**
Actual Value 1	560	0.85	700	80	100	**180**	**Cell with graded electrodes**
Actual Value 2	510	0.9	750	85	125	**155**	**reased gas flow rate**
Actual Value 3	440	0.95	800	90	150	**120**	**Cell with increased rib width**
Actual Value 4	300	1	850	95	175	**50**	**Cell with minimum values of above26 dimensions**

Table 4. Average Current Density & Overall Performance Metrics

Value	Current Density A/cm²	age(V)	Temperature (°C)	Fuel Utilization (%)	Gas Flow Rate (cm³/s)	Normalized Performance (%)	
Reference Value	200	0.5	700	-	-	0	**Reference Cell**
Actual Value 1	560	0.85	700	80	100	180	**Cell with graded electrodes**
Actual Value 2	510	0.9	750	85	125	155	**sed gas flowrate**
Actual Value 3	440	0.95	800	90	150	120	**Cell with increased rib width**
Actual Value 4	300	1	850	95	175	50	**th minimum values ofabove dimensions**

Table 5. Performance Indicators of Parameters

Parameter of performance	At Inlet of Fuel Stream	At the anode surfac	At the cathode surface	Fuel Streamline	At Anode side	At Cathode sid e
MF, H2, Streamline	High	Decrease	Low	Parallel to anode	H_2 used, gives Elect. & H_2O	
MF, H2, Surface	High	Low	Low	Parallel to anode	H_2 used, gives Elect. & H_2O	O_2 used, gives Elect. & H_2O
MF, O2, Streamline	High	Low	Decrease	Parallel to cathode	O_2 is consumed	
MF, O2, Surface	High	High	Low	Parallel to cathode	Inefficient electro chemical	O_2 is consumed
MF, H2 O, Streamline	Highest	Low	High	Parallel to anode	H_2O	
MF, H2 O, Surface	Highest	Highest	Decrease		H_2O	Minimum H_2O
MF, N2, Streamline	Low	Low	Low	Parallel to anode	Very Low	Highest
MF, N2 Surface	Low	Low	Low	Parallel to anode	Very Low	Highest
Velocity	Highest	High	Decrease		High	Low
Pressure	Highest		Decrease		High	Low
Electrolyte Current Density	High	Highest	Low		O ions	O ions
Electrolyte Potential toGround		Highest	Decrease		High	Low

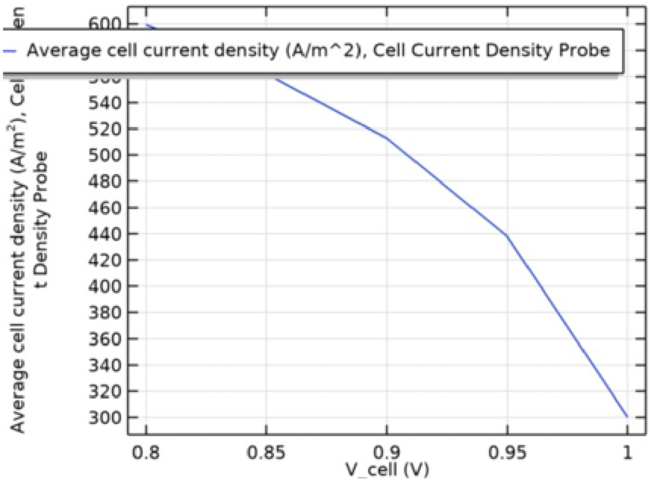


Figure 6. Probe Plot Group

The results and analysis of various parameters provide valuable insights into the behavior of SOFCs, which can inform the design and optimization of these solid oxide fuel cells [9], [10] for a wide range of energy applications as givem in Table. 3, 5 and 5 as well as graph shown in Fig. 3, 4,5, 6 and 7.

CONCLUSION

This study confirms the high impact of electrode kinetics, activation overpotential, and electrode potential on SOFC performance, emphasizing the need for targeted optimization in these areas. The insights gained from the simulations provide a foundation for the design and improvement of SOFCs, contributing to the broader goal of developing efficient and sustainable energy solutions. Future research should focus on further refining these simulations and exploring additional parameters to continue enhancing SOFC performance.

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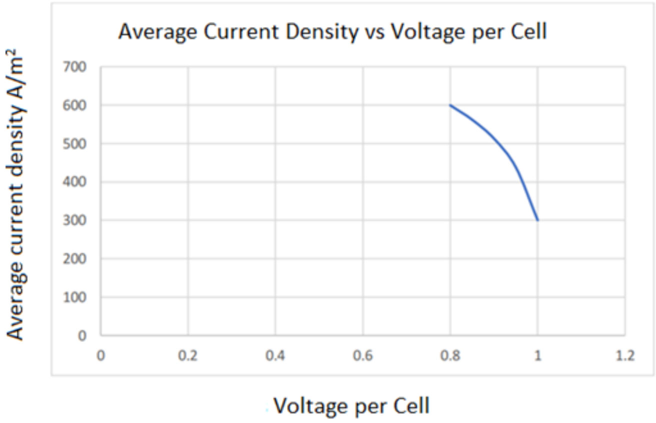

Figure 7. Current Denisty Distribution Peak (A/m2) of SOFC

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