Article

An Overview on Heat Transfer and the Evolution of Thermal Stress in Solid Oxide Fuel Cells

Seshu Kumar Vandrangi

Department of Mechanical engineering,
Universiti Teknologi PETRONAS, Malaysia.
E-mail: seshu1353@gmail.com, (Corresponding author)
https://orcid.org/0000-0002-5806-6913

Abstract. To reduce carbon emissions, solid oxide fuel cells (SOFCs) transform chemical energy into electricity directly. Nevertheless, since SOFCs operate at very high temperatures (600 C to 1000 C), it can be difficult to provide constant stability in electrical power output. Even more concerning is the fact that the SOFC assembling stack is rigid, making it vulnerable to heat stress, which in turn can cause mechanical deformation and, ultimately, a shorter lifetime for the SOFC system. The life expectancy of a SOFC system can be increased by detecting a consistent temperature gradient all across stack, which reduces the thermal stress distributions across the stack. The research analyses the relationship in between the temperature gradients and thermal stress distributions, generating heat sources, heat transfer mechanisms, and temperature gradients and heat transfers.

Keywords: Carbon emissions, Solid Oxide Fuel Cells, Temperature Gradient

Journal of Artificial Intelligence in Fluid Dynamics Volume 1 Issue 1
Received 23 May 2022
Accepted 28 June 2022
Published 10 September 2022
Online at https://www.jaifd.com/

1. Introduction

The endeavours towards cleaner power production technologies were bolstered by a greater understanding of the consequences of greenhouse gases, climate change, and pollution. Fuel cells, in contrast to traditional combustion-based power generating technologies, directly transform chemical energy - electrical power, bypassing the combustion process altogether [1-5]. A deeper comprehension of the effects of greenhouse gases, global warming, as well as pollution has spurred efforts to develop cleaner power generating systems. Unlike orthodox combustion-based power generating systems, fuel cells immediately convert chemical energy - electrical power. Solid oxide fuel cells (SOFCs) have significant potential to be employed as a power generating technology in the future because of its high fuel flexibility, efficiency, & power reliability. Unpredictable energy fluctuations in the grid system could result in catastrophic losses for end users, especially in the industrial sectors, if the power supply were to be interrupted [6-8]. As a result, reliable power generation is essential for satisfying consumer needs. An SOFC stack, assembled with a rivet and bolt to restrict the escape of fuel/oxidant gases [9,10], is a promising power production for satisfying the current demand for energy. Due to the ionic conductivity property in the electrolyte, SOFC stacks produce more power at a better efficiency while it is subjected to high temperature (600C1000C) [11-14]. The SOFC stack is vulnerable to thermal stress generation, especially at the sealant, since thermal stress is created when a rigid body suffers mechanical deformation owing to variation in temperature. Mismatch in thermal expansion coefficient (TEC) [15-19] & temperature gradient [20-25] have been shown to have a significant impact on the onset of thermal stress. Non-uniform temperature gradients create severe thermal stress on elements with incompatible materials, hence it is crucial to choose these materials wisely during the design phase of the cell (TEC). Deformation, creep, & cracks are examples of mechanical flaws caused by thermal stress in a SOFC stack. The likelihood of structural failure is raised as a result of [26,27]. Below, we'll talk about what causes temperature gradients, and how those gradients relate to heat transport in SOFCs. A deeper comprehension of the effects of greenhouse gases, climate change, and pollution has spurred efforts to develop cleaner power generating systems. Unlike conventional combustion-based power generating technologies, fuel cells directly convert chemical energy into electrical power, eliminating the need for any combustion at all in the process. Efforts to create cleaner power generating systems have been bolstered by a greater understanding of the consequences of greenhouse gases, global warming, and pollution. In contrast to traditional combustion-based power producing systems, fuel cells instantly convert chemical energy into electrical power. The high fuel flexibility, efficiency, and power reliability of solid oxide fuel cells (SOFCs) make them an attractive candidate for utilisation as a power generating technology in the near future. Power outages caused by unpredictable energy oscillations in the grid system could have devastating consequences for end users, particularly in the industrial sectors. This means that consistent electricity output is crucial to meeting the demands of the market. There is hope for meeting the current demand for energy through the use of power generated by a SOFC stack, which is assembled with a rivet and bolt to restrict the escape of fuel/oxidant gases. When heated to high temperatures (600C1000C), the ionic conductivity property of the electrolyte allows SOFC stacks to generate more power at a higher efficiency. Since thermal stress is produced when a rigid body suffers mechanical deformation due to temperature change, the SOFC stack is particularly susceptible to its creation at the sealant. The start of thermal stress has been found to be significantly influenced by a mismatch in thermal expansion coefficient (TEC) and a temperature gradient. Extreme thermal stress is placed on components made of incompatible materials by the cell's non-uniform temperature gradients, therefore it's important to make an informed material choice early in the design process (TEC). Mechanical defects in a SOFC stack include deformation, creep, and cracks due to thermal stress. Because of structural failure is more probable. In this section, we will discuss the factors that lead to temperature differences and how these variations impact heat transfer in SOFCs. Therefore, reliable electricity production is essential for satisfying market needs. A SOFC stack, which is assembled using a rivet & bolt to restrict the escape of fuel/oxidant gases, offers promise for satisfying the current need for energy. By increasing the temperature of the electrolyte to high levels (600C1000C), SOFC stacks are able to generate more power with a higher efficiency. In the case of the SOFC stack, thermal stress is generated at the sealant when a rigid body undergoes mechanical deformation owing to temperature change. It has been observed that a temperature gradient and a mismatch in thermal expansion coefficient (TEC) considerably affect the onset of thermal stress. Cell's non-uniform temperature gradients create extreme thermal stress on incompatible components, therefore it's crucial to make an informed material choice early in the design process (TEC). Deformation, creep, & cracks are all mechanical flaws caused by thermal stress in a SOFC stack. Since structural failure is more likely to occur as a result. In this article, we'll go over what causes temperature differences and how it impacts heat transmission in SOFCs. To reduce carbon emissions, solid oxide fuel cells (SOFCs) transform chemical energy into electricity directly. Nevertheless, since SOFCs operate at very high temperatures (600 C to 1000 C), it can be difficult to provide constant stability in electrical power output. Even more concerning is the fact that the SOFC assembling stack is rigid, making it vulnerable to heat stress, which in turn can cause mechanical deformation and, ultimately, a shorter lifetime for the SOFC system.

The life expectancy of a SOFC system can be increased by detecting a consistent temperature gradient all across stack, which reduces the thermal stress distributions across the stack. The research analyses the relationship in between the temperature gradients and thermal stress distributions, generating heat sources, heat transfer mechanisms, and temperature gradients and heat transfers. Also, computational fluid dynamics is used in estimation of convective heat transfer coefficients in nanofluids [60].

2. The Rise and Fall of SOFC Temperatures

Generally speaking, a temperature gradient is the temperature difference between two points along the direction of heat movement. Whether or not the gas flow in a SOFC stack is uniform from input to outlet has a knock-on effect on the heat flow, temperature distribution, & temperature gradient within the stack. By routing the fuel & oxidant gases through the interconnects here between electrodes, the reaction can take place in a variety of flow orientations. In SOFC, both parallel and counter-flow orientations have been extensively researched, as shown in Figure 1. All of these orientations transfer heat differently depending on how the heat is distributed and how steep the temperature gradients are. All of these characteristics are affected by the heat created by the gas flow channels as fuel and oxidant are introduced. More uniform temperature distribution is achieved in a counter-flow orientation, where Gases used as fuel and those used to oxidise it go in opposing directions. Regardless of the boundary condition used, the temperature is found to be greater at the outlet than the intake in a parallel-flow configuration, where both the fuel and the oxidizer gases move in the same direction. [28-31]. Stygar et al. [32] used computational fluid dynamics (CFD) to examine the effects of geometrical alterations on the rate of heat transfer in a SOFC with a mono-block-layer construction. In this investigation, we used the interaction between heat input & fuel mass flow rate to calculate temperature distribution. Results showed a substantially more uniform temperature distribution with in counter-flow orientation, even when the inlet temperature and fuel mass flow rate were held constant. In the meanwhile [33] performed a CFD – Computational Fluid Dynamics analysis based on the hypothesis that the distribution of the temperature is caused by the heat absorption reaction. Mass, energy, momentum, as well as ionic conservation rules were used to create the 3D model's partial differential equations in this research. Because the temperature gradient is steeper in the parallel-flow orientations, the data showed that the current density distribution was less uniform there. This was the case for the counter-flow orientations. This is why the counter-current orientation is favoured because it results in a more consistent temperature throughout.

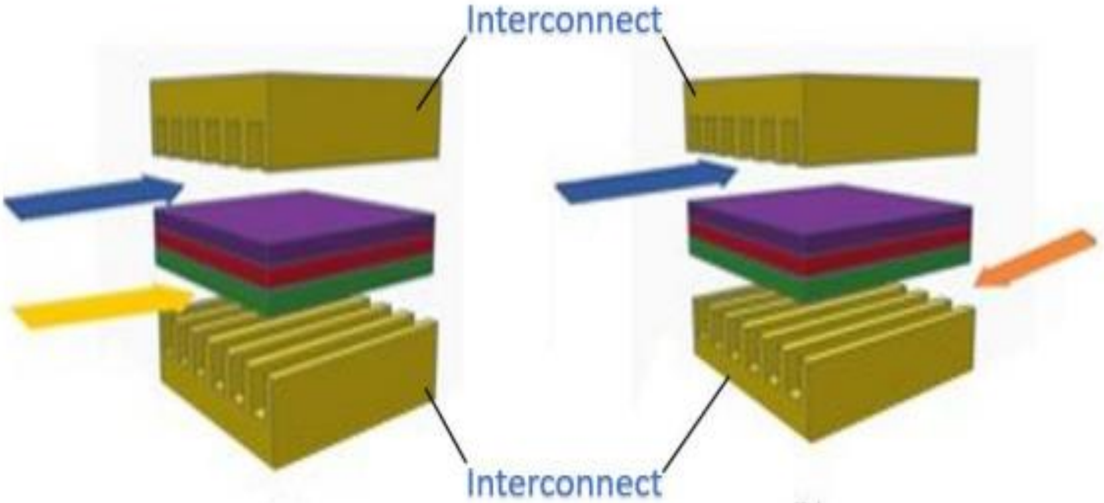

Fig. 1. Orientation of gas flow in a solid-oxide fuel cell

It has been found that the thermal stress distribution is reduced in reverse flow because the temperature gradient is not as sharp as in parallel flow. Since the ionic conductivity of the cell is temperature dependent, an uneven distribution of temperature in the stack, especially among the contact surface of the electrodes & interconnection, can cause the ionic conductivity to fluctuate and, in turn, the output power of the cell to be unreliable [34-37]. The link between thermal stress & temperature gradient was also shown by Choudhary et al. [38]. The results demonstrated that preheating the fuel & oxidant gases before they are introduced to the stack reduces the stress distribution throughout the SOFC components. Consequently, it is crucial to assure constant endothermic reaction and efficient output performance by reducing the steepness of the temperature gradient, which significantly effects the rate of thermal stress distribution in SOFC stacks.

Because the temperature gradient is not as dramatic as it is in parallel flow, the thermal stress distribution is less extreme in reverse flow. Since the cell's ionic conductivity varies with temperature, an imbalance in the stack's temperature, particularly at the surface of contact of the electrodes and the interconnection, can cause the ionic conductivity to fluctuate and the cell's output power to be unreliable [34-37]. Choudhary et al. [38] also demonstrated the connection between thermal stress and temperature gradient. The results showed that stress distribution in the SOFC parts was reduced due to preheating the fuel and oxidant gases before they were delivered to the stack. To guarantee a steady endothermic reaction and high output performance from SOFC stacks, it is necessary to mitigate the steepness of the temperature gradient that has a major impact on the rate of thermal stress distribution.

3. SOFC Heat Transfer

The two main categories for the heat source in SOFC applications are Heat is provided from the outside and created within. There are three primary ways in which heat can be transmitted: conduction, convection, and radiation. Radiative heat exchange between the fuel/oxidant and gas flow channels just at interconnects has not been taken into account when determining the temperature gradient in solid oxide fuel cells [39]. In SOFC applications, there are two primary types of heat sources: Hot air is generated both externally and internally. Heat can be transferred in three main ways: by conduction, by convection, and by radiation. When calculating the temperature gradient in SOFCs, researchers have only considered convective heat transfer between the fuel/oxidant & gas flow channels at interconnects. However, the energy that is introduced into the SOFC stack in the form of fuel and oxidant is converted into conductive and convective energy. Figure 2 shows this procedure in detail. Concentration polarisation, activation polarisation, and ohmic polarisation are all examples of electrochemical and chemical reactions that have been examined in the literature [40–42] and contribute to the internal heat generation of a system. Concentration and activation polarizations, both of which produce heat, were disregarded in their writings. The results demonstrated that the endothermic reaction generates negligible amounts of heat. Moreover, the oxygen ion's conductivity across the electrode is responsible for the Joule effect's heat generation. In this study, the Joule effect is explored in further depth in Section 4. Maintaining a uniform temperature distribution is essential for efficient heat transfer, and this can be accomplished by keeping temperature gradients as small as possible. The consequences of temperature distribution & heat transport in SOFC have been the subject of recent research [43-49]. The steepness of temperature gradient all across stack can be reduced and the cell performance can improve with the help of a heat pipe if it is implemented in SOFC.

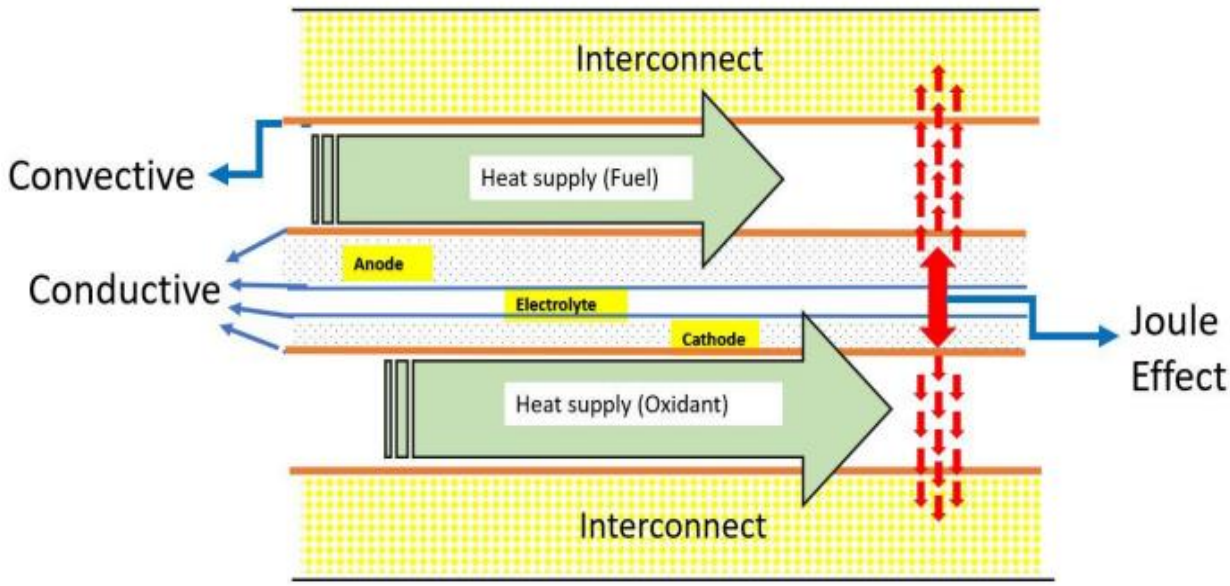

Fig. 2. SOFC heat transport diagram along the x-axis (side view)

Using CFD for validation, Dillig et al. [50] recently shown that the temperature gradient in SOFC might be reduced by as much as 50%. Whenever the rate of heat extraction from the SOFC stack was raised, the temperature disparities between the SOFC elements decreased, which improved efficiency of heat (16 percent). Zeng et al. [51] used a similar method to assess the connection between heat transport and temperature gradients. The results of the studies by Dillig et al. [50] and Zeng et al. [51] are consistent with one another. Microcracking in the cell was further evaluated by observing its cross-section.

The huge temperature disparity typically has a deleterious effect on the cell, leading to the development of micro-cracks. Relative to simulation, wherein the factor was only based on assumption, the aforementioned work reveals greater benefits in measuring the areas of effectiveness & precision in the analysis, as shown in the actual state of the cell. In the next section, we'll dive deeper into the role that temperature gradients play in heat transmission, in particular as they pertain to the SOFC context.

3.1. Transfer of Heat by Convection

When energy is transferred from an external heat source, such as the fuel/oxidant (fluid), to the surface of the interconnect and electrodes, this process is known as convection heat transfer (solid). See how easy it is to calculate convective heat transfer with Newton's Law of Cooling

$$Q_{conv} = hA(T_s - T_F)$$

$$Q_{conv} = hA\left(\frac{dT}{dx}\right)$$

where A is the area in contact with moving fluid, Ts is indeed the temperature of solid, and TF is indeed the temperature of fluid.

When a solid object absorbs heat from a fluid, the heat transfer equation (1) is used. To determine the heat exchange between fluid flow & the contact surface all along gas flow channels, Eq (2). The relationship among the temperature distribution, temperature gradient, and efficiency of cell performance has been studied by Steilen et al. [52] using a computational technique using convective heat exchange as loss of heat from the system. The heat transmission is a major factor in determining the temperature distribution. Consequently, heat transfer has a major impact on output voltage, output power, & efficiency of performance. The heat transfer equation (1) is utilised to describe the process of heat transfer from a fluid to a solid. Transfer of heat between the fluid and the surface of contact is calculated along the gas flow channels using Eq (2). Steilen et al. [52] used a computational method that relied on convective heat exchange as a loss of heat from the system to investigate the connection between the temperature distribution, the temperature gradient, and the efficiency of cell performance. One of the most important aspects of temperature distribution is heat transmission. Therefore, heat transmission significantly affects output voltage, output power, and performance efficiency. [53] came to a similar conclusion, observing that the cell temperature & performance efficiency are affected by an excess of air flow in the interconnection during fuel usage. Since rapid air movement increases the rate of convective heat transfer, the ionic conductivity of the YSZ electrolyte decreases and the pace of electro-catalytic reactions slows. Previous studies have demonstrated that minimising temperature gradients by maintaining a uniform temperature distribution is essential for optimising system performance. Rapid heat removal is caused by the high heat exchange rate in a solid oxide fuel cell stack. The temperature has a significant impact on how abruptly the endothermic reaction ends. As a result, the SOFC system's efficiency can be jeopardised by removing too much heat from it. That's why it's important to factor in the right temperature gradient right from the start of the SOFC stack's design process to maximise the stack's efficiency.

3.2. Conductive Heat Transfer

To put it simply, conductive heat transfer is the process by which energy is transferred from more energetic to less energetic molecules inside the limits of a solid body, or from one solid body to another across their boundaries. An individual cell's anode, electrolyte, & cathode all serve as heat conductors when the fuel transmits its heat convectively. Figure 3 depicts the temperature and heat transfer from the anode to the electrolyte to the cathode of a single cell when using only the fuel just at anode side as a heat source. Fourier's law states that the temperature gradient of a SOFC - Solid Oxide Fuel Cell represents the variation in heat flow with respect to single cell thickness.

Simply described, transfer of conductive heat is the energy transmission from more energetic to the less energetic molecules inside the borders of a solid body, or from one solid body to the other across their boundaries. Whenever the fuel transfers its heat convectively, the anode, electrolyte, and cathode of a single cell all play a role as heat conductors. Using only the fuel at the anode side as a heat source, the heat and pressure transfer from anode to a electrolyte to a cathode of a single cell are shown in Figure 3. Based on Fourier's law, the temperature gradient of a SOFC (Solid Oxide Fuel Cell) reflects the variation in heat flow with respect to single cell thickness.

$$Q_{conv} = -kA\left(\frac{dT}{dx}\right)$$

where k represents conductivity of heat constant (W/mK) and A is the contact surface area, and dt/dx is the temperature gradient across the thickness of the solid oxide fuel cell element. Crack propagation rate was used to examine the impact of heat transfer and fluid flow on thermal stress distribution by Shao et al. [54].

They deduced that the inside heat came from some form of conductive heating. The results showed that the variation in SOFC component value and temperature gradient throughout the stack triggered the fracture propagation. Previous research had only examined convective heat transfer as the heat left the stack, but Amiri et al. [55] used both convective and conductive heat transfer because the heat was generated in the cell via a heat absorption response. The results demonstrated that the conductive heat generated is significantly more important than the convective heat generated. For one thing, gases have a substantially lower heat capacity and heat conductivity compared to solids.

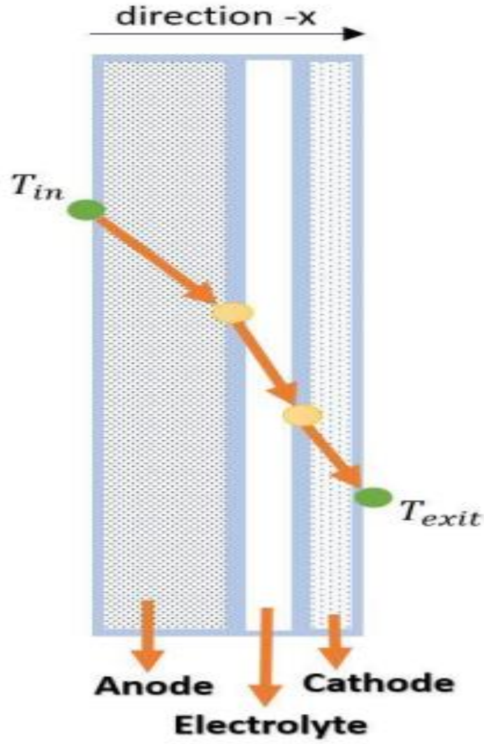

Fig. 3. An electrolyte-cathode-anode configuration produces a temperature gradient across a single cell

3.3. Effect of Joule

Joule effect, or ohmic heating, is the term used to describe the heat created by ohmic overpotential losses in a solid oxide fuel cells stack. Joule effect-generated inside heat is conducted away from electrodes and into the interconnects (Figure 2). The heat produced by ohmic overpotential deficits in a stack of solid oxide fuel cells is referred to as the Joule effect or ohmic heating. Electrical current transfers heat away from the electrodes and then into the interconnects as a result of the Joule effect. Because the Joule effect creates significantly more internal heat than the electrochemical reaction does, ohmic losses have a substantial effect on the temperature distribution as well as the range of the temperature gradient steepness in Solid Oxide Fuel Cells - SOFCs [56].

To calculate the heat generated by the Joule effect, one uses the following formula

$$S_{ohn} = \frac{i^2}{\sigma'}$$

where I stand for the electrical current density and for the conductivity of the material. The impact of geometric modifications on temperature distribution was investigated by Sahli et al. [57] who considered solely the heat production related to ohmic heating. The research showed that the anode, where the temperature differential between the electrolyte and the anode was greatest, had the highest temperature gradient variance. However, because no link was established between current density and heat dispersion rate, the study's applicability is limited. However, when determining the Joule effect's role as a heat source in SOFC, they focused solely on maintaining a constant current density. Razbani et al. [58] modelled chemical & electrochemical processes & transport phenomena on electrolyte-supported solid oxide fuel cells using 3D numerical analysis. Under the hypothesis that heat is produced by electrochemical reactions, the Joule effect, as well as activation losses, it was discovered that densities of current & cell voltages are highly correlated with such a temperature distribution in the cell. This paper sheds light on the topic by dispelling the myth that the interconnect is insulated by demonstrating the presence of ohmic resistance across the connection. Lee et al. [59] investigated the link between temperature and heat conduction. Because of the importance of the Joule effect at very high operating temperatures, 3-D modelling was used to examine the connection between the two.

The results demonstrated that the electrolyte conducted heat generated by the effects of Joule to the anode or cathode depending on which had the lowest thermal conductivity. Therefore, the materials employed in the construction of the electrodes do influence the orientation of the temperature gradient. It is important to account for the heat created from the endothermic reaction, especially in relation to the effect of Joule, because of the effect it has on the temperature distribution in SOFC. The steepness gradient and the output performance of the cell are both affected by the heat released via the Joule effect. Because of this, the increase in power production is most noticeable at high operating temperatures. The results showed that heat created by the Joule effects was carried by the electrolyte to anode or cathode, depending about which had the lower thermal conductivity. Therefore, the materials used to manufacture the electrodes do affect the temperature gradient direction. Since the distribution of temperature in SOFC is affected by the heat created from the endothermic reaction, it is vital to take this into account, especially in respect to the Joule effect. In addition to impacting the cell's output performance, the heat generated by the Joule effect also modifies the gradient's steepness. As a result, the boost in output power is most apparent at high temperatures.

4. Conclusion

Clean, sustainable, and renewable energy sources are quickly becoming the norm in the industry. Since SOFCs provide output power at higher efficiency and provide a wide range of fuel flexibility options, they are among the most popular options for alternative power production technology. For SOFCs to last as long as possible while operating at temperatures in between 600°C and 1000°C, thermal stress distribution across the stack should be taken into account. In this study, we explore the most influential variables of thermal stress distribution in SOFCs: temperature gradients and their influence on conductive, convective, and Joule heat transfer mechanisms. Acquiring precise data and making sense of the analysis requires first pinpointing the optimal temperature gradient condition between the SOFC components. Most previous study into predicting the distribution of thermal stress has relied on computer simulation in an effort to better understand the mechanical breakdown that causes it. This method is suitable since it is inexpensive and simple to alter the parameter.

The use of renewable, sustainable, and environmentally friendly energy sources is quickly becoming the norm. The output power of SOFCs is higher than that of other alternative power generation technologies, and they offer a wide variety of fuel flexibility possibilities. So that SOFCs can endure as long as feasible when subjected to temperatures ranging from 600°C to 1000°C, it is important to consider how thermal stress is distributed across the stack. This research investigates the most important factors that affect the distribution of thermal stress in SOFCs, specifically temperature gradients & their impact on convective, radiative, and Joule heat transfer. Identifying the optimum condition of temperature gradient between the SOFC components is a prerequisite for collecting accurate data and making sense of the analysis. When trying to understand the mechanical breakdown that generates thermal stress, much past research has focused on computer simulation. This method is appropriate since it is low-cost and straightforward to adjust the parameter.

References

[1] Khadyko, Mikhail, Calin Daniel Marioara, Stephane Dumoulin, Tore Børvik, and Odd Sture Hopperstad. "Effects of heat-treatment on the plastic anisotropy of extruded aluminium alloy AA6063." Materials Science and Engineering: A 708 (2017): 208-221.

[2] Baharuddin, Nurul Akidah, Andanastuti Muchtar, Mahendra Rao Somalu, MUHAMMED ALI SA, and Hamimah Abd Rahman. "INFLUENCE OF SINTERING TEMPERATURE ON THE POLARIZATION RESISTANCE OF La0. 6Sr0. 4Co0. 2Fe0. 8O3-δ–SDC CARBONATE COMPOSITE CATHODE." Ceramics–Silikáty 60, no. 2 (2016): 115-121.

[3] Baharuddin, Nurul Akidah, Andanastuti Muchtar, and Mahendra Rao Somalu. "Short review on cobalt-free cathodes for solid oxide fuel cells." International journal of hydrogen energy 42, no. 14 (2017): 9149-9155.

[4] Cinti, G., G. Discepoli, E. Sisani, and U. Desideri. "SOFC operating with ammonia: stack test and system analysis." International Journal of Hydrogen Energy 41, no. 31 (2016): 13583-13590.

[5] Mahmud, L. S., A. Muchtar, and M. R. Somalu. "Challenges in fabricating planar solid oxide fuel cells: a review." Renewable and Sustainable Energy Reviews 72 (2017): 105-116.

[6] Zhu, Jian-hong, Wen-xia Pan, and Xiaoqiang Li. "Energy storage scheduling design on friendly grid wind power." Sustainable Energy Technologies and Assessments 25 (2018): 111-118.

[7] Merino, Julia, Carlos Veganzones, Roberto Álvaro-Hermana, and Jesús Fraile-Ardanuy. "Electrical machines based multi-disturbance device for testing distribution grid technologies." International Journal of Electrical Power & Energy Systems 99 (2018): 57-68.

[8] Wang, Keyou, Chen Qi, Xin Huang, and Guojie Li. "Large disturbance stability evaluation of interconnected multi-inverter power grids with VSG model." The Journal of Engineering2017, no. 13 (2017): 2483-2488.
[9] Lin, Chih-Kuang, Yu-An Liu, Si-Han Wu, Chien-Kuo Liu, and Ruey-Yi Lee. "Joint strength of a solid oxide fuel cell glass–ceramic sealant with metallic interconnect in a reducing environment." Journal of Power Sources 280 (2015): 272-288.
[10] Jiang, Wenchun, Yucai Zhang, Yun Luo, J. M. Gong, and S. T. Tu. "Creep analysis of solid oxide fuel cell with bonded compliant seal design." Journal of Power Sources 243 (2013): 913-918.
[11] Anwar, M., A. Muchtar, and M. R. Somalu. "Effects of Various Co-Dopants and Carbonates on the Properties of Doped Ceria-Based Electrolytes: a Brief Review Electrolytes for SOFCs." Int J Appl Eng Res 11 (2016): 9921-9928.
[12] Anwar, Mustafa, Muhammed Ali SA, Abdalla M. Abdalla, Mahendra Rao Somalu, and Andanastuti Muchtar. "Effect of sintering temperature on the microstructure and ionic conductivity of Ce." (2017).
[13] Xenos, Dionysios P., Philipp Hofmann, Kyriakos D. Panopoulos, and Emmanuel Kakaras. "Detailed transient thermal simulation of a planar SOFC (solid oxide fuel cell) using gPROMS™." Energy 81 (2015): 84-102.
[14] Lei, Libin, Zetian Tao, Tao Hong, Xiaoming Wang, and Fanglin Chen. "A highly active hybrid catalyst modified (La 0.60 Sr 0.40) 0.95 Co 0.20 Fe 0.80 O 3-δ cathode for proton conducting solid oxide fuel cells." Journal of Power Sources389 (2018): 1-7.
[15] Gao, Peipei, Amy Bolon, Manisha Taneja, Zhilin Xie, Nina Orlovskaya, and Miladin Radovic. "Thermal expansion and elastic moduli of electrolyte materials for high and intermediate temperature solid oxide fuel cell." Solid State Ionics 300 (2017): 1-9.
[16] Xu, Min, Ting Shuai Li, Ming Yang, Martin Andersson, Ida Fransson, Tara Larsson, and Bengt Sundén. "Modeling of an anode supported solid oxide fuel cell focusing on thermal stresses." International Journal of Hydrogen Energy 41, no. 33 (2016): 14927-14940.
[17] Molla, Tesfaye Tadesse, Kawai Kwok, and Henrik Lund Frandsen. "Transient deformational properties of high temperature alloys used in solid oxide fuel cell stacks." Journal of Power Sources 351 (2017): 8-16.
[18] Jiang, Xuening, Jiao Wang, Guoqiang Jia, Zijian Qie, Yuchao Shi, Asim Idrees, Qingyu Zhang, and Lei Jiang. "Characterization of PrBa0. 92CoCuO6− δ as a potential cathode material of intermediate-temperature solid oxide fuel cell." International Journal of Hydrogen Energy 42, no. 9 (2017): 6281-6289.
[19] Wei, S-S., T-H. Wang, and J-S. Wu. "Numerical modeling of interconnect flow channel design and thermal stress analysis of a planar anode-supported solid oxide fuel cell stack." Energy 69 (2014): 553-561.
[20] Amiri, Amirpiran, Periasamy Vijay, Moses O. Tadé, Khaliq Ahmed, Gordon D. Ingram, Vishnu Pareek, and Ranjeet Utikar. "Planar SOFC system modelling and simulation including a 3D stack module." International Journal of Hydrogen Energy 41, no. 4 (2016): 2919-2930.
[21] Xu, Min, Tingshuai Li, Ming Yang, and Martin Andersson. "Solid oxide fuel cell interconnect design optimization considering the thermal stresses." Science bulletin 61, no. 17 (2016): 1333-1344.
[22] Wen, H., J. C. Ordonez, and J. V. C. Vargas. "Optimization of single SOFC structural design for maximum power." Applied Thermal Engineering 50, no. 1 (2013): 12-25.
[23] Ramadhani, F., M. A. Hussain, H. Mokhlis, and S. Hajimolana. "Optimization strategies for Solid Oxide Fuel Cell (SOFC) application: A literature survey." Renewable and Sustainable Energy Reviews 76 (2017): 460-484.
[24] Razbani, Omid, Ivar Wærnhus, and Mohsen Assadi. "Experimental investigation of temperature distribution over a planar solid oxide fuel cell." Applied energy 105 (2013): 155-160.
[25] Duan, Liqiang, Kexin Huang, Xiaoyuan Zhang, and Yongping Yang. "Comparison study on different SOFC hybrid systems with zero-CO2 emission." Energy 58 (2013): 66-77.
[26] Huang, Yingcai, Qiubao Lin, Huiying Liu, Meng Ni, and Xiuqin Zhang. "Evaluation of the waste heat and residual fuel from the solid oxide fuel cell and system power optimization." International Journal of Heat and Mass Transfer 115 (2017): 1166-1173.
[27] Luo, Yun, Wenchun Jiang, Qian Zhang, W. Y. Zhang, and Muming Hao. "Effects of anode porosity on thermal stress and failure probability of planar solid oxide fuel cell with bonded compliant seal." International Journal of Hydrogen Energy 41, no. 18 (2016): 7464-7474.
[28] Skrzypkiewicz, Marek, Michał Wierzbicki, Jakub Kupecki, and Michał Stępień. "Selected Aspects of Design, Construction, and Operation of SOFC-Based Micro-Combined Heat and Power Systems." In Modeling, Design, Construction, and Operation of Power Generators with Solid Oxide Fuel Cells, pp. 205-231. Springer, Cham, 2018.
[29] Martinez, Andrew S., Jacob Brouwer, and G. Scott Samuelsen. "Comparative analysis of SOFC–GT freight locomotive fueled by natural gas and diesel with onboard reformation." Applied energy 148 (2015): 421-438.
[30] Canavar, Murat, and Yuksel Kaplan. "Effects of mesh and interconnector design on solid oxide fuel cell performance." International Journal of Hydrogen Energy 40, no. 24 (2015): 7829-7834.
[31] Guo, Hang, Mao Hai Wang, Jia Xing Liu, Zhi Hua Nie, Fang Ye, and Chong Fang Ma. "Temperature distribution on anodic surface of membrane electrode assembly in proton exchange membrane fuel cell with interdigitated flow bed." Journal of Power Sources 273 (2015): 775-783.

[32] Stygar, Mirosław, Tomasz Brylewski, and Mieczysław Rękas. "Effects of changes in MOLB-type SOFC cell geometry on temperature distribution and heat transfer rate in interconnects." International Journal of Heat and Mass Transfer 55, no. 15-16 (2012): 4421-4426.
[33] Amedi, Hamid Reza, Bahamin Bazooyar, and Mahmoud Reza Pishvaie. "Control of anode supported SOFCs (solid oxide fuel cells): Part I. mathematical modeling and state estimation within one cell." Energy 90 (2015): 605-621.
[34] Meng, Qingshan, Jitian Han, Lingjian Kong, Hai Liu, Tao Zhang, and Zeting Yu. "Thermodynamic analysis of combined power generation system based on SOFC/GT and transcritical carbon dioxide cycle." International Journal of Hydrogen Energy 42, no. 7 (2017): 4673-4678.
[35] Tucker, Michael C. "Dynamic-temperature operation of metal-supported solid oxide fuel cells." Journal of Power Sources395 (2018): 314-317.
[36] Cai, Yixiao, Baoyuan Wang, Yi Wang, Chen Xia, Jinli Qiao, Peter A. van Aken, Bin Zhu, and Peter Lund. "Validating the technological feasibility of yttria-stabilized zirconia-based semiconducting-ionic composite in intermediate temperature solid oxide fuel cells." Journal of Power Sources 384 (2018): 318-327.
[37] Meng, Yuanjing, Xunying Wang, Chen Xia, Baoyuan Wang, Wenjing Dong, Yuan Ji, and Bin Zhu. "Highperformance SOFC based on a novel semiconductor-ionic SrFeO3-δ–Ce0. 8Sm0. 2O2-δ membrane." International Journal of Hydrogen Energy (2018).
[38] Choudhary, Tushar, and Mithilesh kumar Sahu. "CFD Modeling of SOFC Cogeneration System for Building Application." Energy Procedia 109 (2017): 361-368.
[39] Moussa, Hocine Ben, Bariza Zitouni, Kafia Oulmi, Bouziane Mahmah, Maiouf Belhamel, and Philippe Mandin. "Hydrogen consumption and power density in a co-flow planar SOFC." International journal of hydrogen energy 34, no. 11 (2009): 5022-5031.
[40] Shariatzadeh, O. Joneydi, A. H. Refahi, M. Rahmani, and S. S. Abolhassani. "Economic optimisation and thermodynamic modelling of SOFC tri-generation system fed by biogas." Energy Conversion and Management 105 (2015): 772-781.
[41] Rabuni, Mohamad Fairus, Tao Li, Puvich Punmeechao, and Kang Li. "Electrode design for direct-methane microtubular solid oxide fuel cell (MT-SOFC)." Journal of Power Sources384 (2018): 287-294.
[42] Badur, Janusz, Marcin Lemański, Tomasz Kowalczyk, Paweł Ziółkowski, and Sebastian Kornet. "Zero-dimensional robust model of an SOFC with internal reforming for hybrid energy cycles." Energy (2018).
[43] Dong, Sang-Keun, Woo-Nam Jung, Kashif Rashid, and Akiyoshi Kashimoto. "Design and numerical analysis of a planar anode-supported SOFC stack." Renewable Energy 94 (2016): 637-650.
[44] Nguyen, Xuan-Vien, Chang-Tsair Chang, Guo-Bin Jung, Shih-Hung Chan, Chia-Chen Yeh, Jyun-Wei Yu, and Chi Yuan Lee. "Improvement on the design and fabrication of planar SOFCs with anode–supported cells based on modified button cells." Renewable Energy 129 (2018): 806-813.
[45] Fardadi, Mahshid, Dustin F. McLarty, and Faryar Jabbari. "Investigation of thermal control for different SOFC flow geometries." Applied Energy 178 (2016): 43-55.
[46] Kupecki, Jakub, Konrad Motylinski, and Jaroslaw Milewski. "Dynamic analysis of direct internal reforming in a SOFC stack with electrolyte-supported cells using a quasi-1D model." Applied Energy 227 (2018): 198-205.
[47] Ramírez-Minguela, J. J., V. H. Rangel-Hernández, J. A. Alfaro-Ayala, A. R. Uribe-Ramirez, J. M. Mendoza-Miranda, J. M. Belman-Flores, and B. Ruiz-Camacho. "Energy and entropy study of a SOFC using biogas from different sources considering internal reforming of methane." International Journal of Heat and Mass Transfer 120 (2018): 1044-1054.
[48] Peksen, M. "Safe heating-up of a full scale SOFC system using 3D multiphysics modelling optimisation." International Journal of Hydrogen Energy 43, no. 1 (2018): 354-362.
[49] Spallina, Vincenzo, Pasquale Nocerino, Matteo C. Romano, Martin van Sint Annaland, Stefano Campanari, and Fausto Gallucci. "Integration of solid oxide fuel cell (SOFC) and chemical looping combustion (CLC) for ultra-high efficiency power generation and CO 2 production." International Journal of Greenhouse Gas Control 71 (2018): 9-19.
[50] Dillig, Marius, Thomas Plankenbühler, and Jürgen Karl. "Thermal effects of planar high temperature heat pipes in solid oxide cell stacks operated with internal methane reforming." Journal of Power Sources 373 (2018): 139- 149.
[51] Zeng, Hongyu, Yuqing Wang, Yixiang Shi, Ningsheng Cai, and Dazhong Yuan. "Highly thermal integrated heat pipesolid oxide fuel cell." Applied Energy 216 (2018): 613-619.
[52] Steilen, Mike, Costanza Saletti, Marc P. Heddrich, and K. Andreas Friedrich. "Analysis of the influence of heat transfer on the stationary operation and performance of a solid oxide fuel cell/gas turbine hybrid power plant." Applied Energy 211 (2018): 479-491.
[53] Bhattacharya, Deepra, Jayanta Mukhopadhyay, Nayan Biswas, Rajendra Nath Basu, and Prasanta Kumar Das. "Performance evaluation of different bipolar plate designs of 3D planar anode-supported SOFCs." International Journal of Heat and Mass Transfer 123 (2018): 382-396.

[54] Shao, Q., L. Bouhala, D. Fiorelli, M. Fahs, A. Younes, P. Núñez, S. Belouettar, and A. Makradi. "Influence of fluid flow and heat transfer on crack propagation in SOFC multi-layered like material with anisotropic porous layers." International Journal of Solids and Structures 78 (2016): 189-198.
[55] Amiri, Saeid, R. E. Hayes, K. Nandakumar, and Partha Sarkar. "Modelling heat transfer for a tubular micro-solid oxide fuel cell with experimental validation." Journal of Power Sources 233 (2013): 190-201.
[56] Li, Ang, Ce Song, and Zijing Lin. "A multiphysics fully coupled modeling tool for the design and operation analysis of planar solid oxide fuel cell stacks." Applied Energy 190 (2017): 1234-1244.
[57] Sahli, Youcef, Bariza Zitouni, Hocine Ben Moussa, and Hafsia Abdenebi. "Three-Dimensional Numerical Study of the Heat Transfer on The Planar Solid Oxide Fuel Cell: Joules Effect." In Progress in Clean Energy, Volume 1, pp. 449-461. Springer, Cham, 2015.
[58] Razbani, Omid, Mohsen Assadi, and Martin Andersson. "Three dimensional CFD modeling and experimental validation of an electrolyte supported solid oxide fuel cell fed with methane-free biogas." international journal of hydrogen energy 38, no. 24 (2013): 10068-10080.
[59] Lee, Sanghyeok, Mansoo Park, Hyoungchul Kim, Kyung Joong Yoon, Ji-Won Son, Jong-Ho Lee, Byung-Kook Kim, Wonjoon Choi, and Jongsup Hong. "Thermal conditions and heat transfer characteristics of high-temperature solid oxide fuel cells investigated by three-dimensional numerical simulations." Energy 120 (2017): 293-305.
[60] Seshu Kumar Vandrangi, Sampath Emani, Hassan S, Sharma KV. Fluid dynamic simulations of EG-W (ethylene glycol–water) mixtures to predict nanofluid heat transfer coefficients. Environmental Technology & Innovation. 2020 Nov 1;20:101113.