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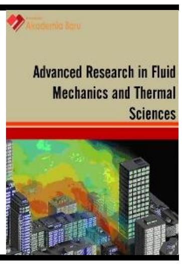

Influence of Heat Transfer on Thermal Stress Development in Solid Oxide Fuel Cells: A Review

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ABSTRACT

Solid oxide fuel cells (SOFCs) directly convert chemical energy into electrical power with minimal carbon emission. However, maintaining consistently stable electrical power generation can be challenging for SOFCs that operate at high temperatures ranging from 600°C–1000°C. Furthermore, the rigid SOFC assembly stack is prone to the development of thermal stress that leads to mechanical deformation, which subsequently shortens the lifetime of the SOFC system. Hence, identifying a uniform temperature gradient across the stack can minimize the thermal stress distribution across the stack and help prolong the service life of an SOFC system. This paper discusses the sourceof generated heat, the heat transfer mechanism, and their relationwith the temperature gradient and thermal stress distribution.

Keywords:
SOFC, thermal stress, heat transfer, temperature gradient

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1. Introduction

Increasing awareness oftoday's environmental diseases, such as the effects of greenhouse gas, climate change, andpollution, enhanced the initiatives towards cleaner power generation technologies. Unlike the conventional combustion-based power generation technologies, fuel cells directly convert chemical energy into electrical power without undergoing the combustion process [1-5]. Among the different types of fuel cells, solid oxide fuel cells (SOFCs) exhibiting excellent fuel flexibility, efficiency, and power reliability have great potential to be used as a power generation technology in the future. Disturbance in power supply could lead to energy instability in the grid system, which causes immeasurable losses to the end users, particularlythose in the industrial sectors [6-8].Hence, in meeting the electricity demand, maintaining a stable power output is inevitable.

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An SOFC stack, which is sealed to prevent the leakage of fuel/oxidant gases [9,10] and assembled using a rivet and bolt, is a promising power generation for meeting the electricity demand of today. SOFC stacks generate a higher power output at a higher efficiency when itis operated at high temperature (600°C–1000°C) [11-14], due to ionic conductivity characteristic in the electrolyte. However, given that thermal stress is developed when a rigid body undergoesmechanical deformation due to the variation of temperature, SOFC stacks are susceptible to the development of thermal stresses, particularly at the sealant. A strong relation between thermal expansion coefficient TEC mismatch [15-19] and temperature gradient [20-25] on thermal stress development has been widely reported. A careful selection of the cell components material at the designstage is essential as non-uniform temperature gradients induce excessive thermal stress on those components with incompatible (TEC). Thermal stress in an SOFC stack leads to mechanical instability and defects, such as deformation, creep, and cracks. [26,27], which in turn, increase the probability of structural failure. The following discussions focus on factors that influence temperature gradient, as well as the relation between temperature gradient and heat transfer in SOFC.

1.1 Temperature Gradient in SOFC

The temperature gradient is generally defined as the variation of temperature concerning the distance in the direction of the heat flow. The heat flow, temperature distribution, and temperature gradient of an SOFC stack are indirectly influenced by the uniformity of gas flow distribution from the inlet towards the outlet. The fuel and oxidant gases are channeled through the interconnects between the electrodes in different flow orientations. Figure 1 illustrates two widely studied flow orientations in SOFC; namely parallel-flow orientation and counter-flow orientation. Each of these orientations has their heat transfer characteristics, in term of temperature distributions and temperature gradients. These attributes are influenced by the heat accumulated when the fuel/oxidant is supplied through the gas flow channels. In a counter-flow orientation, in which fuel and oxidant gases flow in opposite directions, a more uniform temperature distribution can be obtained than that in a parallel-flow orientation. In a parallel-flow orientation, in which fuel and oxidant gases flow in the same direction, the temperatureincreases as the flow distance increases, and a higher temperature is observed at the outlet than at the inlet regardless of which boundary condition is adopted [28-31].

In the work of Stygar *et al*., [32], the effects of geometrical changes on the heat transfer rate were investigated using computational fluid dynamics (CFD) on an SOFC of the mono-block-layer build type. Temperature distribution in this study was determinedon the basis of the reaction between heat supplied to the system and fuel mass flow rate. The results showed that the temperature distribution of the counter-flow orientation is more uniform than that of the co-flow orientation at constant inlet temperature and fuel mass flow rate. Meanwhile, Reza *et al*., [33] conducted a CFD analysis under the assumption that the temperature distribution is emanated from the endothermic reaction. In this study, the partial differential equations for the three-dimensional (3D) model were derivedon the basis of mass, energy, momentum, and ionic conservation laws. The results showed better uniformity in the current density distribution of the counter-flow orientations than that in the current density distribution of the parallel-flow orientations because of the higher temperature gradient steepness at the parallel-flow orientations. Therefore, the counter-flow orientation that produces uniform temperature distribution is preferred.

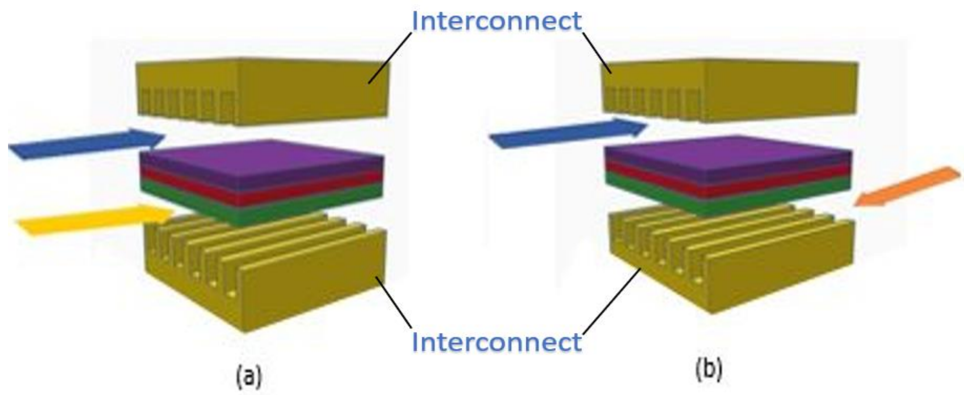

Fig. 1. Schematic of the SOFC gas flow orientation: (a) parallel flow and (b) counterflow

Uniform temperature distribution in counter-flow especially, reduces the thermal stress distribution with the steepness of the temperature gradient is lessened compared to the parallel-flow orientation. Given that the power output of the cell is closely related to the temperature-dependent ionic conductivity, unsteady temperature distribution in the stack, particularly that between the contact surface of the electrodes and interconnection, results in unstable ionic conductivity and hence unstable power output [34-37]. In addition, Choudhary *et al.*, [38] established a relationship between thermal stress and temperature gradient. The results showed that the stress distribution across SOFC component decreases when fuel and oxidant gases undergo a preheating process before being supplied into the stack. Therefore, minimizing the steepness of the temperature gradient, which considerably influences the rate of thermal stress distribution in SOFC stacks, is essential to ensure consistent endothermic reaction and effective output performance.

1.2 Heat Transfer in SOFCs

In SOFC applications, the heat source can generally be classified into two: external heat supply and internal heat generation. Basically, heat can be transferred through three mechanisms: conductive, convective, and radiation.Given that radiative heat transfer, which occurs between the fuel/oxidant and gas flow channels at the interconnects, does not influence the temperature gradient in SOFCs [39], the radiative heat transfer has not been considered in establishing the temperature gradient in SOFCs. On the other hand, conductive and convective are mapped to external heat supply and carrying energy, which is derived from a fuel and oxidant supply into the SOFC stack. This process is illustrated in Figure 2.

Internal heat generation refers to heat generated from the electrochemical and chemical reaction, such as concentration polarisation, activation polarisation and ohmic polarisation which has been studied in earlier works [40-42]. In their works, the heat from concentration and activation polarisations were ignored. The results showed that the amount of heat emitted from the endothermic reaction is small. Meanwhile, the heat generated by the Joule effect is due to the ion transfer across the electrode owing to the conduction of the oxygen ion. More on the Joule effect will be discussed in Section 4 of this paper.

The effectiveness of heat transfer is closely related to the consistency of temperature distribution, which can be maintained by minimizing the steepness of the temperature gradient. Recent studies have focused on the effects of temperature distribution and heat transfer in SOFC

[43-49]. It is believed that by incorporating the heat pipe in SOFC, this will enhance the rate of heat transfer, thereby reducing the steepness of the temperature gradient across the stack and increasing the cell performance.

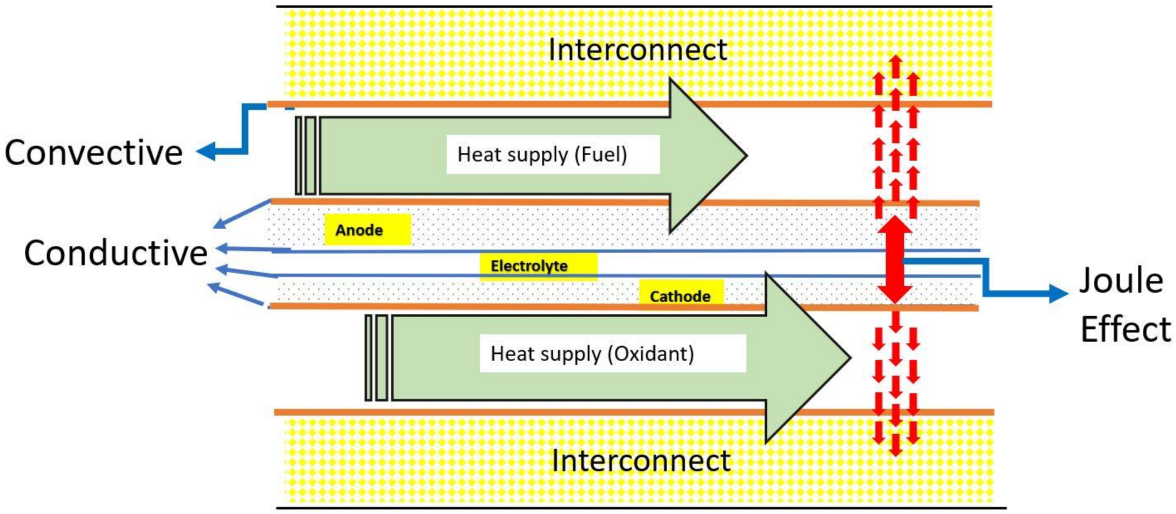

Fig. 2. Schematic of the heat transfer in SOFCs along the x-direction (side view)

Recently, a reduction of the temperature gradient of 50% in SOFC was observed by Dillig *et al*., [50] where the CFD was used for validation purposes. The temperature differences between the SOFC components were reduced when the rate of heat extracted from the SOFC stack is increased; leading to an improvement of thermal efficiency (16%). Similarly, Zeng *et al*., [51] applied the same approach to evaluate the correlation between heat transfer and temperature gradient. The finding by Zeng *et al*., [51] is in agreement with the previous study by Dillig *et al*., [50]. Further observation was performed on the cross-section of the cell to assess the development of micro-cracks. Typically, micro-cracks are prone to develop as the large temperature gradient causes a detrimental impact upon the cell. The above -mentioned work reveals more advantages in assessing the aspects of effectiveness and accuracy in the analysis, as reflected in the actual cell condition when compared to simulation, in which the parameter was solely based on assumption. The influence of the temperature gradient on heat transfer, particularly in the SOFC application, is discussed further in the next section.

1.3 Convective Heat Transfer

Convective heat transfer occurs when heat is transmitted from the external heat supply, particularly the fuel/oxidant (fluid), to the surface of interconnect and electrodes (solid). The convective heat transfer can be determined using Newton's Law of Cooling as shown below

$$Q_{conv} = hA(T_s - T_F) \tag{1}$$

$$Q_{conv} = hA\left(\frac{dT}{dx}\right), \tag{2}$$

where h is the film heat transfer coefficient, A is the surface that is directly in contact with the fluid flow, T_s is the temperature at the solid surface, and $T_F$is the temperature of the fluid.

Eq (1) is adopted when the heat is transferred from the fluid to the solid surface. Meanwhile, Eq (2) is adopted to determine heat transfer between fluid flow and the contact surface over the length of the gas flow channels.

A work established to study the relationship among temperature distribution, temperature gradient, and cell performance efficiency by using the numerical method with convective heat transfer as the heat loss from the system has been conducted by Steilen *et al*., [52]. Temperature distribution strongly depends on the transferred heat. Thus, the heat transfer considerably influences the voltage output, power output, and performance efficiency. Similarly, Bhattacharya *et al*., [53] found that excessive air flow in the interconnection during fuel utilization affects the cell temperature and performance efficiency. The high rate of convective heat transfer due to fast air movement reduces the rate of electro-catalytic reactions and the ionic conductivity in the YSZ electrolyte. The studies mentioned above showed that the performance efficiency is highly dependent on the consistency of the temperature distribution, which can be maintained by minimizing the steepness of the temperature gradient. High heat transfer rate in a SOFC stack induces rapid heat extraction. The smoothness of the endothermic reaction is highly temperature dependent. Thus, excessive heat extraction from the SOFC system can jeopardize its performance efficiency. Therefore, proper temperature gradient should be considered at an early stage of designing the SOFC stack to ensure its effectiveness.

1.4 Conductive Heat Transfer

Conductive heat transfer refers to the transmission of energy from the higher energy to the lower energy molecules within the boundaries of a solid body or crossing the boundaries within two solid bodies that come into contact with each other. In the SOFC context, conductive heat transfers through the anode–electrolyte–cathode configured single cell when the convective heat is transferred from the fuel. Figure 3 illustrates the heat and temperature gradient through the anode–electrolyte–cathode configured single cell, with the assumption that the fuel at the anode side is the only heat source. A temperature gradient of an SOFC refers to the changes of heat flow with respect to the thickness of single cell as described by Fourier's law

$$Q_{cond} = -kA\left(\frac{dT}{dx}\right), \tag{3}$$

where dt/dx is the temperature gradient crossing the thickness of SOFC component, k is the constant of thermal conductivity (W/mK), and A is the contact surface area.

Shao *et al*., [54] investigated the effects of heat transfer and fluid flow on thermal stress distribution through crack propagation rate. They assumed that the internal heat is generated through conductive heating. The results showed that the mismatch between the SOFC component value and the variation in the temperature gradient across the stack induce the crack propagation. Different from previous works that only considered convective heat transfer as the heat dissipated from the stack, Amiri *et al*., [55] applied a combination of conductive and convective heat transfer principles as the heat was generated in the cell through an endothermic reaction. The results showed that the generated conductive heat is substantially more significant than the convective heat because the heat capacity and thermal conductivity of gas are relatively smaller than those of solids.

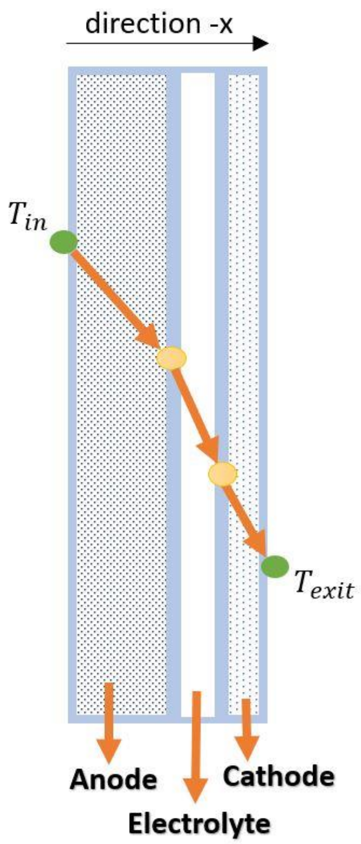

Fig. 3. Temperature gradient across the anode–electrolyte cathode configured single cell

1.5 Joule Effect

The Joule effect, also known as ohmic heating, refers to the heat generated by ohmic overpotential losses in an SOFC stack. The internal heat generated by the Joule effect radiates from the electrodes towards the interconnects (Figure 2). Given that the internal heat generated by the Joule effect is much higher than those generated by the electrochemical reaction, the ohmic losses profoundly influence the temperature distribution and range of temperature gradient steepness in the SOFCs [56].
The heat caused by the Joule effect is given as follows

$$S_{ohn} = \frac{i^2}{\sigma}, \quad (4)$$

where i is represent for current density meanwhile σ is for electrical conductivity.

Sahli *et al*., [57] studied the effect of geometrical changes on temperature distribution by weighing only the heat generation due to ohmic heating. Based on their analysis, the highest temperature gradient variance was noted at the anode due to the significant temperature difference between electrolyte and anode. Nonetheless, the scope of this study was limited because they did not establish the relationship between current density and heat distribution rate in the system. On the other hand, they only considered stable current density while establishing the heat source in SOFC using the Joule effect.

Razbani *et al*., [58] simulated chemical and electrochemical processes, as well as transport phenomena, on electrolyte-supported SOFC via three-dimensional (3D) numerical analysis. With the assumption that heat source is generated from electrochemical reactions, Joule effect, and activation losses; it was discovered that current densities and cell voltages were closely linked with a temperature distribution in the cell. This work offers clarity into the subject through the revelation of ohmic resistance across the interconnect, as opposed to the frequent assumption that it is insulated. Correlation between thermal conditions and heat transfer has been probed by Lee *et al*., [59]. Upon considering the Joule effect at high operating temperatures, the 3D modeling was applied to analyse the relationship. The outcomes portrayed that heat generated by the Joule effects flowed from the electrolyte towards either anode or cathode, whichever one with lower thermal conductivity. Therefore, the direction of the temperature gradient does depend on the materials used to design the electrodes.

Heat generated from the endothermic reaction, particularly in connection with the Joule effect, should be weighed in mainly due to its impact on temperature distribution in SOFC through heat distribution. Heat emitted from the Joule effect influences the steepness gradient and the cell performance output. Therefore, the increment in power output is evident when the working temperature is high.

2. Conclusion

The current trend in power generation technology is shifting towards clean, sustainable and renewable energy. SOFC is among the preferred choices for alternative power generation technology as they produce power output at higher efficiency and offer wide-ranging fuel flexibility choices. Given that SOFCs operate at high temperatures ranging from 600℃–1000℃, consideration of thermal stress distribution across the stack is essential to prolong the life of the system. The effects of the temperature gradient on each type of heat transfer mechanism, conductive, convective and Joule effect were discussed in this paper as the most influencing factors of thermal stress distribution in SOFCs. Identifying a suitable temperature gradient condition between the SOFC components is necessary to acquire an accurate data and to interpret the results of the analysis. To elucidate the mechanical failure that induces thermal stress, computer simulation is the most common approach applied by past researchers to analyze the prediction of thermal stress distribution. This approach is acceptable due to economical viability and ease of varying the parameter.

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