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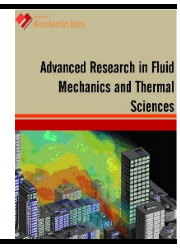

Factors Influencing Thermal Stress Development in Solid Oxide Fuel Cells

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Noor Shieela Kalib[1,2], Andanastuti Muchtar[1,3,*], Mahendra Rao Somalu[1], Ahmad Kamal Ariffin Mohd Ihsan[4], Nurul Ashikin Mohd Nazrul Aman[1], Nurul Akidah Baharuddin[1]

[1] Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[2] School of Engineering & Physical Science-Mechanical, Heriot-Watt University, 62200 Putrajaya, Malaysia
[3] Centre for Materials Engineering and Smart Manufacturing, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[4] Centre for Integrated Design for Advanced Mechanical System, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

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ABSTRACT

Solid oxide fuel cells (SOFCs) are favorable alternatives to fossil fuels because SOFCs have minimal carbon emission and can thus provide clean sustainable energy. They also have higher power-generation efficiency than traditional energy sources. However, improvements in the power and performance of SOFCs have caused the SOFC stack to be subjected to high thermal load and thermal stress, which should be minimized to prolong the stability and durability of a fuel stack. This paper presents a review on SOFCs from the perspective of thermal stress and its influencing factors.

1. Introduction

Global climate change requires that energy should be delivered sustainably, and it should produce low CO2 emission; increasing CO2 emission will increase risk toward greenhouse gas emission. Solid oxide fuel cell (SOFC) offers high potential deliver energy at high efficiency [1]; this option also shows a considerable range of fuel flexibility and utilizes clean technology [2-5]. In addition, SOFC can support clean technology perception by waste heat recovery concept through gathering waste heat during operation and channeling it to domestic heating facilities [6].

Although SOFC delivers energy with remarkable benefits, it still requires system modification to improve the performance efficiency and operate it at an economical state by reducing the cost of fabrication and operation [7,8]. A challenge with SOFC is to deliver at an increased operating temperature (700–1000 ◦C) [9] and at the same time maintain the mechanical stability as SOFC consists of the thin ceramic layers; such a layer is highly susceptible mechanical failure when operating under rapid cyclic operation [10]

[*] *Corresponding author.*
E-mail address: muchtar@ukm.edu.my (Andanastuti Muchtar)

During operation, SOFC is subjected to combined effects of a chemical reaction while delivering electrical power, temperature variation, and mechanical loading. This combination factors and with the condition of SOFC running at increased temperature may induce mechanical stress development and decrease the fatigue level, especially when the system operates at high temperature [11]. Mechanical stress is among the important factors affecting mechanical instability in SOFC; delamination, creep, and stack detachment are examples of mechanical failure occurring in SOFC [12-14]. However, the thermal stress effect on structural stability should also be considered.

2. Thermal Stress in SOFC

Mechanical stress is mostly induced by structure loading. Failures tend to occur when the loading force exceeds the yield point, and the structure undergoes material deformation. Thermal stress occurs when a constraint component tends to expand or contract under temperature variation. These changes dependence on the value of the thermal expansion coefficient (TEC).

Therefore, thermal stress development in SOFC, along with mechanical stress during fuel design stage, should be considered to minimize the risk of mechanical failure. Few factors are influencing the thermal stress development in SOFC; these factors include the difference in TEC between SOFC components [15], residual stress during manufactures due to sintering temperature [14,16], reaction between sealant and SOFC's structure [17,18], thermal cycling operation condition [19], and temperature gradient material [20,21].

3. Factors Contributing to Thermal Stress

The discussion on the following part focuses on factors contributing to thermal stress development in SOFC. This section is consisted of two parts. Part I would discuss factors affecting thermomechanical properties and part II would review the factors influencing thermal stress developments in terms of design considerations.

3.1 Effect of TEC

Material properties should be considered when selecting SOFC components because material properties will influence thermal stress development. Thermal stress deformation in SOFC is mostly generated as a consequence of the mismatch between the TECs of SOFC components. Table 1 provides a list of TEC values for the anode, cathode, and electrolyte for various working temperature conditions. The TEC value for electrolyte is lower than that of an electrode. Hence, the thermal stress between the anode and electrolyte is large, which is supported by studies conducted by Mahato *et al*., [22] and Liu *et al*., [19].

3.2 Effect of Young's Modulus Properties

Young's modulus is a scale to measure the flexibility of the material and commonly used to describe material behavior. Thermal stress contributes to structural failure because cracks may develop when the material at microstructure tends experiences a material's propagation Hence, the material structure geometry changes during operation. He *et al*., [23] stated, when Young's modulus an increase during operation of SOFC, affects the residual stress and residual stress contributes to thermal stress. Vaida and Kim [24] found that the thermal stress concentration at the cathode (LSM-

YSZ) is relatively lower than that at the anode (NiO-YSZ) when operating at increased temperatures; such an increase in temperature will decrease the effecting of the Young modulus.

3.3 Effect of Sealing Techniques

Sealants play critical roles in SOFC, especially during stacking. A sealant should adhere at high working temperature and minimize the risk of fuel and oxidant leakages. Sealing techniques in SOFC are classified into two methods, namely, rigid-bonded or rigid seal [25,26] and compressive seals [27,28]. The glass-based material is commonly applied in rigid-bonded technique. Mica-based composite is used in the compressive seal. An important requirement in the rigid-bonded seal is that the TEC value at the sealant's contact region should be similar or closely matched, as stated by Jiang *et al*., [18], Puig *et al*., [26] and Ye *et al*., [29] in their analysis.

A constant pressure tightness should be applied in the compressive seal and achieved during operation to eliminate the risk of leakages [30-32]. Therefore, the relations between sealants and thermal stress are inevitable because SOFC material tends to undergo geometry changes due to long-term operation cycle, rapid cycle, and operation at increased temperature [33,34].

Solutions being developed should reduce stress concentration, which subsequently influences the thermal stress distribution when a cooling mechanism is applied between the glass–ceramic sealant and fuel component. This result is attributed to that increasing the rate of heat transfer in the system lowers the elongation rate of SOFC components [35].

3.4 Influence of Interconnect Material

An interconnect joins individual SOFC components into a stack application. This part ensures stack stability and delivers electrical connection from electrochemical reaction toward the external circuit current collector. With the ability to withstand high temperature, the TEC match between electrodes and electrolytes and chemical and mechanical stabilities during the reaction are among important requirements for an interconnect to meet. Ceramic and metallic interconnect are commonly used to satisfy these requirements; nevertheless, a metallic alloy interconnect is preferred because it can operate at low thermal stress, although its heat conductivity rate is higher than that of the ceramic [36]. Lee *et al*., [37] studied the influence of thermal condition and heat transfer characteristics on thermal resistances by simulation using computer numerical analysis. The involvement of a metallic interconnect exerts the most remarkable influence on heat, and temperature increase resulted from a low thermal conductivity.

3.5 Influence of Gas Flow Orientation

Gas flow orientation plays a crucial role in SOFC design to ensure the stability and efficiency of fuel stacking and minimize the thermal stress level. Figure 1 shows the images of gas flow orientation for SOFC application; such orientation consists of parallel flow, co-flow, and counter-flow. The gas flow orientation influences temperature distribution and the temperature gradient in SOFC.

The temperature gradient is associated with the movement of energy from active molecules to low energy molecules. Hence, a sharp gradient occurs when the temperature differences between the inlet and outlet are significantly substantial.

Table 1
Material data for solid oxide fuel cell (SOFC) material

Materials	Thermal expansion coefficient ($\alpha \times 10^{-6}$)			Refs
	Electrolyte	Anode	Cathode	
8YSZ	10			[36,38]
YSZ	10.4			[39]
NiO-SDCC		11.1–11.7		[40]
NI+8YSZ		11.6		[41]
LSM-YSZ			11-12.4	[36,42–44]
LSCF-SDCC			3.6	[45]

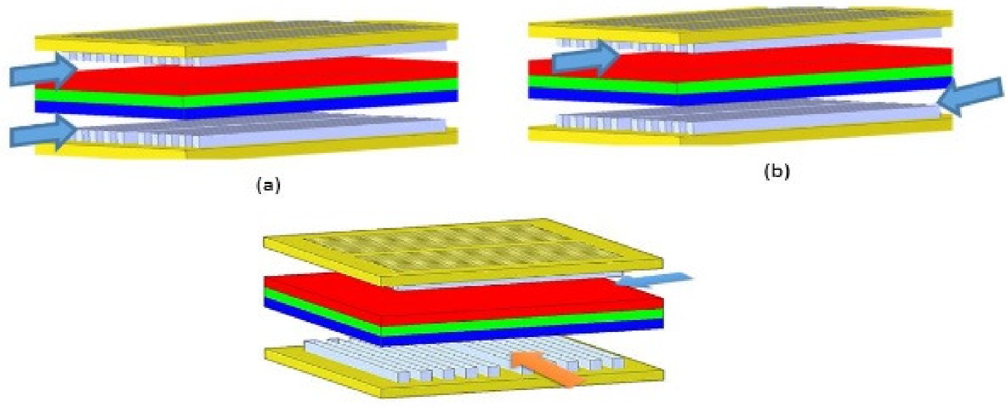

Fig. 1. Gas flow orientation in planar SOFC: a) parallel flow, b) co-flow, and c) counter-flow

Recknagle *et al.*, [46] revealed that gas flow orientation largely influence the temperature distribution, and co-flow delivers the most uniform temperature distribution, unlike that of counter-flow. However, Ahn 2012 [47] used numerical modelling to analyze the thermal fluid characteristics in planar SOFC. Analysis showed that the inlet temperature in counter-flow is higher than that at the co-flow gas pattern. Additionally, Aguiar *et al.*, [48] discovered that the temperature gradient of counter-flow is higher than that of co-flow. Djamel *et al.*, [49] investigated the effect of varying supply temperature between fuel and oxidant on the parallel gas flow by using Ni-YSZ as based material for anode and YSZ for the electrolyte. They found that although the temperature between fuel and oxidant is the same, the maximum temperature of the fuel is the influential factor as it is an endothermic chemical reaction, which increases the energy.

4. Conclusion

A significant understanding of the thermal stress development in SOFC is essential as it influences the performance and structural stability of fuel when the stress exceeds the allowable limits. To minimize the thermal stress concentrations during operation, TEC and Young modulus should be considered, during the design because they influence the material properties. Also, the sealant flexibility, interconnect, and gas flow orientation should also be taken into consideration during the design stage as they also influence the thermal stress in SOFC. In conclusion, the gas flow orientation significantly affects thermal stress, but studies on this parameter are limited. Hence, there is a need for further investigation.

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