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Thermomechanical Analysis of Various Solid-oxide-fuel-cell Components Using Simple Analog Micrometer Measurements

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Abstract

The solid oxide fuel cell (SOFC) is a device that can convert the energy stored in gaseous chemicals such as hydrogen into electricity. Because SOFCs are operated at high temperatures, their structures must be stable and durable. The thermomechanical compatibility of SOFC components is the main issue, as negligence in regard to material compatibility leads to cell destruction. In this study, we investigated the thermal expansion coefficient (TEC) of SOFC components, which characterizes their thermomechanical properties. We measured the TEC value of various electrolyte and electrode materials [La0.33Sr0.67O2.6 (LSO), Ce0.9Gd0.1O1.92 (CGO), La0.8Sr0.2Gd0.3Mg0.7O2.55 (LSGM), LSO-CGO, LSO-LSGM, and La0.5Ca0.5MnO3 (LCM)] using an analog micrometer at temperatures between 298 K and 1073 K. The obtained TEC values matched well with the theoretical references, with errors between 1.80% and 8.00% for LSO, CGO, LSGM, and LCM. The TEC of composite SOFC materials, LSO-LSGM and LSO-CGO, were 10.29 × 10⁻⁶ K⁻¹ and 10.10 × 10⁻⁶ K⁻¹, respectively. Given the slight difference in their TEC values, these electrolytes would thermomechanically match an LCM cathode.

Keywords: SOFC electrolytes, SOFC electrode components, TEC, analog micrometer, thermomechanical compatibility

Introduction

The solid oxide fuel cell (SOFC) is a device that can convert gaseous hydrogen into electricity. SOFCs operate in temperatures ranging from 873 K to 1473 K (600 °C–1200 °C). Because SOFCs can be constructed using a multiple-cell stack design, they are a promising energy source for high-temperature-operation systems and have the potential to produce up to 10 MW of electricity [1]. To withstand such high operation temperatures, SOFCs must be built to ensure thermomechanical and physical durability. An SOFC contains three main components: an electrolyte, anode, and cathode. To maintain good performance, these three components must be compatible. The thermal expansion coefficient (TEC) is an important parameter used to characterize the thermomechanical compatibility of an SOFC. All SOFC components must have similar TEC values. Negligence regarding the mismatch of TECs will lead to performance degradation from delamination, cracks, and vigorous cell destruction [2]. The basic features of the SOFC components, i.e., their chemical properties and structure of the materials, affect their TEC values [3].

Based on fundamental principles for determining expansion coefficients, dilatometric analysis is usually performed using a dilatometer [4–6]. This instrument provides the best accuracy by measuring the in-situ expansion as the temperature increases. However, the simultaneous measurement of all the materials leads to a very costly analysis. Letilly et al. [7] analyzed the TEC of the BIT07 electrolyte using X-ray diffraction (XRD) analysis at room temperature, whereby each sample was sintered at different temperatures, with the underlying assumption that the chemical expansion could transform the TEC value. Blum [8] conducted TEC measurements using a standard F-design. Based on the fact that material expansion occurs simultaneously in all directions, this author combined the basic principles of linear expansion that can be observed with room temperature measurements after sintering at a certain temperature, which is similar to the assumptions made by Letilly et al. [7]. The TEC measurements by Blum [8] were simply made using an analogous micrometer.

As a common anode material, NiO was used as the anode in a comparison study with other SOFC component materials. In that study, the main electrolyte
selected was La$_{0.33}$Si$_2$O$_{26}$ (LSO), which was further processed using the solid-state method to produce composite electrolytes with other electrolyte materials, Ce$_{0.6}$Gd$_{0.4}$O$_{1.92}$ (CGO) and La$_{0.8}$Sr$_{0.2}$Ga$_{0.8}$Mg$_{0.2}$O$_{2.55}$ (LSGM) [9]. LSO and CGO are considered to be intermediate-temperature SOFC electrolytes, whereas LSGM is a well-known good ionic conductor electrolyte in the low-to-mid temperature range [10]. To monitor the TEC values in low- and mid-range operation temperatures, the electrolytes were treated as variables. The cathode, La$_{0.7}$Ca$_{0.3}$MnO$_3$ (LCM), was synthesized using a solid-state method. This cathode was selected because it exhibits high electronic conductivity. Theoretically, all the possible combinations were predicted to be good SOFC single-stack constructions. To determine the thermomechanical compatibility of all the components in practical terms, the experimental TEC values must be measured.

The main purpose of this study was to construct a SOFC prototype and explore its TEC values. To study the TEC behavior, both the electrolyte and electrode components were observed. TEC is traditionally measured using a dilatometer [11,12]. In this study, we used a new and simpler method to monitor the TEC value of the SOFC components. This method is based on dilatometric analysis but does not involve the use a dilatometer. Instead, we used a manual micrometer over the experimental temperature range (298 K to 1073 K).

Methods

CeO$_2$ (99.9%), Gd$_2$O$_3$ (99.9%), MnO$_2$ (99.9%), CaCO$_3$ (99.9%), and NaOH (99.9%) were obtained from Merck Singapore. LSGM (99.99%), La$_2$O$_3$ (99.99%), Na$_2$SiO$_3$·5H$_2$O (≤95%), and La$_2$O$_3$ (99.99%) were obtained from Sigma–Aldrich. The desired materials were all produced using the methods reported in our previous study [13]. XRD analysis was performed using a Rigaku MiniFlex600 X-Ray Diffractometer (29 K system, Cu Ka radiation, $\lambda = 0.15418$ nm, $T = 298$ K, $v = 0.02^\circ$ in the 20 range 20°–80°). Data fitting was conducted using PANalytical X’Pert Highscore Plus© software and the ICSD/ International Crystallographic Structure Database. Sample pellets (0.4–0.6 g) were uniaxially pressed to a diameter of ~1 cm using a Graseby Specac and then sintered at 1473 K to obtain similar initial densification conditions. The dimensions of the sample pellets were then measured using an analog micrometer at 298 K to obtain the initial dimensions. Thereafter, the sample pellets were heated at a rate of 5 K min$^{-1}$ to the desired temperature, which was maintained for 2 h. The pellet dimensions were measured every 100 K up to 1073 K. The measured dimensions of the pellets were then applied in the TEC calculations using Equation 1.

Results and Discussion

Figures 1 and 2 present the XRD patterns of the SOFC components that were successfully prepared in this study. All the patterns were analyzed using the Rietveld refinement technique to obtain their lattice parameters, reliability profiles ($Rp$), reliability weight profiles ($Rwp$), and goodness of fit. The XRD patterns conformed to the ICSD standards 98-015-5624 (LSO), 98-002-8795 (CGO), 98-009-8170 (LSGM), and 98-008-8389 (LCM). These materials were then used for TEC measurements. Table 1 lists the refinement parameters of the samples.

| Sample | Structure       | Space Group | a/ Å  | b/ Å  | c/ Å  | $R_{expected}$ | $Rp$   | $Rwp$  | Gof  |
|--------|----------------|-------------|-------|-------|-------|----------------|-------|-------|-----|
| LSO    | Hexagonal      | P 63/m      | 9.7271(8) | 9.7271(8) | 7.1863(6) | 18.4538        | 20.9223 | 27.0724 | 2.1522 |
| CGO    | Cubic          | F m - 3 m   | 5.4128(7) | 5.4128(7) | 5.4128(7) | 16.9718        | 12.0553 | 17.1487 | 1.0210 |
| LSGM   | Cubic          | P m - 3 m   | 3.9123(4) | 3.9123(4) | 3.9123(4) | 7.2910         | 10.1499 | 13.5389 | 3.4482 |
| LSO-CGO| Hexagonal-Cubic|             | -      | -      | -      | 5.5358         | 8.6783  | 10.9325 | 3.9000 |
| LSO-LSGM| Hexagonal-Cubic|             | -      | -      | -      | 8.6988         | 11.0689 | 15.0148 | 2.9793 |
| LCM    | Orthorhombic  | P n m a      | 5.4640(1) | 5.7270(5) | 5.4781(2) | 15.6077        | 12.8506 | 16.7095 | 1.1462 |

TEC is one of the most important parameters for evaluating the thermomechanical compatibility of SOFC components. In this study, we calculated the TEC values as follows:

$$TEC = \frac{(\Delta L)}{(L_0)} / (T - T_{initial}).$$

where $\Delta L$ is the change in length, $L_0$ is the initial length, $T_{initial}$ is the initial temperature, and $T$ is the final temperature.
Figure 1. XRD Patterns of LSO, CGO, and LSO-CGO. LSO were Synthesized Hydrothermally, CGO and LSO-CGO were Prepared by Solid-state Synthesis (Left). XRD Patterns of LSO, LSGM, and LSO-CGO. LSO-LSGM was Prepared by Solid-state Synthesis (Right)

Figure 2. XRD Pattern of the LCM Cathode Prepared by Solid-state Synthesis

Table 2 presents the TEC values obtained in this study along with the values reported in the literature (theoretical values). From the reported and experimental values, we can quantify the differences by calculating the relative error percentage (Rel. error) using the following equation:

\[ \text{Rel. error} = \left( \frac{\text{TEC}_{\text{practical}} - \text{TEC}_{\text{theoretical}}}{\text{TEC}_{\text{theoretical}}} \right) \times 100\% \]  

(2)

Except for LSO, for which a significant statistical error was found, the relative errors were less than 5%. To study the TEC behavior further, we examined the changes in the cell dimensions and volumes that occurred within the test range of 298 K to 1073 K. Figures 3 to 6 show plots of the results for each component. Each figure shows a trend of increasing length with increases in temperature [8]. The positive gradient value emphasizes this trend, however, the gradient of each component was slightly different due to the respective properties of the materials.

Table 2. TEC Values of the Studied SOFC Component Materials

| Components | References | Theoretical/10^6K | This Study/10^6K |
|------------|------------|-------------------|------------------|
| LSGM       | [14]       | 11.5              | 11.77            |
| LSO        | [15]       | 9.88              | 10.67            |
| CGO        | [16]       | 12–12.7           | (not studied)    |
| LSO-CGO    | -          | (not reported)    | 10.10            |
| LSO-LSGM   | -          | (not reported)    | 10.29            |
| LCM        | [17]       | 10.5              | 10.30            |
| NiO        | [18]       | 13.9              | (not studied)    |

Table 3. Relative Error of TEC Values for Various SOFC Components

| SOFC Components | Relative error/\% |
|-----------------|-------------------|
| LSGM            | 2.35              |
| LSO             | 8.00              |
| CGO             | -                 |
| LSO-CGO         | -                 |
| LSO-LSGM        | -                 |
| LCM             | 1.92              |

In Figure 3, we can also observe a gap between points that may have a similar order as those of LSO-CGO. With increases in temperature, the sample lengths increased linearly for LSO-LSGM and LCM. However, for LCM, we found that the linear length increased dramatically between 873 K and 1072 K, which is similar to the behavior of NiO-CGO, although that increase began at 773 K. This behavior significantly affected the TEC value. To examine the shift, we measured these changes carefully (Table 3).
Table 4. Expansion of SOFC Component Dimensions with Increasing Temperature

| Temperature (T)/ K | Linear dimension (A/t)/ cm |
|------------------|---------------------------|
|                  | LSO-CGO       | LSO         | LCM         | LSO-LSGM     | LSGM         |
| 298              | 76.1551       | 43.2363     | 42.9239     | 40.8494      | 37.8690      |
| 373              | 76.1551       | 43.2363     | 42.9700     | 40.9314      | 38.0215      |
| 473              | 76.3958       | 43.4198     | 42.9732     | 40.9574      | 38.1361      |
| 573              | 76.7752       | 43.5608     | 42.9766     | 40.9475      | 38.5408      |
| 673              | 76.8512       | 43.6897     | 42.9802     | 40.9798      | 38.5792      |
| 773              | 77.0033       | 43.7329     | 42.9841     | 40.9798      | 38.5792      |
| 873              | 77.0794       | 43.7437     | 42.9881     | 41.0207      | 38.5621      |
| 973              | 77.0794       | 43.7979     | 43.0379     | 41.0369      | 38.6005      |
| 1073             | 77.1187       | 43.8089     | 43.1294     | 41.1187      | 38.6220      |

| Temperature (T_2-T_1)/ cm | LSO-CGO       | LSO         | LCM         | LSO-LSGM     | LSGM         |
|---------------------------|----------------|-------------|-------------|--------------|--------------|
| 373–298                   | 0.0000         | 0.0000      | 0.04607     | 0.0820       | 0.1525       |
| 473–373                   | 0.2407         | 0.1835      | 0.0032      | 0.0160       | 0.1146       |
| 573–473                   | 0.3794         | 0.1404      | 0.0034      | 0.0000       | 0.4046       |
| 673–573                   | 0.0760         | 0.1295      | 0.0036      | 0.0323       | 0.0384       |
| 773–673                   | 0.2282         | 0.0432      | 0.0038      | 0.0000       | 0.0000       |
| 873–773                   | 0.0761         | 0.0109      | 0.0040      | 0.0409       | 0.0170       |
| 973–873                   | 0.0000         | 0.0541      | 0.0499      | 0.0163       | 0.0384       |
| 1073–973                  | 0.0392         | 0.0111      | 0.0914      | 0.0818       | 0.0215       |

Figure 3. Expansion of LSO

Figure 4. Expansion of LCM

Figure 5. Expansion of LSO-CGO

Figure 6. Expansion of LSO-LSGM
The positive gap shown in Table 4 indicates that the value of each point increased with increasing temperature. A zero value indicates that no meaningful change occurred as the temperature increased, whereas a negative value indicates a slight decrease in linear length as the temperature increased. Negative changes have yet to be reported and may have been caused by the late ratio phenomenon observed in this study due to dilatation of the material in every direction. A late ratio occurs when the ratio between the areas of a cylinder to its thickness at higher temperature is lower than the ratio at a lower temperature. The occurrence of this phenomenon suggests that linear expansion, as obtained from the ratio, did not occur at certain temperature, whereas volume expansion did occur. Since the TEC values obtained in this experiment are linear expansion coefficients, the area of the cylinder had to be divided by its thickness. As such, a negative value indicates a late ratio, which means that no linear expansion occurred at certain temperature between 873–773 K. Further study to learn more about this phenomenon is required to better understand how the late ratio behaves.

Figure 7 shows the variation in $\Delta L/Lo$ for each sample. LSGM experienced a sudden shift at 800 K. LSO-CGO and LSO also underwent a sudden shift at temperatures above 800 K. The LSO-CGO composite showed a slight change in its curve above that of its original matrix material, LSO. On the other hand, the electrolyte composite LSO-LSGM experienced a much smaller change than its original material, LSO, or even LSGM. This difference verifies the conclusions that could be drawn based on the TEC values, as shown in Figure 8.

Figure 8 shows the TEC values at every temperature point of all the above materials. Three materials (LSGM, LSO-CGO, and LSO) showed a negative gradient or decreasing TEC value with increases in temperature. This implies a tendency that increases in temperature could cause infinite expansion of the material until it reaches a point of maximum expansion in its linear length before becoming permanently deformed. At that time, a positive gradient implies a lower rate of linear length expansion to a finite point near and above 800 K. Until this point, the average TEC would reflect the overall TEC behavior, although the TEC might vary at different temperatures, as shown in Table 3. The TEC also might differ in some temperature ranges based on the materials used, with expansion occurring until a certain high temperature, after which deformation takes over. However, in this study, the temperature was set to 1073 K as a mid-range SOFC operational temperature.

### Table 5. TEC Shifts with Increases in Temperature

| $\Delta T$ | LSO-CGO $/ 10^{-6}K^{-1}$ | LSO $/ 10^{-6}K^{-1}$ | LCM $/ 10^{-6}K^{-1}$ | LSO-LSGM $/ 10^{-6}K^{-1}$ | LSGM $/ 10^{-6}K^{-1}$ |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 775       | 16.3268         | 17.090          | 6.1758          | 8.5061          | 25.6579         |
| 700       | 18.0761         | 18.921          | 5.3042          | 6.5489          | 22.6524         |
| 600       | 15.8203         | 15.001          | 6.0634          | 6.9874          | 21.3837         |
| 500       | 9.0200          | 11.507          | 7.1168          | 8.3849          | 4.2904          |
| 400       | 8.7802          | 6.8968          | 8.6854          | 8.5040          | 2.8282          |
| 300       | 5.0492          | 5.8649          | 11.2844         | 11.3387         | 3.7709          |
| 200       | 2.5768          | 7.5402          | 16.4596         | 12.0008         | 7.8976          |
| 100       | 5.1536          | 2.5629          | 21.2991         | 20.0217         | 5.6653          |
| AVG       | 10.1004         | 10.6730         | 10.2986         | 10.2866         | 11.7683         |
The TEC values observed in Table 5 also reveal that the presence of LSGM and CGO would lead to an increasing TEC value for LSO. From this finding, we can also estimate the effect of other reinforcement materials in the compound matrix. From all the obtained TEC values, we can conclude that the LSO-LSGM composite electrolyte might be the best electrolyte for an LCM cathode, as its TEC is only slightly different at approximately $1.2 \times 10^{-6} \text{K}^{-1}$ (negligible difference of 0.012). However, the TEC value of the cathode must be slightly higher than that of the corresponding electrolyte. Hence, the electrolyte would experience compression during cell-cooling at the fabrication temperature. A great mismatch in TEC values will lead to cell destruction due to buckling [17].

**Conclusion**

In this study, the TEC behaviors of various materials were studied via dilatometric analysis using an analog micrometer in the temperature range of 298 K to 1073 K. The observed behaviors confirmed the characteristics and compatibilities of these materials as SOFC components. The measured TEC values compared well with the theoretical references, with the relative errors ranging from 1.80% to 8.00% for LSO, CGO, LSGM, and LCM. The TEC values of the composite SOFC materials, LSO-LSGM and LSO-CGO, were $10.29 \times 10^{-6} \text{K}^{-1}$ and $10.10 \times 10^{-6} \text{K}^{-1}$, respectively, which indicate their suitability for use in an LCM cathode (TEC $10.30 \times 10^{-6} \text{K}^{-1}$). We found the most thermomechanically compatible material for an LCM cathode, with respect to the TEC difference, to be the LSO-LSGM electrolyte.

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**References**

[1] Owens, B.B., Mcguinness, J.J. GE Fuel Cells the Power of Tomorrow. Boston. 2015. https://www.ge.com/sites/default/files/GE_FuelCells.pdf.

[2] Li, X., Shao, G., Luo, J., Lu, J., Xue, M., Hou, Y., Deng, L. 2013. Fabrication and characterization of GDC Electrolyte/Electrode Integral SOFC with BaO/Na/GDC Anode. Mater. Res. Bul. 50: 337–340, https://doi.org/10.1016/j.materresbull.2013.11.034.

[3] Gao, Z., Mogni, L.V., Miller, E.C., Railsback, J.G., Barnett, S.A. 2016. A Perspective on Low-Temperature Solid Oxide Fuel Cells. Energy Environ. Sci. 9(5): 1602–1644, https://doi.org/10.1039/C5EE03858H.

[4] Wang, F., Zhou, Q., He, T., Li, G., Ding, H. 2010. Novel SrCo_{1−x} Nb_{x}O_{3−δ} cathodes for intermediate-temperature solid oxide fuel cells. J. Power Sources. 195(12): 3772–3778, https://doi.org/10.1016/j.jpowsour.2009.12.081.

[5] Zhang, L., Liu, M., Huang, J., Song, Z., Fu, Y., Chang, Y., Li, C., He, T. 2014. Improved Thermal Expansion and Electrochemical Performances of Ba_{0.6}Sr_{0.4}Co_{0.9}Nb_{0.1}O_{3−δ}–Gd_{0.1}Sr_{0.9}O_{1.95} Composite Cathodes for IT-SOFCs. Int. J. Hydro. Energy. 39(15): 7972–7979. https://doi.org/10.1016/j.ijhydene.2014.03.055.

[6] Zhang, L., Long, W., Jin, F., He, T. 2013. Electrical Conductivity, Thermal Expansion and Electrochemical Performances of Ba-doped SrCo_{0.6} Nb_{0.4}O_{1.9} Cathodes for IT-SOFCs. Int. J. Hydrog. Energy. 38(19): 7947–7956. https://doi.org/10.1016/j.ijhydene.2013.04.107.

[7] Letilly, M., Salle, A.L.G.L., Lachgar, A., Joubert. O. 2010. Synthesis, structural analysis and electrochemical performances of BLSITCFX as new cathode materials for solid oxide fuel cells (SOFC) based on BIT07 electrolyte. J. Power Sources. 195(15): 4779–4784. https://doi.org/10.1016/j.jpowsour.2010.02.052.

[8] Blum, L. 2017. An Analysis of Contact Problems in Solid Oxide Fuel Cell Stacks Arising from Differences in Thermal Expansion Coefficients. Electrochimica Acta. 223: 100–108, https://doi.org/10.1016/j.electacta.2016.12.016.

[9] Macedo, D.A., Souza, G.L., Cela, B., Paskocimas, C.A., Martinelli, A.E., Figueiredo, F.M.L., Marques, F.M.B., Nascimento, R.M. 2013. A versatile route for the preparation of Ni–CGO cermets from nanocomposite powders. Ceram. Int. 39(4): 4321–4328, https://doi.org/10.1016/j.ceramint.2012.11.014.

[10] Peña-Martínez, J., Marrero-López, D., Ruiz-Morales, J.C., Buergler, B.E., Núñez, P., Gauckler, L.J. 2006. SOFC test using Ba_{0.6}Sr_{0.4}Co_{0.9}Fe_{0.1}O_{3−δ} as cathode on La_{0.8}Sr_{0.2}Ga_{0.5}Mg_{0.5}O_{2.85} electrolyte. Solid State Ionics. 177(19–25 SPEC. ISS.): 2143–2147, https://doi.org/10.1016/j.ssi.2006.05.042.

[11] Bonhomme, C., Beaudet-Savignat, S., Chartier, T., Gefroy, P.M., Sauvet, AL. 2009. Evaluation of the La_{0.75}Sr_{0.25}Mn_{0.5}Co_{0.5}O_{3−δ} system as cathode material for ITSOFCs with La9Sr1Si6O26.5 apatite as electrolyte. J. Eur. Ceram. Soc. 29(9): 1781–1788, https://doi.org/10.1016/j.jeurceramso.2008.11.009.

[12] Gil, V., Tartaj, J., Moure, C. 2009a. Chemical and Thermomechanical Compatibility between Neodymium Manganites and Electrolytes Based on Ceria. J. Eur. Ceram. Soc. 29(9): 1763–1770, https://doi.org/10.1016/j.jeurceramso.2008.03.004.

[13] Malik, Y.T., Noviyanti, A.R., Syarif, D.G. 2018. Lowered Sintering Temperature on Synthesis of

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[14] Tao, S., Irvine, J.T.S., Kilner, J.A. 2005. An Efficient Solid Oxide Fuel Cell Based upon Single-Phase Perovskites. Adv. Mater. 17(14): 1734–1737, https://doi.org/10.1002/adma.200402007.

[15] Zhou, J., Ye, X.F., Li, J.L., Wang, S.R., Wen, T.L. 2011. Synthesis and Characterization of Apatite-Type La$_{9.67}$Si$_6$Al$_{x}$O$_{26.5}$x/2 Electrolyte Materials and Compatible Cathode Materials. Solid State Ionics. 201(1): 81–86, https://doi.org/10.1016/j.ssi.2011.07.014.

[16] Gil, V., Tartaj, J., Moure, C. 2009b. Chemical and Thermomechanical Compatibility between Ni-GDC Anode and Electrolytes Based on Ceria. Ceram. Int. 35(2): 839–846, https://doi.org/10.1016/j.ceramint.2008.03.004.

[17] Kawada, T., Horita, T. 2016. Cathode. In High-Temperature Solid Oxide Fuel Cells for the 21st Century: Fundamentals, Design and Applications. London: Elsevier. pp. 161–193.

[18] Madelung, O., Rössler, U., Schulz, M. (eds.) 2018. NiO: lattice parameter, thermal expansion: Datasheet from Landolt-Börnstein-Group III Condensed Matter-Volume 41D: "Non-Tetrahedrally Bonded Binary Compounds II" in Springer Materials, https://doi.org/10.1007/10681 735_510.