Original Article

Yttria-stabilized zirconia (YSZ) film produced from an aqueous nano-YSZ slurry: preparation and characterization

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ABSTRACT

Research on preparing yttria stabilized-zirconia film was conducted with polyacrylic acid (PAA) dispersant (YSZ film-A) and mix of PAA with surfactant blend as a dispersant (YSZ film-B). The YSZ powder was prepared by introducing nano-yttrium dioxide powder to nano-zirconia powder through solid-state reaction. The surfactant blend consists of sodium dodecyl sulfate, SDS (HLB 40), and Tween-80 (HLB 15) at a definite ratio to produce a required-HLB (Hydrophilic-Lipophilic-Balance) value. The prepared-YSZ films were analyzed to study its crystallinity, crystal structure and its cell parameters, surface morphology, particle size, the thickness of the film, thermal properties, the functional group content, and the electrical conductivity. The result found that both YSZ film is in cubic structure with a space group of Fm3m. The crystal structure is exactly similar to the YSZ powder. A characteristic peak of Zr (Y)-O vibration at 561.31–561.24 cm⁻¹ appears from both YSZ film as well as from the prepared YSZ powder. SEM image shows YSZ film-A more compact than YSZ film-B, with the particle size of 11.92 ± 1.41 μm. Meanwhile, the particle size of the YSZ film-B is 14.41 ± 2.08 μm. Both YSZ film shows a proper ionic conductivity for solid electrolyte purpose at 600 °C, i.e., 2.08 × 10⁻⁴ Scm⁻¹ and 2.25 × 10⁻⁴ Scm⁻¹ for YSZ film-A and YSZ film-B, respectively. The measured activation energies (Ea) for ionic migration are 0.687 eV and 0.562 eV for YSZ film A and YSZ film-B, respectively.

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1. Introduction

Solid Oxide Fuel Cells, SOFCs, has been known as a technology for power generation, power and heat supply, portable and auxiliary power sources. A SOFC stack consists of tens of hundreds of single cells, in which a single cell contains an anode, electrolyte, and cathode [1]. The single cells are usually fabricated through some methods in which tape casting is a suitable one due to its large-scale reproducibility and less-expensive [2,3]. Yttria-stabilized zirconia (YSZ) is frequently used in SOFC as electrolyte material, due to its high ionic conductivity and good chemical stability [4,5]. Manufacturing YSZ film for solid oxide fuel cell is an important consideration in accordance with the simple and low-cost method, availability for mass production, inexpensive raw material, and also contribution to minimizing environmental impact. Tape casting is a simple method for a large surface manufactur-
ing with a controllable thickness [6]. Tape casting usually uses a ceramic suspension in an organic solvent. Even though an aqueous ceramic suspension provides more contribution to minimize environmental impact, however, it still shows drawbacks such as slurry sedimentation, foam production during milling, and also low densities of the green film [7]. The aqueous slurry is known to have a high surface tension that may cause agglomeration due to incomplete-dispersion [8]. Some organic solvents show good dispersion performance, such as acetone, ethanol, methanol, 1-propanol, ethylene glycol, o-xylene, n-hexane [9]. However, recently some countries claim down the use of those organic solvents due to carcinogenic effect and concerning environmental problems [5].

A requirement on shaping ceramics to a homogeneous film is also essential to achieve optimum sintered properties [10,11]. Therefore, having a well-dispersed and stable ceramic slurry is crucial. The degree of dispersion stability depends on the balance of attractive and repulsive force between interacting particles. The forces are mostly depending on the presence of surface charge and/or an adsorbed organic layer. In this way, a dispersant addition is crucial [12]. Many dispersant that usually used for a slurry preparation of zirconia based-powder such as ammonium polycyrate [5], a commercial dispersing agent of DISPERSBYK-2012 [13], some carboxylic dispersant such as anhydrous citric acid, oxalic acid, and ethylene diamine tetra-acetic acid [14], tri-ammonium citrate surfactant [15], phosphate based-dispersant, α-terpineol [16], and also α-terpineol mix with a blend of surfactant tween-80 and span-60 [17].

Our previous research on preparing YSZ tape found that α-terpineol and a mix of α-terpineol with surfactant blend of tween 80 (HLB 15) and span 60 (HLB 4.5) successfully produce a homogeneous YSZ slurry. However, YSZ tape that produced from YSZ slurry with a mix dispersant of α-terpineol with surfactant blend is hygroscopic and become wet soon under room condition [17]. Other research has used Poly-acrylic acid, PAA, and surfactant 2, 4, 7, 9-tetramethyl-5-decyn-4,7-diolethoxylate, and found that surfactant increase dispersion ability and produce a soft, flexible thin-film [18]. However, the surfactant used in that previous research is toxic and also expensive. Meanwhile, sodium dodecyl sulfate, an anionic surfactant, and tween 80 are easily found commercially. Both have a high HLB value of 40 and 15 for SDS and tween 80, respectively, confirming good solubility in the aqueous phase [19,20]. Complete solubility of both surfactant molecules may inhibit the presence of surfactant-free molecules to interact with humidity in the environment that cause the film always wet under room condition.

2. Methods

2.1. Preparation of YSZ powder

Zirconia was synthesized from zircon sand concentrate, ZrSiO₄, through solid-state reaction with NaOH followed by acid leaching with HCl solution and then precipitation of Zr(OH)₄ with NH₄OH solution. Zirconia, ZrO₂ production was conducted by heating the Zr(OH)₄ to 1000 °C [21]. In this research, the particle size of zirconia was reduced through dissolving ZrO₂ powder by a hydrothermal method with 10 M NaOH solution as a solvent. The ratio between zirconia powder and NaOH solution was 2 g to 17.5 mL, as it was applied in our previous result [17]. The next steps were centrifugation, acid leaching, water leaching to remove hydroxide and chlorine ions, and then calcination. The commercial Y₂O₃ (99% Sigma–Aldrich) was also treated by the hydrothermal method to reach nano-size particles. The produced powder was then analyzed by XRD (Rigaku Miniflex 600 Benchop) equipped with Le Bail refinement by RIETICA (a free edition) to analyze its crystallinity, crystal structure, and cell parameters. FTIR analysis (Prestige 21- Shimadzu) identify functional groups presented in the material. Surface morphology and particle size distribution were analyzed by SEM (JEOL JED-2300 series) equipped with MeasureIT software (a free edition). Each SEM image was divided into 4 areas. Within each area, MeasureIT measured the diameter of 10 particles. Therefore, each SEM image provided 40 data of diameter. The data were then analyzed statistically to determine the mean diameter and the standard deviation, SD. In which, SD calculation follows the formula as depicted in Eq. (1).

\[
SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}
\]

In which, SD is standard Deviation (provided with ± value), n is the number of data, X_i each value of data, X is the mean of X_i [22].

2.2. Determination of the required HLB

An HLB kit was prepared by blending SDS with tween 80 at a definite composition based on Eq. (2) and (3) to provide HLB number of 15, 21, 26, 29, 33, 38, and 40. The 0.25 g of nano-YSZ powder was poured into surfactant solution, and then ultra-sonicated for 15 min. The 8 jars of YSZ slurry were then kept under room condition. The longest time needed for the slurry to separate into 2 phases was the required HLB.

\[
\%\text{SDS} = \frac{100(X - \text{HLB}_{\text{Tween80}})}{\text{HLB}_{\text{SDS}} - \text{HLB}_{\text{Tween80}}}
\]

\[
\%\text{tween80} = 100\%\text{SDS}
\]

X is the targeted HLB.

2.3. Slurry preparation and casting

There were two kinds of slurry with composition as listed in Table 1. A definite amount of nano-YSZ powder based on the composition listed in Table 1, was poured into a surfactant solution. The surfactant solution was a blend of SDS and Tween 80 at a definite composition to achieve an HLB value of 26. The HLB value was found as the required value to provide the most stable YSZ slurry. The PAA dispersant was then poured into YSZ-surfactant mixture and then was stirred by ultra-sonication for 1 h.

The PVA binder and isopropyl alcohol antifoaming agent were then poured into the mixture, and followed by contin-
uous ultra-sonication for 1 h to have a homogeneous slurry. The slurry was cast on a polypropylene substrate with a microcoater (EduLab, Indonesia, sliding rate of 60 cm.min⁻¹ with a sliding gap of 1 mm). The YSZ film on polypropylene was then dried over 60–70 °C for 10 min and continued by drying over room temperature, to produce a YSZ film-A. Slurry B was also prepared at the similar way with the composition as listed in Table 1, and then was cast on polypropylene substrate and was dried to produce YSZ film-B.

The prepared YSZ films were characterized by XRD (Rigaku Miniflex 600 Benchop) equipped with Le Bail refinement to identify characteristic peaks of YSZ by comparing with the YSZ standard peak. The refinement confirms the fitness with the standard, includes its crystal structure, and cell parameters. A TGA (Linseis PT1600 heating rate 10 °C.min⁻¹) analysis was conducted over room temperature to 600 °C to investigate its thermal properties. FTIR spectrophotometer (Prestige 21 Shimadzu) analyzed the functional group content in the prepared-tapes. Meanwhile, their electrical conductivity was studied by impedance measurement (LCR meter, EUCOL 20 Hz-5 MHz equipped with ZView software for impedance fitting in CS Studio 5). The YSZ slurry was cast on anode Ni-YSZ pellet and then fired at 1250 °C for 2 h with a heating rate of 5 °C.min⁻¹. The Ni-YSZ anode was prepared previously by mixing nickel powder with YSZ powder at a mass ratio of 80:20, then cold press at 138.8 MPa and was fired at 1000 °C for 2 h with a heating rate of 5 °C.min⁻¹. Morphology of the prepared film was analyzed by Scanning Electron Microscopy, SEM (JEOL JED 2300 series) equipped with elemental analysis, EDX.

3. Result and discussion

Zirconia that was prepared from zircon sand has a diffraction pattern with characteristic peaks similar to standard diffraction pattern of ICSD #157403. The result is in agreement with our previous result in zirconia preparation from zircon sand, in which zirconia crystallized in tetragonal P42/NMC and monoclinic P21/C [23]. The difference with the zirconia standard diffraction is on the peak’s wide, as we can see in Fig. 1 that the prepared zirconia shows some broad peaks indicating smaller particle size. Meanwhile, the prepared nano-YSZ powder shows characteristic peaks which are in agreement with YSZ standard diffraction of ICSD #280135 and #90894. Le Bail refinement confirm that the prepared nano YSZ powder is in two phases of monoclinic P21/C and cubic Fm3m. The refinement result is depicted in Table 2.

Meanwhile, diffraction patterns of YSZ film-A and YSZ film-B compared to the prepared nano-YSZ powder (Fig. 2), shows that major peaks of YSZ present at 2θ of 50.11°, 59.48°, 62.64°, and 73.79°, which are in agreement with ICDS#280135. Some small monoclinic peaks at 2θ of 29.96°, and 34.73° are also weakly available. Le Bail refinement according to standard diffraction of ICSD#280135 proceed well with the result as listed in Table 3. Meanwhile, the Le Bail plots of both YSZ film-A and YSZ film-B are depicted in Fig. 3.

Optical image of YSZ film-A shows smoother and more homogeneous than YSZ film-B as shown in Fig. 4(a) and (d). It seems that surfactant molecules increase the dispersion of YSZ particles to produce a more homogeneous slurry and then produce smoother YSZ film. SEM images as shown in

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**Table 1 – Composition of YSZ slurry.**

<table>
<thead>
<tr>
<th>Components</th>
<th>Composition (%)</th>
<th>Slurry A</th>
<th>Slurry B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano YSZ powder</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Surfactant blend solution</td>
<td>21</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Polyacrylic acid dispersant</td>
<td>2</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Poly-vinyl alcohol binder</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Isopropyl alcohol</td>
<td>1.5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>De-foaming agent</td>
<td>0.5</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1 – Diffraction patterns of the prepared zirconia powder and nano-YSZ powder.**

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**Table 2 – Crystal structure and cell parameters of zirconia and the prepared YSZ powder based on Le Bail refinement result.**

<table>
<thead>
<tr>
<th>Cell parameters</th>
<th>Zirconia</th>
<th>YSZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monoclinic P21/C</td>
<td>5.1660</td>
<td>5.1585</td>
</tr>
<tr>
<td>Tetragonal P42/NMC</td>
<td>3.70199</td>
<td>5.1546</td>
</tr>
<tr>
<td>a (Å)</td>
<td>5.0663</td>
<td>5.1044</td>
</tr>
<tr>
<td>b (Å)</td>
<td>5.6870</td>
<td>5.1858</td>
</tr>
<tr>
<td>c (Å)</td>
<td>148.091</td>
<td>5.1858</td>
</tr>
<tr>
<td>V(Å³)</td>
<td>71.170</td>
<td>5.1456</td>
</tr>
<tr>
<td>w; χ; θ</td>
<td>90;84;22;90</td>
<td>140.656</td>
</tr>
<tr>
<td>Rwp (%)</td>
<td>7.14</td>
<td>90;78;86;90</td>
</tr>
<tr>
<td>Rwp (%)</td>
<td>8.78</td>
<td>9.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.02</td>
</tr>
</tbody>
</table>
Fig. 2 – Diffraction patterns of the prepared YSZ film-A, YSZ film-B, compared to diffraction pattern of the prepared nano-YSZ powder and standard diffraction of ICSD#280135.

Fig. 3 – Le Bail plots of (a) YSZ film-A, and (b) YSZ film-B.

| Table 3 – Le Bail refinement result of YSZ film-A and YSZ film-B. |
|-----------------|-----------------|-----------------|
| Cell parameters | YSZ film-A      | YSZ film-B      |
| Crystal structure | Cubic Fm 3m | Cubic Fm 3m |
| a (Å)           | 5.1378          | 5.1473          |
| b(Å)            | 5.1378          | 5.1473          |
| c(Å)            | 5.1378          | 5.1473          |
| V(Å³)           | 135.62          | 136.37          |
| α;β;γ           | 90;90;90        | 90;90;90        |

Fig. 4(b) and (e) show that slurry A produced more compact YSZ film than slurry B. The YSZ film-B looks runny (Fig. 4(e)), meanwhile YSZ film-A compactly deposited on the substrate. It because YSZ particles disperse well assisted by surfactant molecules to interact with water molecules producing a homogeneous and viscous slurry. Meanwhile, in slurry B the YSZ particle less dispersed in water molecule producing a more dilute slurry with some YSZ particles loose from the substrate, as it can be seen in Fig.4(e). Particle size analysis by MeasureIT software (a free edition) to SEM images found that YSZ film-B shows broader particle distribution confirming less homogeneous dispersion than YSZ film-A. The particle size in YSZ film-B is 14.42 ± 2.08 μm, meanwhile the particle size in YSZ film-A is 11.92 ± 1.41 μm. Chart of particle size distribution is depicted in Fig. 5. The presence of surfactant seems to prevent agglomeration between YSZ particles and also increase the attachment of YSZ film on the polypropylene substrate. A cross-section SEM image shows the thickness of YSZ film-A is 65.47 ± 18.59 μm (Fig. 4(b)). Meanwhile, YSZ film-B is 14.93 ± 2.71 μm (Fig. 4(e)). YSZ film-B is thinner than YSZ film-A because YSZ slurry B is more dilute than YSZ slurry A, and easily loose when casting on polypropylene substrate.

The FTIR spectrum (Fig. 6) shows characteristic peaks at 561.31 cm⁻¹ and 563.24 cm⁻¹ indicate the vibration of Zr(Y)-O...
Fig. 4 – The optical images of the green YSZ film-A (a), cross section SEM image of the green YSZ film-A (b), surface morphology SEM of the green YSZ film-A (c), the optical image of the green YSZ film-B (d), cross section SEM image of the green YSZ film-B (e), and surface morphology SEM of the green YSZ film-B (f) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 5 – Particle size distribution of YSZ particle in YSZ tape A and YSZ tape B.

in the YSZ film-A (Fig. 6(h)) and in the YSZ film-B (Fig. 6(g)). The vibration peaks are similar to vibration peak of Zr(Y)-O at 561.31 cm\(^{-1}\) of YSZ powder. It confirms that the film mainly contains YSZ. An additional peak at 3442.12 cm\(^{-1}\) in YSZ film-A and YSZ film-B (Fig. 6(h) and (g)) indicates the presence of O–H stretch from surfactant. Meanwhile, the O–H stretch of defoaming agent appears at 3447.91 cm\(^{-1}\), O–H stretch of polyacrylic acid at 3450.80 cm\(^{-1}\), O–H stretch of polyvinyl alcohol at 3412.15 cm\(^{-1}\), O–H stretch of SDS at 3477.80 cm\(^{-1}\) and O–H stretch of Tween 80 at 3419.94 cm\(^{-1}\). The presence of all the content is also confirmed by TGA analysis with the curve as depicted in Fig. 7.

TGA curve (Fig. 7) that was recorded under a heating rate of 10\(^{\circ}\)C.min\(^{-1}\) shows that YSZ film-A starts to decompose at 34.5–243 \(^{\circ}\)C releasing 4.11\% of weight, and 37.64\% of weight at 243–630.1 \(^{\circ}\)C. Meanwhile, YSZ film-B decompose 28.91\% at 230–357.5 \(^{\circ}\)C, and 18.42\% at 390–611.8 \(^{\circ}\)C. Water molecules may be released at 30–100 \(^{\circ}\)C, due to vaporization, and also released as water vapor after reaching boiling point. The de-foaming agent would also be released at 35 \(^{\circ}\)C. The relative phase such as Tween 80, polyacrylic acid, and SDS would be decomposed at 100–400 \(^{\circ}\)C [24]. PVA molecules decompose at two stages of 200–400 \(^{\circ}\)C and secondly at 400–500 \(^{\circ}\)C [25]. Meanwhile, polypropylene decompose at 160–165 \(^{\circ}\)C [26]. Above 600–800 \(^{\circ}\)C the curve shows flat line for YSZ film-A and B indicating that YSZ particle requires high temperature to decompose, i.e., \(\geq 1000 \,^{\circ}\)C. Another result on preparing YSZ aqueous slurry by a reverse strike co-precipitation found that dried amorphous gel of YSZ was changed to a pure cubic YSZ at around 430 \(^{\circ}\)C, exhibited a mass loss of 23\% [27].

Impedance analysis was conducted to YSZ film on Ni-YSZ or it is named as anode supported- electrolyte, YSZ|Ni-YSZ. The Nyquist plots of both YSZ film-A and YSZ film-B are depicted in Figs. 8 and 9. Fig. 8 shows that at 300 \(^{\circ}\)C YSZ film-A provide three semicircles. Data fitting found that the plot fits well with three resistor-capacitor networks in series.
connection, as the model can be seen inserted in Fig. 8. The appropriate capacitor is constant phase element, CPE, a non-intuitive circuit element for a real-world system [28], in which the center distance in Y-direction is below the center distance in X-direction. It describes the non-homogeneous properties of real-world materials. Nyquist plots of YSZ film-A at 400, 500, and 600 °C showed two semicircles which also fits well with an R-CPE network model. ZView fitting found that the impedance consists of grain- and grain boundary resistance, and resistance of electrolyte-electrode. Those are confirmed by the capacitance value calculated by the software. It is known that the value 0.1 pF is grain capacitance, 1.4 nF is grain bound-

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**Table 4** - The ionic migration resistance, $R$ (Ω) and ionic conductivity, $\sigma$ (S cm$^{-1}$) of YSZ film-A, and YSZ film-B at a various temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>YSZ tape A</th>
<th>YSZ tape B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{ionic migration}}$ (Ω)</td>
<td>$\sigma_{\text{ionic conductivity}}$ (S cm$^{-1}$)</td>
</tr>
<tr>
<td>300</td>
<td>256652</td>
<td>2.75 × 10$^{-6}$</td>
</tr>
<tr>
<td>400</td>
<td>19590</td>
<td>3.61 × 10$^{-5}$</td>
</tr>
<tr>
<td>500</td>
<td>6047</td>
<td>1.17 × 10$^{-4}$</td>
</tr>
<tr>
<td>600</td>
<td>3401</td>
<td>2.08 × 10$^{-4}$</td>
</tr>
</tbody>
</table>

**Table 5** - The electrolyte-electrode resistance, $R$ (Ω) of YSZ film-A|Ni-YSZ, YSZ film-B|Ni-YSZ, and Ni-YSZ electrode at a various temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>YSZ tape A</th>
<th>YSZ tape B</th>
<th>Ni-YSZ R (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{electrolyte-electrode}}$ (Ω)</td>
<td>$R_{\text{electrolyte-electrode}}$ (Ω)</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>218000</td>
<td>199370</td>
<td>64893</td>
</tr>
<tr>
<td>400</td>
<td>27975</td>
<td>39479</td>
<td>4988</td>
</tr>
<tr>
<td>500</td>
<td>4645</td>
<td>4170</td>
<td>1027</td>
</tr>
<tr>
<td>600</td>
<td>1475</td>
<td>1011</td>
<td>1282</td>
</tr>
</tbody>
</table>
ary capacitance, and more than 1 μF is electrode-electrolyte capacitance [29]. The electrode-electrolyte resistance usually appears at low frequency as shown by the scheme of Nyquist plot and its interpretation (Fig. 7(b)). Similar patterns are shown for Nyquist plots of YSZ film-B|Ni-YSZ, which consist of two semicircles confirming the resistance of ionic migration (grain or grain boundary), and electrode-electrolyte resistance. The electrode-electrolyte resistance appears at low frequency, as it can be seen in Fig. 9 along with simulated R-CPE network inserted. The values of ionic migration resistance, R (Ω), ionic conductivity, ς (Scm⁻¹) for YSZ film-A and YSZ film-B at various temperature are listed in Table 4. Meanwhile, the electrode-electrolyte resistance value, R (Ω) of YSZ film-A|Ni-YSZ, YSZ film-B|Ni-YSZ and the single Ni-YSZ are listed in Table 5. It shows in Table 5, that electronic resistance to migrate between or to pass the boundary of YSZ film to Ni-YSZ electrode is higher than the electronic resistance inside the Ni-YSZ. It indicates that requires higher energy for electrons to migrate through a phase boundary than to migrate inside the Ni-YSZ composite. The presence of Ni metal reduces the resistance due to metal is a good electronic conductor with 1.462 × 10⁷ Sm⁻¹ and low resistivity of 6.842 × 10⁻⁸ Ω-m [30].

Table 6 – Activation energy, Ea (eV) of ionic migration in YSZ film-A and YSZ film-B, the pre-exponential factor, and the linearity constant, R.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Ea (eV)</th>
<th>Ln σ₀</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSZ tape A</td>
<td>0.687</td>
<td>7.731</td>
<td>0.973</td>
</tr>
<tr>
<td>YSZ tape B</td>
<td>0.562</td>
<td>5.577</td>
<td>0.977</td>
</tr>
</tbody>
</table>

The energy of migration was determined by plot conductivity to temperature following the Arrhenius equation. A linear fit to the plot was used to determine the activation energy values Ea (eV) with the results as listed in Table 6. The activation energy for ions to migrate inside YSZ film-A is 0.687 eV, which is higher than the energy needed to migrate in YSZ film-B, i.e., 0.562 eV. The presence of surfactant molecules seems to increase activation energy even only 0.125 eV besides to develop the film quality. The activation energy values are lower than YSZ layer produced by spin coating on an Al₂O₃ substrate, which is 0.99 eV [31]. The presence of surfactant also seems to increase pre-exponential factor, Ln σ₀, from 5.577 to 7.731 for YSZ film B to YSZ film-A, respectively, confirming more crystal defect that may provide high ionic conduction at high temperature [32]. It can be seen in Fig. 10, that at high temperature or low x value, the ionic conductivity of YSZ film-A is higher than YSZ film-B. The pre-exponential factor is a function of defect concentration as shown by Eq. (4) for Frenkel defect and Eq. (5) for Schottky defect [33].

\[
\sigma_0 = \frac{n_f}{\exp \left( \frac{-g_f}{2kT} \right)} \left( \frac{a^2 q^2}{kT} \right) \nu_0
\]  
(4)

\[
\sigma_0 = \frac{n_s}{\exp \left( \frac{-g_s}{2kT} \right)} \left( \frac{a^2 q^2}{kT} \right) \nu_0
\]  
(5)

In which σ₀ is the pre-exponential factor, n_f is the number of Frenkel defects and n_s is the number of Schottky defects, a is inter-atomic space, q is a charge, ν₀ is vibrational frequency, T is absolute temperature, g_f and g_s are energy for Frenkel and Schottky defect formation, respectively [33]. It is clear that the pre-exponential factor, σ₀, proportional to defect number whether Frenkel or Schottky defect. It confirms that higher the pre-exponential value indicates higher defect number. The defect number correlates to ionic conductivity of the materials because the material with defects would provide ionic migration through vacancies mechanism, interstitial mechanism, or vacancies-interstitial mechanism [34].

4. Conclusion

A surfactant blend of high HLB type, i.e., tween-80 (HLB 15) and SDS (HLB 40) able to increase the dispersion of nano-YSZ particle in aqueous solution. It proves by smoother film optically, the smaller particle size of the film, and also more compactness of film on polypropylene substrate. Both YSZ film that was prepared with surfactant blend or without surfactant blend has a similar crystal structure of cubic with a space group of Fm3m. Ionic conductivity of YSZ film with surfactant blend is 2.08 × 10⁻⁴ Scm⁻¹ at 600 °C. The value is appropriate for fuel cell application. The value may higher if fuel cell operates...
Fig. 8 – (a) Nyquist plot of YSZ film-A|Ni-YSZ at a various temperature, along with R-CPE network models for data fitting (inserted), (b) scheme of Nyquist plot along with its interpretation based on frequency (Hz) value (adopted from Ramanathan and Kakade, 2011 [27]).

Fig. 9 – Nyquist plots of YSZ film-B|Ni-YSZ at a various temperature along with the R-CPE network models for data fitting (inserted).
over 600 °C. This finding may promote the use of an aqueous solvent for the manufacture of solid electrolyte paste.

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