Journal of Metals, Materials and Minerals, 35(2), e2019, 2025

Development of ceramic based novel materials for application in low temperature solid oxide fuel cell (LTSOFC) – A critical review

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Received date:
2 April 2024
Revised date:
4 February 2025
Accepted date:
5 March 2025

Keywords:
Solid oxide fuel cell;
Low temperature;
Electrode and electrolyte;
Fabrication techniques;
Performance evaluation

Abstract

In the field of renewable energy, fuel cell research has emerged as a promising source of energy for the future. Fuel cells utilize fuels more efficiently compared to other energy generation systems. Solid oxide fuel cell (SOFC) systems are gaining prominence due to their applications in military operations, mobile power supplies, and stationary power generation. Significant research efforts are being made to lower the operating temperature of SOFCs from 1000°C to approximately 600°C, leading to the development of low-temperature solid oxide fuel cells (LTSOFCs). This is being achieved by selecting alternative electrode and electrolyte materials, particularly ceramics, to enhance their application effectiveness. To ensure the efficient utilization of LTSOFCs, new nanocomposite materials with superior performance characteristics are essential. Research has focused on NiO-based anodes, perovskite-based cathodes, and ceria-based electrolytes for LTSOFC applications. Intercell connectors suitable for low-temperature SOFCs have also been explored. In addition to developing new materials, innovative fabrication technologies, such as dip coating, have been investigated. This article discusses recent trends in the development of novel materials and technologies aimed at advancing LTSOFC research and development, as well as its potential commercialization in the near future.

1. Introduction

The science fraternity is working hard in the past 2 or 3 decades to produce new materials to suit the current generation's energy needs as a result of the rising population. It is necessary to switch from the available sources of energy to utilizable ones because the supply of fossil fuels is continuously running out [1-4]. Among the available variety of energy generation systems, fuel cell finds a special attention because which can transform the chemical energy of the fuel directly into electrical energy with greater efficiency (70%). The constraint of Carnot can be circumvented by fuel cell stacks since this energy conversion avoids the process of converting heat to mechanical work [5]. The best way to reduce the greenhouse effect can be found through the application of transparent energy conversion technology like fuel cells, which use hydrogen to transform chemical energy straight into electrical energy [6]. Currently, fossil fuels supply the majority of the energy needed for variety of applications. Still, there is a growing interest in developing renewable energy technologies with less of negative ecological effect especially to minimize greenhouse gas emissions [7-10]. Fuel cells find application in variety of fields since no hazardous gases are from them. The material aspects of different types of fuel cells are presented in Table 1. Among the different variety of fuel cell systems, SOFCs operate between 600 to 1000°C. The schematic diagram of the SOFC device is presented in Figure 1. In a SOFC, the cathode reduces oxygen (from air) to O^{2-}, which the electrolyte transports from the cathode to the anode, where it reacts with a fuel to produce H_2O, CO_2, and electrons. The reactions take place in SOFC systems are indicated below (Equations (1-5)):

Anode reactions:

$$H_{2\,(g)} + O^{2-} \rightarrow H_2O_{\,(g)} + 2e^- \quad (1)$$

$$CO_{\,(g)} + O^{2-} \rightarrow CO_{2\,(g)} + 2e^- \quad (2)$$

Combined anode reaction:

$$a\,H_{2\,(g)} + b\,CO_{\,(g)} + (a+b)\,O^{2-} \rightarrow a\,H_2O_{\,(g)} + b\,CO_{2\,(g)} + 2\,(a+b)\,e^- \quad (3)$$

Overall cathode reaction:

$$\tfrac{1}{2}\,(a+b)\,O_{2\,(g)} + 2\,(a+b)\,e^- \rightarrow (a+b)\,O^{2-} \quad (4)$$

Overall cell reaction

$$\tfrac{1}{2}\,(a+b)\,O_{2\,(g)} + a\,H_{2\,(g)} + b\,CO_{\,(g)} \rightarrow a\,H_2O_{\,(g)} + b\,CO_{2\,(g)} \quad (5)$$

SOFCs did not require any costly catalysts made of platinum, rhodium, or other precious metals due to its high temperature operating conditions, which makes these devices with excellent fuel flexibility and greater efficiency. SOFC is an emerging energy technology which finds applications in electrolysis and chemical to electrical conversion

Table 1. Material aspects of different fuel cells.

S. No	Various fuel cells	Electrolyte	Anode	Cathode	Electrolyte	Reference
1.	Alkaline fuel cells (AFC)	Liquid electrolyte	Pt-Pd	Pt-Au	KOH	[18]
2.	Proton exchange membrane fuel cells or solid polymer fuel cells (PEMFC)	Liquid electrolyte	PTFE-bonded Pt on C	PTFE-bonded pt on C	Perfluoro sulfonic acid	[18,22]
3.	Phosphoric acid fuel cells (PAFC)	Liquid electrolyte	PTFE bonded Pt on C	PTFE bonded Pt on C	H_3PO_4	[18,23]
4.	Direct methanol fuel cells (DMFC)	Liquid electrolyte				[18]
5.	Molten carbonate fuel cells (MCFC)	Liquid electrolyte	Ni	Li-doped NiO	Molten Li_2CO_3-K_2CO_3	[18]
6.	Regenerative fuel cells (RFC)	Liquid electrolyte	-	-	-	[18]
7.	Zinc-air fuel cells (ZAFC)	Liquid electrolyte	-	-	-	[18,24]
8.	Solid oxide fuel cells (SOFC)	Solid electrolyte	Ni/YSZ	Sr-doped $LaMnO_3$	Solid Y_2O_3 stablilized ZrO_2 (YSZ)	[19-21]

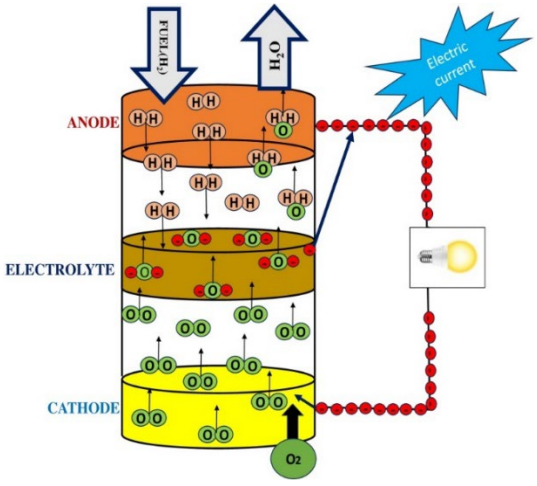

Figure 1. The schematic diagram of the SOFC device [13].

[11-13]. Stationary power generation has dominated a large portion of SOFC development. The fuel conversion efficiency of stationary SOFC power plants is predicted to be greater than that of heat-engine power plans that use coal, biomass, or hydrocarbons as fuels [14-17]. By lowering the temperature of operation of SOFC, its functional application of the device can be enhanced. Further, the development of LTSOFC can lower the system costs, reduce the material deterioration, and enhance the life of the systems. Further, research is being done on the electrolysis mode of operation of SOFCs as a way to generate extra renewable energy for efficient utilization. This review article discusses various materials and fabrication technologies utilized in the development of LTSOFCs.

2. Electrolyte materials for LTSOFCs

8 mol% Y_2O_3 stabilized ZrO_2 (YSZ) is the state of the art electrolyte material in SOFC research. However, YSZ electrolyte may undergo chemical reaction with the adjoining electrode materials and reduce the performance of SOFC to a greater level [25]. YSZ electrolyte combined with a $La_{1-x}Sr_xMnO_3$ (LSM) cathode is the most used SOFC electrolyte-cathode combination. It was found that beyond 900°C, LSM may react with YSZ to yield $La_2Zr_2O_7$ pyrocholore phases which retards the performance of SOFC [26]. To avoid this problem, catalyst layers may be coated in between the electrolyte and electrode components [27-31]. Similar to zirconia, ceria is a common electrolyte material for SOFCs and it has a fluorite structure. Further, ceria has a lower polarization resistance and a greater conductivity than zirconia, especially at low temperatures [32]. Electronic conduction at low oxygen partial pressures is the main drawback of ceria electrolyte. In ceria, cerium may be doped with certain metal ions like Sm^{3+} and Gd^{3+} to improve its conductivity [33-36]. Electrodes based on $La_{0.8}Sr_{0.2}Fe_{0.8}Co_{0.2}O_{3-\delta}$ and $LaFe_{0.5}Ni_{0.5}O_{3-\delta}$, and $LaCoO_{3-\delta}/La_2Zr_2O_7$ composites may be suitable for $Ce_{1-x}Gd_xO_2$ (CGO) based electrolytes. Ceria based electrolytes tend to exhibit better conductivity than that of YSZ based electrolyte. It was found that CGO, the most used ceria-based electrolyte, showed greater ionic conductivity than that of YSZ and ScSZ based electrolytes [37-40]. Strontium and magnesium may be doped into the perovskite $LaGaO_3$ to create $La_{1-x}Sr_xGa_{1-y}Mg_yO_3$ (LSGM), a material with strong low-temperature oxygen ion conductivity. SOFC was tested with LSGM electrolyte having gadolinia doped ceria (GDC) mixed with silver as anode and cathode [41]. CeO_2 can have an open structure when doped with alkali or rare earth lanthanide metals, which might further boost its ionic conductivity. Even though rare earth lanthanides are soluble in cerium, alkali earth metals are favored as dopants. According to reports, materials based on Bi_2O_3 have the maximum oxygen ion conductivity at SOFC operating temperatures [42]. It has been observed that at 500°C, $Bi_{0.8}Er_{0.2}O_{1.5}$ and $Bi_{0.85}Nb_{0.15}O_{1.65}$ are, respectively, ~2.6×10^{-2} S·cm^{-1} at 500°C and 3.7×10^{-1} S·cm^{-1}. However, at lower temperatures, conductivity may drop dramatically due to the δ-Bi_2O_3 phase changing into a rhombohedral phase and the creation of super-structures [43]. Larger lattice dimensions are predicted to result in better ion conductivity. A thin layer of Sm_2O_3 doped CeO_2 (SDC) was placed between the anode and the LSGM electrolyte to prevent the

reaction between the Ni-based anode and the electrolyte [44]. It was reported that the area of grain boundaries or interfaces is substantially bigger in the materials based on nanostructured ceramics which is the main cause for the enhancement in the electrolyte's ionic conductivity [45]. A new ceramic electrolyte with the composition, $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC)/Na_2CO_3 nanocomposite electrolyte resulted with better ionic conductivity for application in SOFC systems [46]. Novel nano-composite electrolyte with the composition of $Ce_{0.7}Sm_{0.15}Ge_{0.15}O_{2-\delta}$ (SGeDC) showed a conductivity of 0.074 S·cm^{-1} at 650°C. LTSOFC assembled with this electrolyte delivered an extraordinary performance [47]. LTSOFC assembled with an electrolyte Y^{3+} doped Gd_2O_3 exhibited a good great performance of 1046 mW·cm^{-2} at 550°C. The electrolyte showed an oxide ion conductivity of 0.19 S·cm^{-1} [48]. An electrolyte based on $CuFeO_2$ (30 wt%) and ZnO (70 wt%) has been proposed for LTSOFC application. The device based on 3CFO-7ZnO (CFO in 30 wt% and ZnO in 70 wt%) electrolyte exhibits an open circuit voltage (OCV) of 1.06 V and a peak power density (PPD) of 557 mW·cm^{-2} at 550°C, apparently superior to both of the direct mixture of CFO-ZnO nanocomposite (468 mW·cm^{-2}) and single-phase ZnO electrolytes (300 mW·cm^{-2}) at the same operating temperature [49]. The composite electrolyte material based on YSZ-CeO_2 with Ni-NCAL ($Ni_{0.8}Co_{0.15}Al_{0.05}LiO_{2-\delta}$) as the electrodes has been used to construct SOFC which delivered a power density of 680 mW·cm^{-2} at 450°C [50]. The factors, such as, type of dopants, their concentration, impurities, etc. are mainly involved in the development of electrolyte for LTSOFC applications. The performance characteristics of certain electrolyte components for LTSOFC are presented in Table 2.

3. Cathode materials for LTSOFCs

Oxygen reduction reaction (ORR) is performed at the cathode in SOFC device. However, the cathode needs to fulfil the following conditions in order to function as an effective ORR site: a) improved electronic conductivity (>100 S·cm^{-1}), b) comparable thermal expansion coefficient with the adjoining electrolyte and other components, c) to allow better O_2 flow between the cathode and the electrolyte, d) better catalytic activity, e) optimum cost and f) excellent chemical and mechanical stability [61]. SOFC has faster electrode kinetics than other low temperature fuel cells. However, cathodic polarization losses are found to be a big risk in the SOFC demonstration; hence the materials must be chosen to exhibit better results [62]. LSM cathode and YSZ electrolyte in SOFC may tend to produce $La_2Zr_2O_7$ and/or $SrZrO_3$ impurity phases after prolonged operation [63,64]. It was reported that ceria interlayer may hinder the reactions between LSM and YSZ. The lesser oxygen flow in cathode side may also influence the performance of LTSOFCs to a greater level [65-72]. Silver metal was chosen as an alternate cathode material because of its strong catalytic activity and excellent electrical conductivity and affordable price for SOFC working below 800°C. Copper substituted bismuth vanadate ($Bi_2V_{0.9}Cu_{0.1}O_{5.35}$) was utilized as alternate cathode materials because of its high reactivity in LTSOFC. Composites consisting of silver and bismuth vanadates exhibit remarkable catalytic activity for oxygen reduction at 550°C and greatly reduce the cathode-electrolyte interfacial polarization resistances of low-temperature SOFCs, down to about 0.53 Ω·cm^2 at 500°C and 0.21 Ω·cm^2 at 550°C. The observed power densities of 231 mW·cm^{-2}, 332 mW·cm^{-2}, and 443 mW·cm^{-2} at 500°C, 525°C, and 550°C, respectively, make it possible to operate SOFCs at temperatures about 500°C [73]. $L_{0.6}Sr_{0.4}Co_{0.8}Fe_{0.2}O_3$-CGO-Ag based composite cathode was made using a variety of techniques; it has been reported that the Ag coating on the composite increased the cathode's oxygen exchange reaction activity and interface conductivities at 600°C [74]. One more efficient and affordable method for enhancing the cathode performance is the infiltration of Ag nanoparticles [75]. During 200 h of annealing at 750°C, the Ag-LSC electrodes demonstrated good stability. It is notable that while cathodes based on silver have good electrochemical characteristics, oxygen dissolves readily in silver

Table 2. The performance characteristics of certain electrolyte components for LTSOFC

Electrolyte composition	Oxide ion conductivity [S·cm^{-1}]	Other components	Temperature range [°C]	Power density [mW·cm^{-2}]	Reference
Hematite/$LaCePrO_x$-$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$	0.15	Cathode - NCAL-Ni Anode - NCAL-Ni	500 to 700	221	[51]
$Ce_{0.85}Sm_{0.09}Gd_{0.06}O_{1.925}$	2.68x10^{-3}	-	500 to 700	-	[52]
$BaCe_{0.8}Sm_{0.2}O_{3-\delta}$-$Ce_{0.8}Sm_{0.2}O_{1.9}$	-	Cathode - $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) Anode - NiO-BSCZYSm	400 to 800	-	[53]
$Ba_{0.9}Sr_{0.1}Ce_{0.5}Zr_{0.35}Y_{0.1}$ $Sm_{0.05}O_{3-d}$ (BSCZYSm)	-	Cathode - $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) Anode - NiO-BSCZYSm	700 to 1000	-	[54]
8YSZ+4Yb_2O_3-NaCl/KCl	0.3	Cathode - 8YSZ+4Yb2O Anode - 8YSZ+4Yb2O	500 to 700	-	[55]
GDC-KAlZn nanocomposite	0.06	Cathode - ZnO/NiO and GDC-KAlZ Anode - ZnO/NiO and GDC-KAlZn	550	480	[56]
Strontium & samarium co-doped CeO_2/Na_2CO_3	3.8 x10^{-3}	-	400	-	[57]
SDC-$(Li/Na)_2CO_3$	-	Cathode - Lithiated NiO + SDC-$Li/Na)_2CO_3$ Anode - NiO + SDC-$(Li/Na)_2CO_3$	600	532	[58]
SDC-carbonate composite.	-	Cathode - Lithiated NiO Anode - NiO (50 vol %) and electrolyte (50 vol %)	600	500	[59]
$Sm_{0.2}Ce_{0.8}O_{2-\delta}$ (SDC) + $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (LNCA)	0.12	-	520	735	[60]

to generate Ag/Ag_2O solid solution. To avoid these issues, another noble metal that is frequently utilized to enhance SOFC cathode performance is Pd. Pd was added to an LSCF cathode to work at 650°C for LTSOFC application. The area-specific resistance (ASR) of the $La_{0.8}Sr_{0.2}FeO_{3-\delta}$-$Gd_{0.2}Ce_{0.8}O_{2-\delta}$ (LSF-GDC) cathode, modified with 9.12 wt% $BaCO_3$, is 0.1 $\Omega \cdot cm^2$ at 750°C, which is about 2.2 times lower than that of the bare cathode (0.22 $\Omega \cdot cm^2$). As a result, the anode-supported single cells, with the modified LSF-GDC cathode, deliver a high peak power density of 993 $mW \cdot cm^{-2}$ at 750°C, about 39.5% higher than that of the bare cell (712 $mW \cdot cm^{-2}$) [76]. The catalytic activity of $La_{0.8}Sr_{0.2}FeO_3$-$Ce_{0.8}Sm_{0.2}O_{1.9}$ composite cathode was improved considerably when Pd is added in it [77]. When cathodes like (La, Sr)MnO_3 and (La, Sr) (Co, Fe)O_3 are used, presence of any impurity elements may influence the oxygen reduction process at the cathode which in turn quickly degrade the performance of the SOFC [78]. The performance characteristics of certain cathode components for LTSOFC are presented in Table 3.

4. Anode materials for LTSOFCs

Anode materials play key role in exhibiting the electro-oxidation reaction in LTSOFC systems. Primarily, the anode materials need to have enough electronic conductivity (usually in the range of 100 $S \cdot cm^{-1}$) which mainly depends on their physico-chemical properties. Apart from this, the anode materials must meet other important criteria to have consistent anode performances. These requirements include a) adequate ionic conductivity (about 10^{-2} $S \cdot cm^{-1}$), b) chemical stability in a reducing atmosphere, c) thermo-mechanical compatibility with other LTSOFC components, such as interconnect and electrolyte, d) adequate porosity of at least 30% to 40%, e) great adhesion with electrolyte component, f) large effective triple phase boundary (TPB) length, g) ease of fabrication, and h) relatively low cost [89]. Modern LTSOFCs are fabricated with thin layers of anode components which usually supported by the oxide ion conducting electrolyte layers [90-92]. For reduced temperature SOFCs, materials based on metal substituted conducting oxides are used because they may give low polarization resistance [93,94] in real time application. Further, the materials that are used as anode components must have similar thermal expansion co-efficient values with the adjoining electrolyte components. The catalytic behaviour of the anode is also a significant factor in understanding the fuel oxidation characteristics of LTSOFC systems [95]. The primary cause of Ni-YSZ cermet's degradation is mainly morphological alteration brought out by the sintering process. During the high temperature annealing process, the size and shape of anode component is altered. Additionally, the catalytic activity of Ni-YSZ anode is reported to be affected mainly due to carbon deposition when the hydrocarbon based fuels are used in SOFC devices. Sulfur present in anode feed gases may tend to poison the Ni-YSZ cermet anodes [96,97]. It was reported that Cu in Cu-YSZ does not stimulate the formation of C-C bonds during the carbon deposition and has a higher more resilient than Ni-YSZ to sulphur contaminants [98]. La-$SrTiO_3$ based anode materials is also found to demonstrate high chemical stability and electrical conducting properties for ITSOFC [99,100]. Ru-substituted perovskite catalysts, including $La_{0.8}Sr_{0.2}Cr_{0.95}Ru_{0.05}O_{3-\delta}$ (LSCR) and $Sm_{0.8}Ba_{0.2}Cr_{0.95}Ru_{0.05}O_{3-\delta}$ (SBCR), were investigated for the partial oxidation (POX) of diesel to produce hydrogen-rich gases for SOFC applications. They showed superior tolerance over sulphur at 950°C [101,102]. $La_{0.70}Sr_{0.30}VO_3$ has been reported as an alternative anode which showed high activity for oxidation of H_2S at 950°C [103]. $La_{0.4}Sr_{0.6}Ti_{1-x}Mn_xO_{3-\delta}$ perovskite anode maintained stability in hydrogen humidified atmosphere and showed insignificant electrocatalytic activity for methane oxidation 810°C to 817°C [104]. For intermediate temperature SOFC (ITSOFC) application, $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ anode exhibited comparable electrochemical performance to Ni/YSZ cermets for methane fuel [105,106]. Due to the low polarization resistance of the LSTM4646 ($La_{0.4}Sr_{0.6}Ti_{1-x}Mn_xO_{3-\delta}$)/YSZ anode, 0.32 $\Omega \cdot cm^2$, an electrolyte-supported H_2/air fuel cell with an LSM/YSZ cathode yields a power density of 365 $mW \cdot cm^{-2}$ at 0.7 V at 856°C [104]. Cu-CeO_2 cermet anode resulted in better performance at 700°C especially for ITSOFC application [107,108]. $LaSrFe_{0.75}Ni_{0.25}O_4$, based anode demonstrated excellent stability, enhanced sulphur tolerance and thermal and redox stability at intermediate temperature range [109]. Rare earth doped CeO_2 is a viable anode material for LTSOFC due to its advantageously high electrocatalytic activity that enables the direct oxidation of low hydrocarbon gases [110,111]. $BaCe_{0.9}Yb_{0.1}O_{3-\delta}$ impregnated Ni-GDC at 550°C to 650°C exhibited better performance with high power density, improved water adsorption and resistant to sulphur poisoning [112]. Ni + $BaZr_{0.4}Ce_{0.4}Y_{0.2}O_{3-\delta}$ based anode material showed excellent performance with greater sulphur tolerance in SOFC [113]. $Zr_{1-x-y}Ti_xY_yO_2$ anode resulted with greater activation energy and lowest value of ionic conductivity at 800°C [114]. CeO_2 based anode has high catalytic activity and sulphur tolerant at low temperature [115,116]. Exsolved perovskites based on $La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_3$ can be used as a coating layer or catalytic pre-layer of a conventional Ni-YSZ anode. This anode electrocatalyst can be combined with a full density electrolyte based on Gadolinia-doped ceria or with $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_3$ (LSGM) or $BaCe_{0.9}Y_{0.1}O_{3-\delta}$ (BYCO) to form a complete perovskite structure-based SOFC [117,118]. Vanadium-based materials showed the lowest polarization resistance, and so were chosen for subsequent full cell tests using the configuration [H_2S, AV_2S_4/YSZ/Pt, air] (where A = Ni, Cr, Mo). MoV_2S_4 anode had superior activity and performance in the full cell setup, consistent with results from symmetrical cell tests [119]. SOFC with $CuFe_2S_4$ anode at 900°C showed high value of open circuit potential (OCP) about 1.04 V [120]. SOFC with $Li_{0.33}La_{0.56}TiO_3$ based anode delivered excellent performance at 950°C for 70h [121]. $Sr_2Mg_{1-x}Mn_xMo_{6-\delta}$ double perovskite anode exhibited better sulphur tolerant at 650°C<T<1000°C and showed long term stability [122,123]. Ni-Fe bimetallic anode reported to provide improved resistance against carbon deposition, and exhibited better electrical conductivity at 650°C [124,125]. Cu-Ceria-YSZ/ScSZ based anode worked at 700°C delivered greater power output with ethanol or methanol based fuels at its operation temperature [126]. NiO–$Ce_{0.9}Gd_{0.1}O_{1.95}$ (NiO-GDC) based LTSOFCs showed greater electrical performance. A single cell prepared from the NiO–GDC nanocomposite powders exhibits an OCV of 0.935 V and a maximum power density of 713 $mW \cdot cm^{-2}$ at 650°C [127]. The performance characteristics of certain anode components for LTSOFC are presented in Table 4.

Table 3. The performance characteristics of certain cathode components for LTSOFC.

Cathode composition	Conductivity [S·cm^{-1}]	Other components	Temperature range [°C]	Power density [mW·cm^{-2}]	Reference
$La_{0.10}Sr_{0.90}Co_{0.20}Zn_{0.80}O_{5-\delta}$	20.29	Anode - Ni-NSDC Electrolyte NSDC	500 to 600	850	[79]
$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ / $Sm_{0.2}Ce_{0.8}O_{1.9}$	15	Anode - Ni-YSZ Electrolyte-YSZ	400 to 650	936	[80]
$Ce_{0.9}Mo_{0.1}O_{2+\delta}$	5.08×10^{-2}	-	500 to 600	-	[81]
$BaFe_{0.85}Cu_{0.15}O_{3-\delta}$	12.8	-	26.85 to 999.85	-	[82]
$Sr_2Sc_{0.1}Nb_{0.1}Co_{1.5}Fe_{0.3}O_{6-2}$	48	-	400 to 650	-	[83]
$Ba_{0.05}Cu_{0.25}Fe_{0.10}Zn_{0.60}O$ (BCFZ)	6.15	Anode - $Ba_{0.05}Cu_{0.25}Fe_{0.10}Zn_{0.60}O$ (BCFZ) Electrolyte - NK-CDC	550	741.87	[84]
$Ba_{0.5}Sr_{0.5}Co_{0.2}Fe_{0.8}O_3$ (BSCF)		Anode - Ni Electrolyte -$Sm_{0.2}Ce_{0.8}O_2$(SDC)-carbonate composite	500	860	[85]
$SrFe_{0.9}Al_{0.1}O_{3-\delta}$ (SFA) - SDC	-	Anode - LSGM	800	512	[86]
$LaNi_{0.8}Cu_{0.2}O_3$	-	Electrolyte - $Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC) and (Na_2CO_3, Li_2CO_3) composite Anode - NiO	550	390	[87]
$Zn_{0.60}Cu_{0.20}Mn_{0.20}O$ (CMZO)	12.567	Electrolyte - Carbonated samarium doped ceria composite (NSDC)	550	728.86	[88]

Table 4. The performance characteristics of certain anode components for LTSOFC.

Anode composition	Conductivity [S·cm^{-1}]	Other components	Temperature range [°C]	Power density [mW·cm^{-2}]	Reference
$Ni/Gd_{0.1}Ce_{0.9}O_{1.95}$	-	Cathode $La_{0.8}Sr_{0.2}Co_{0.2}Fe_{0.8}O_{3-\delta}$-GDC Electrolyte-GDC	500 to 700	909	[128]
$Cu_{0.10}Ni_{0.27}Zn_{0.37}Ce_{0.16}Gd_{0.04}$	4.14	Cathode-BSCF Electrolyte-NKSDC	-	570	[129]
$Ni_{0.9}Fe_{0.1}O$-YSZ	-	Anode-YSZ Cathode-LSM-YSZ	600 to 850	1238	[130]
Ni-doped $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$	29	Electrolyte-LSGM	650 to 800	968	[131]
$BaCe_{0.8}Fe_{0.1}Ni_{0.1}O_{3-\delta}$-impregnated Ni–GDC	-	Electrolyte-GDC Cathode - SCF–GDC composite	600 to 750	920 to 1440	[132]
ZnO + $Li_{0.28}Ni_{0.72}O$ + CuO-NSDC	-	Electrolyte - Samarium doped ceria-sodium carbonate composite (NSDC) Cathode - LiNiCuZn oxides-NSDC	470	1000	[133]
$La_{0.75}Sr_{0.25}Co_xMn_{1-x}O_{3-\delta}$ (x=0.3–0.7)(LSCM)	5.25	-	800	360	[134]
GDC + $TiO_{0.2}C_{0.8}$	-	Electrolyte - $Ce_{0.9}Gd_{0.1}O_{3-\delta}$ Cathode - $La_{0.8}$ $Sr_{0.2}Co_{0.2}Fe_{0.8}$ $O_{3-\delta}$	700	130	[135]
$La_{0.43}Ca_{0.37}Ti_{0.94}Ni_{0.06}O_{3-\delta}$ (LCTNi)	-	-	800	425	[136]
$La_{0.20}Sr_{0.25}Ca_{0.45}TiO_3$ ($LSCT_A^-$)	-	Electrolyte - 6ScSZ Cathode - LSM-YSZ/LSM composite	1000	-	[137]

5. Efficient interconnecting materials for LTSOFC

SOFCs require efficient interconnecting materials to enhance their performance and durability. Interconnects play a critical role in connecting individual cells in a stack, providing electrical conductivity, gas sealing, and mechanical support. Efficient electron conduction is a crucial parameter to minimize the electrical losses within the SOFC stack. Interconnect materials must withstand in the harsh operating conditions, including high temperatures and corrosive environments, without undergoing chemical reactions which may degrade the overall performance of the SOFC [138]. SOFCs generally operate at elevated temperatures (around 800°C), where materials experience significant thermal expansion. Interconnects should have a thermal expansion coefficient closely matched to that of adjacent cell components to prevent mechanical stress and cracking during thermal cycling. Interconnects should provide a gas-tight seal to prevent the leakage of fuel and oxidant gases, ensuring efficient operation and safety. Interconnects should possess adequate mechanical strength to support the cell stack and withstand mechanical stresses during operation, installation and maintenance.

Two primary materials are suggested for SOFC interconnects: metallic alloys and ceramics. Materials based on doped lanthanum chromite ($LaCrO_3$) are generally used as intercell connectors in SOFC systems. It was reported that these materials exhibit high electrical conductivity and excellent chemical stability at the operation temperature of SOFC systems [139]. Ferritic stainless steels (Crofer®22 APU alloy) based intercell connectors have excellent electrical conductivity, thermal expansion matching with other components, and good corrosion resistance in the SOFC environment. However, they may require protective coating to improve oxidation resistance [140]. Emerging materials like conducting polymers have shown promise for SOFC interconnect applications due to their high electrical conductivity,

flexibility, and potential for low-cost fabrication. However, challenges remain in terms of long-term stability and compatibility with SOFC operating conditions [141]. SiC-based interconnect materials offer excellent thermal and chemical stability at high temperatures and can provide good electrical conductivity [142]. However, achieving suitable interconnect properties requires careful material design and processing. In a SOFC, connecting materials establish a connection of electricity between the cathode and anode of two cells. It also functions as a physical barrier to divide two compartments and to stop gas mixtures [143]. Apart from the above materials, alloys based on iron, chromium and nickel have been suggested as SOFC connecting components [144]. Because of the inert properties and stability in oxidizing environments, silver is also chosen as a viable option for the cathode connection material in ITSOFCs [145]. We must utilize appropriate metallic components with superior electrical stability for LTSOFCs in conjunction with other components [146]. Researchers still continue to explore new novel materials and fabrication techniques to develop interconnects with improved performance, durability and cost effectiveness for LTSOFC applications. Additionally, advancements in coating technologies and interface engineering are being pursued to address challenges related to corrosion, oxidation, and gas tightness.

6. Component fabrication in LTSOFCs

The methods employed in the fabrication of nanostructured ceramic components have a significant impact on SOFC performance. To enhance the performance characteristics of SOFC, the components should be fabricated carefully using suitable techniques. In general, the electrolyte thickness should be minimal to have better performance in SOFC. Many methods are used now to lower the thickness of the electrolyte film in SOFCs. Lowering the thickness of the components may improve the reaction kinetics at comparatively low temperatures in SOFC systems [147]. The methods, such as, screen printing, dip coating, tape casting and sputtering are generally adopted by researchers for fabricating the components in the SOFC systems. For the commercialization of SOFC device, straightforward and affordable way of fabricating SOFC components is mandatory [148-151]. Brief discussion about various techniques is presented in the following sections.

6.1 Screen printing technology

Screen printing is a cost effective technique which can be used easily for the fabrication of thin components in SOFCs. It was found that a simple and affordable processing technique for creating planar SOFCs is screen printing [152-154]. A simple screen printing set-up used for the fabrication of SOFC components is shown in Figure 2.

The components having the thickness in the range of 10 μm to 100 μm can be fabricated using screen printing process with superior quality and enhanced performance. In screen printing, ready-made suspension of a specific ceramic material is poured in the screen which will flow by applying suitable pressure [155]. For preparing the suspension i.e., screen printing ink, stable ceramic powder (anode or electrolyte or cathode) along-with suitable plasticizer, organic binder and solvent needs to be mixed in an appropriate composition.

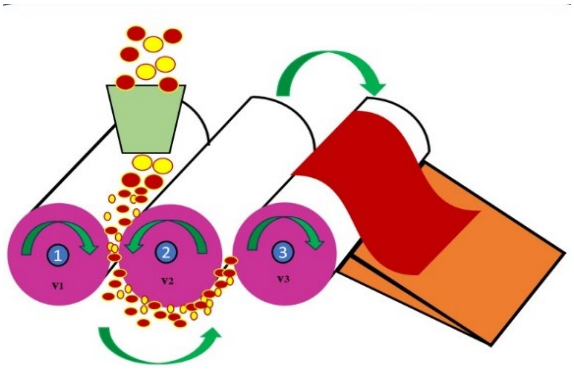

Figure 2. A simple screen printing set-up used for the fabrication of SOFC components [154].

The shape and size of the grain boundary, the packing density within the mixture, and other factors related to particle size and powder dispersion affect the rheology of the ink. The fundamental process of the screen-printing technique began with the inks being fed into the open screen meshes and then being flattened into a thin, formed layer using a squeegee with the appropriate force. After fabrication of SOFC component by screen printing technique, the process of sintering and drying is required to improve the quality of the component and eliminate any surplus solvent [156-158]. Total wires per linear inch are the definition of the screen's mesh count. The number of times the ink/paste is printed on the target is determined by the ingredients used to prepare the paste/ink [159]. Previous studies have shown that extra care must be taken to guarantee the fabrication ink's quality, which is connected to the rheological characteristics of the ink [160]. The rheological properties of NiO/ScSZ anode inks were studied and reported. Their electrochemical characteristics, mechanical hardness and conductivity of the anode were found to be excellent [161]. Planar SOFC device was successfully fabricated using screen printing technology. The single chamber SOFC resulted with a power density of 1.2 $mW \cdot cm^{-2}$ at 800°C [162].

6.2 Tape casting technology

A common shaping method for creating flat ceramic sheets with thicknesses ranging from 10 μm to 1 mm is called tape casting [163]. Glenn Howatt created the tape casting process in the 1940s to produce semiconductors in transistors, which is still considered to be a significant method in making thin films for electronic and optical applications [164]. This technique is a wet-shaping method in which the slurry or slip casting of pseudoplastic is carried out. The slurry is usually made up of an inorganic powder mixed with an organic or water-based liquid that serves as a as a medium for the ceramic particles to undergo uniform dispersion in slurry. The slurry consists of other organic additives like plasticizers, binders, and dispersants also to get unique characteristics of the ceramic tape [165]. The slurry can be cast over a glass plate using a doctor's blade. The thickness of the tape can be adjusted by a screw gauge arrangement available in the doctor's blade. Modifying the viscosity of the tape casting slurry is necessary to produce tapes that meet certain quality requirements, including a) no drying flaws, b) cohesiveness for easy handling of dried sheets, c) microstructural homogeneity, d) good thermo pressing

(lamination) ability, e) simple handling with adequate mechanical strength, and f) sintering properties [166]. To guarantee the creation of homogenous tapes, the slurry should exhibit pseudoplastic behaviour. In this instance, shear forces between the blade and the carrier cause the viscosity to decrease during casting. Immediately upon casting, the viscosity quickly rises to control erratic flow and stop the ceramic particles from sedimenting [167]. After drying, the tapes can be cut into different sizes based on the requirement. The green tape can be laminated to create thicker pieces too. The dried laminates need to be heat treated in a programmable furnace under specific atmosphere to have proper densification and to eliminate the organics present in the laminate [168,169]. A schematic of the tape casting machine is shown in Figure 3. The anode supported SOFC is prepared by five layer tape casting technique. The Ni-ScCeSZ composite IT-SOFC delivered a power density of 46 $W{\cdot}cm^{-2}$ in in H_2:N_2 fuel (85% H_2) fuel and air oxidant at 650°C and 800°C [170]. Metal supported SOFC was fabricated using tape casting process. It was found that by altering the addition of pore former, the sintering characteristics of the components were modified [171]. The composite multi-layer components were fabricated by tape casting process successfully. Each stack repeat unit (one cell and one interconnect) generates around 28.5 W of electrical power at a 300 $mA{\cdot}cm^{-2}$ current density and 700°C [172].

6.3 Sputtering technology

Thin film SOFCs (TF-SOFCs) are fabricated efficiently by optimized sputtering process. In this technique, the anode, electrolyte and cathode materials were sputtered over porous anodized aluminium oxide substrate. The SOFC fabricated by sputtering technique yielded good performance with a power density of 3 $W{\cdot}cm^{-2}$ at 650°C under hydrogen fuel [173]. YSZ based TF-SOFCs with $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{2.95}$(LSCF)-based cathode were fabricated by magnetron sputtering technique. They reached the power density of 2.5 $W{\cdot}cm^{-2}$ at low temperature range (600°C to 650°C) [174]. Single layers of SDC based electrolyte and multilayers SDC/YSZ/SDC thin film electrolyte were fabricated by magnetron sputtering techniques. However, the SOFCs with single layer SDC electrolyte resulted in better performance with a power density of 651 $mW{\cdot}cm^{-2}$ [175]. Ni-based anodes for SOFC were fabricated by sputtering process. SOFC with these anode resulted with a greater power density in the range of 304 $mW{\cdot}cm^{-2}$ to 477 $mW{\cdot}cm^{-2}$ at low temperature (450°C to 500°C) [176]. Magnetron sputtering is used to prepare single layer YSZ or CGO and bilayer YSZ/CGO electrolyte for SOFC application. Among the different thick electrolytes, the SOFC with YSZ/CGO electrolyte layer delivered a power density of 1 $W{\cdot}cm^{-2}$ at 750°C and 1.25 $W{\cdot}cm^{-2}$ at 800°C [177]. The schematic of the magnetron sputtering setup is shown in Figure 4.

6.4 Dip coating technology

Fully dispersed YSZ electrolyte films were coated on NiO-YSZ anode using dip coating process. After high temperature calcination process, dense crack free films were obtained. The SOFC fabricated with this electrolyte exhibited a power density of 190 $mW{\cdot}cm^{-2}$ at 800°C [178]. 8 YSZ thin films were fabricated by dip coating process effectively on the anode support in SOFC system. For the dip coating process, sol-gel prepared YSZ nanoparticles were mixed with ethanol solvent, phosphate ester dispersant and poly vinyl butyral binder respectively [179]. YSZ electrolyte was dip coated on green Ni-YSZ anode layer followed by co-firing. The SOFC fabricated with the dense YSZ electrolyte resulted in a power density of 460 $mW{\cdot}cm^{-2}$ at 800°C [180]. It was reported that dip coating is one of finest techniques in developing micro-tubular SOFCs [181]. Dip coating can be combined with a simple phase-transition process to develop and fabricate the anode supported SOFC systems. The SOFC fabricated with NiO-YSZ anode and YSZ electrolyte delivered a power density of 752 $mW{\cdot}cm^{-2}$ [182]. NiO-YSZ anode substrates were fabricated successfully by dip coating technique. SOFC fabricated with LSM—YSZ/YSZ/ NiO-YSZ components delivered a power density of 1.0 $W{\cdot}cm^{-2}$ at 850°C [183]. The schematic diagram of the dip-coating process is presented in Figure 5.

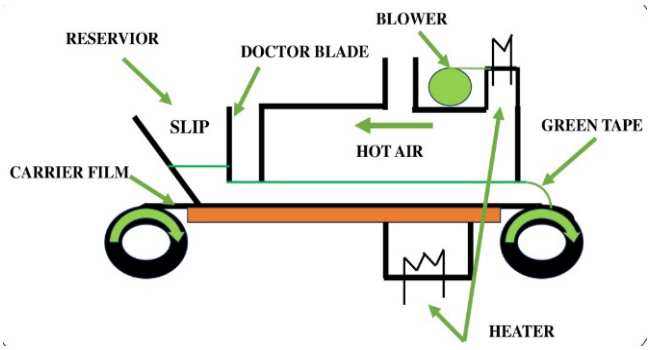

Figure 3. A schematic diagram of the tape-casting machine [169].

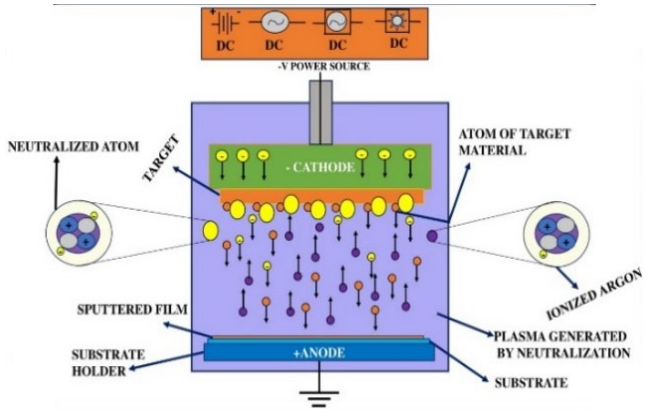

Figure 4. The schematic of the magnetron sputtering setup [172].

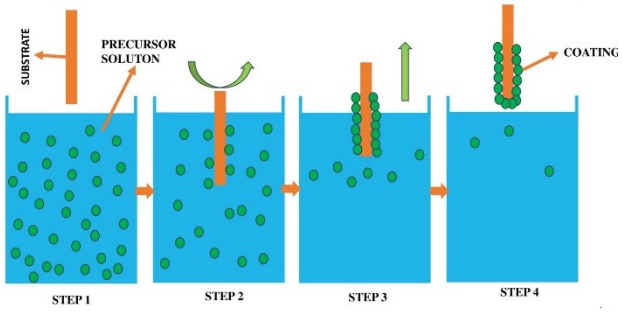

Figure 5. The schematic diagram of the dip-coating process [183].

7. Conclusion

Different nanostructured materials used in SOFC and possible fabrication technologies were evaluated in this article. SOFCs did not require any costly catalysts made of platinum, rhodium, or other precious metals due to its high temperature operating conditions, which makes these devices with excellent fuel flexibility and greater efficiency. However, because of its high operating temperature (1000°C), the commercialization of SOFC is not yet completed. To reduce the operating temperature of SOFC, novel electrode and electrolyte materials are required. Ceria based electrolyte materials were found to exhibit better performance for LTSOFC application. $L_{0.6}Sr_{0.4}Co_{0.8}Fe_{0.2}O_3$-CGO-Ag based composite cathode and Cu-Ceria-YSZ/ScSZ anode were found to exhibit better performance in LTSOFC. Ferritic stainless steel based intercell connectors showed high electronic conductivity and similar thermal expansion coefficient with the adjoining components in LTSOFC which makes them as the alternative to $LaCrO_3$ based intercell connectors. For the fabrication of SOFC components, dip coating and sputtering technologies were found to be useful in developing thin layers with specific requirements. LTSOFC with alternate materials could deliver a power density of 1.5 $W.cm^{-2}$ at 650°C to 800°C at a nominal OCV of 0.7 V to 0.8 V.

Acknowledgements

The authors express their sincere gratitude to the management of Kalasalingam Academy of Research and Education for its support to initiate fuel cell based research activity in the Department of Chemistry.

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