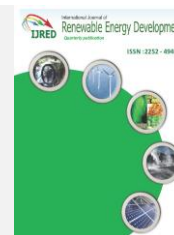




Contents list available at IJRED website

Int. Journal of Renewable Energy Development (IJRED)

Journal homepage: www.ijred.com



Materials and Components for Low Temperature Solid Oxide Fuel Cells – an Overview

D. Radhika and A. S. Nesaraj*

Department of Chemistry, School of Science and Humanities, Karunya University, Coimbatore – 641 114, INDIA

Article history:

Received March 16, 2013
Received in revised form April 28, 2013
Accepted April 30, 2013
Available online

ABSTRACT: This article summarizes the recent advancements made in the area of materials and components for low temperature solid oxide fuel cells (LT-SOFCs). LT-SOFC is a new trend in SOFC technology since high temperature SOFC puts very high demands on the materials and too expensive to match marketability. The current status of the electrolyte and electrode materials used in SOFCs, their specific features and the need for utilizing them for LT-SOFC are presented precisely in this review article. The section on electrolytes gives an overview of zirconia, lanthanum gallate and ceria based materials. Also, this review article explains the application of different anode, cathode and interconnect materials used for SOFC systems. SOFC can result in better performance with the application of liquid fuels such methanol and ethanol. As a whole, this review article discusses the novel materials suitable for operation of SOFC systems especially for low temperature operation.

Keywords: components, low temperature operation, materials, performance characteristics, solid oxide fuel cell

1. Introduction

In recent years the development of fuel cell technology has been rapid, and several types of fuel cell have been developed depending on the intended application. Of the many types of fuel cell available, the solid oxide fuel cell (SOFC) has shown considerable promise for a variety of applications, from the portable 1 kWe (kilowatt of electrical energy) size devices for transport applications to the >100 kWe stationary plants currently being pursued by companies such as Siemens Westinghouse (Ahmet *et al.* 2003). Fuel cells operate by electrochemical combination of a fuel with an oxidant without hot combustion. This is achieved by placing an electrolyte between two electrodes in contact with the fuel and the oxidant, respectively. An ideal electrolyte can conduct ions, but no electrons, in order to combine the fuel (e.g. hydrogen) with the oxidant (e.g. air). In a fuel cell, the oxygen has to be reduced to oxygen ions at the cathode side of the electrolyte so that they can be transported by ionic conduction through

the electrolyte. At the anode side of the electrolyte, the oxygen ions combine with the hydrogen producing water and electrons. The driving force will be the oxygen gradient in the oxidant gas (air) and the fuel gas mixture with low partial oxygen pressure. The operation principle of a fuel cell (Gort & Vohs 2003) is shown in Fig. 1. SOFCs have been known for more than 70 years and were first created by Bauer and Pries in 1937. However, the development of practically usable SOFCs only started in the beginning of the 1960's. An SOFC essentially consists of two porous electrodes separated by a dense, oxygen ion conducting electrolyte. Today the most commonly used electrolyte, anode and cathode materials for state-of-the art SOFC are 10 mol% yttria stabilized zirconia (YSZ), Ni-YSZ cermet and strontium doped lanthanum manganite ($\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$). Apart from this, calcium / strontium doped LaCrO_3 is used as an interconnecting material which is being developed to connect each cell in SOFC in series. CO and hydrocarbons such as CH_4 can also be used as fuels in an SOFC system apart from H_2 . SOFCs are attractive as -

* Corresponding author:
E-mail: drsamson@karunya.edu

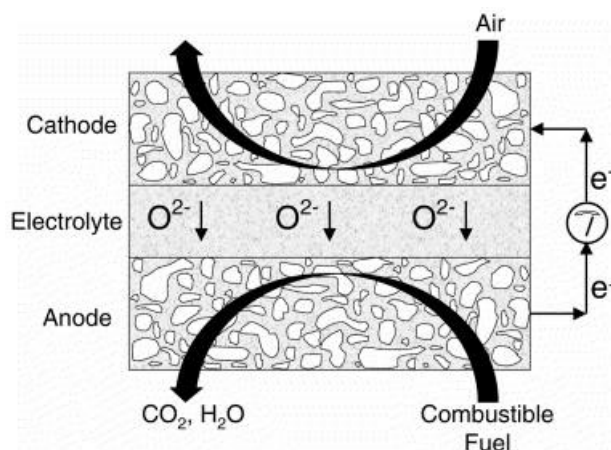


Fig.1. Operating principle of a fuel cell (Gort & Vohs 2003)

energy sources because they are clean, reliable, and almost entirely nonpolluting. Because there are no moving parts and the SOFCs are therefore vibration-free, the noise pollution associated with power generation is also eliminated. Norbert *et al.* (2010), reviewed recent developments in SOFC research regarding materials, processing and microstructure-property relationships. SOFC devices are attractive alternatives to conventional power sources; however they suffer from some technological deficiencies like high operating temperatures (1000°C) which detract them from commercialization. In recent years, great efforts have been devoted to develop low temperature or intermediate temperature SOFCs (LT or IT-SOFCs) operating at 500–800°C. Because, lowering the operating temperature can suppress degradation of components and extend the range of acceptable material selection; this also serves to improve cell durability and reduce the system cost (Chunwen *et al.* 2010). Also, the performance of SOFC strongly depends on the morphology and composition of the electrodes and electrolytes (Rampon *et al.* 2006). Hence, new materials with good low temperature performance in terms of level of conductivity, chemical and mechanical compatibility have to be identified and developed especially for application in LT or IT-SOFCs. This article reviews the novel materials and components being developed world-wide towards this purpose.

2. Choice of Electrolytes

It was reported that the state-of-the art electrolyte (YSZ) reacted with the cathode (Sr-doped LaMnO₃) which may can resulted in an insulating phase (La₂Zr₂O₇) (Danjela *et al.* 1995) after prolonged operation of SOFC. Hence, new and novel electrolyte materials were developed as alternatives to replace the existing YSZ. Scandia-doped Zirconia (SDZ) (Nomura *et al.* 2000) was quite attractive as the electrolyte for SOFC's, especially for the intermediate temperature

(600–800°C) SOFC's. However, problems with regard to the stability of this kind of materials is yet to be solved yet. LaGaO₃-based perovskite type oxides as electrolytes, in particular, Sr- and Mg-doped LaGaO₃ (LSGM) were studied by several groups (Goodenough 2000; Kumar *et al.* 2004; Rambabu *et al.* 2006; Lu & Zhu 2008; Ishihara *et al.* 2012). The conductivity of La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-x} is 0.12 S/cm at 800°C and 0.32 S/cm at 1000°C, which is similar to 9 mol % Sc₂O₃ doped ZrO₂ (0.31 S/cm) and higher by a factor of two compared to 8YSZ (0.16 S/cm) (Dusastre & Kilner 1999). The major contributions to the high performance of LSGM electrolyte based fuel cells are the improvements in electrolyte conductivity and, more importantly, the exceptional structural and chemical compatibility with perovskite cathode materials, such as lanthanum cobaltite. Datta (2009) reviewed the application of LaGaO₃ based electrolyte materials in SOFC systems elaborately. Even though LSGM is a most favourable solid electrolyte for ITSOFC systems; it undergoes serious interfacial reactivity with anode and resulted in the formation of a La-deficient La-Sr-Ga-O phase at the LSGM/NiO interface in fuel cell operating conditions (Jong-Ho Lee *et al.* 2012).

The ceria-based electrolytes for SOFCs have shown good performance improvements that have demonstrated a breakthrough in SOFC research. CeO₂ doped with different cations, notably Gd₂O₃ doped CeO₂, Sm₂O₃ doped CeO₂ and Y₂O₃ doped CeO₂ has much higher ionic conduction and may operate at lower temperatures (350–700°C), at which it becomes a predominantly ionic conductor even in a reducing atmosphere. New research activities on the ceria-based materials showed super ionic and dual or hybrid H⁺/O²⁻ conduction with a conductivity of 10⁻¹ S cm⁻¹ below 600°C (Zhu 2006; Fuentes & Baker 2008). Mogensen *et al.* (2000) and Steele (2000) reviewed the electrical conductivity and mechanism of conduction in ceria-based electrolytes. In the case of doped ceria, Sm₂O₃ and Gd₂O₃ doped CeO₂ resulted in highest conductivity values with optimal dopant concentrations of 10–20% (Wang *et al.* 2003; Wang *et al.* 2004; Zang *et al.* 2004; Kamruddin *et al.* 2004; Nesaraj *et al.* 2010). Inaba & Tagawa (1996) reviewed the performance of ceria based electrolytes. The ionic conductivity of doped ceria is approximately an order of magnitude greater than that of stabilized zirconia for comparable doping conditions. This is a result of the larger ionic radius of Ce⁴⁺ (0.87 Å in 6-fold coordination) than Zr⁴⁺ (0.72 Å), which produces a more open structure through which O²⁻ ions can easily migrate (Matović *et al.* 2005). Even though, gadolinia and samaria doped ceria are indeed very good oxide ion conductors, all-types of ceria based electrolytes have the disadvantage of being relatively easy to reduce. The reduction of Ce⁴⁺ to Ce³⁺ gives rise to electronic conductivity, which in turn causes an electronic leakage current through the electrolyte in operating SOFCs -

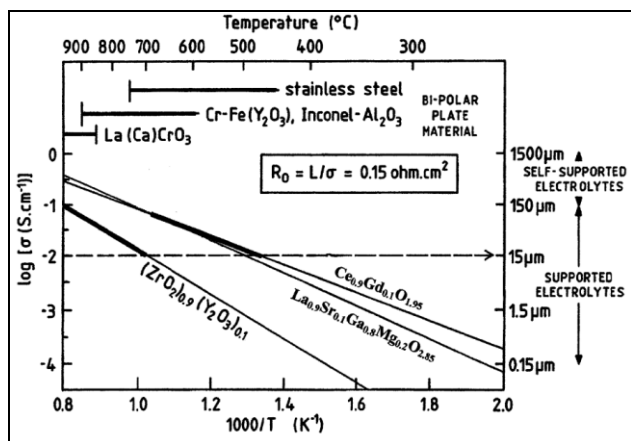


Fig. 2 A comparison of ionic conductivities of potential electrolyte materials for IT-SOFC applications (Kesapragada *et al.* 2003)

- (Singhal & Mizusaki 2005). Of course, the ceria-based electrolytes are a relatively recent technology, so there are still problems with the technology and solutions being developed. A comparison of ionic conductivities of potential electrolyte materials for IT-SOFC applications is indicated in Fig 2.

To overcome the problem caused by ceria reduction, functional composite materials based on doped ceria and various salts (carbonates, sulphates, halides or hydrates) are being developed world-wide. Ying Ma (2009) has reported that samaria doped ceria/amorphous Na_2CO_3 based nanocomposite is used as an electrolyte for LT-SOFC and the cell has shown excellent performance of 0.8 Wcm^{-2} at 550°C . Similarly, Liu *et al.* (2010) have reported the electrical properties of composite electrolytes composed of Sm^{3+} and Nd^{3+} co-doped ceria (SND) and binary carbonates (Li_2CO_3 - Na_2CO_3) and the ionic conductivity was found to be 0.01 Scm^{-1} at 481°C . Ketzial & Nesaraj (2010), have developed nanoceramic composite materials based on $\text{BaCe}_{0.9}\text{Gd}_{0.1}\text{O}_{3-\delta}$ - $\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_{2-\delta}$ and $\text{BaCe}_{0.8}\text{Sm}_{0.2}\text{O}_{3-\delta}$ - $\text{Ce}_{0.8}\text{Sm}_{0.2}\text{O}_{2-\delta}$ for LT-SOFC application by simple co-precipitation process. Raza *et al.* (2011) have developed electrolytes based on nanotechnology and two-phase nanocomposite approaches using non-oxygen ion or proton conductors, e.g., lithium aluminate-lithium sodium carbonate, with great freedom in material design and development for LT-SOFC application. From the recently published research articles, it was found that functional nano-ceramic composite materials might be the suitable alternative to the existing YSZ based electrolyte for SOFC application.

3. Choice of Anodes

Aside from its role as electrolyte, YSZ is often used in SOFC electrodes (anode, cathode) to provide some ionic conductivity to electrode materials that don't have enough, and, in some SOFC, as a structural cell support.

Ni-YSZ cermet is commonly used as anode material in SOFC (Norbert *et al.* 2010). Porous Ni/YSZ cermet (YSZ: yttria stabilized zirconia) is currently the most common anode material for SOFC applications because of its low cost. It is also chemically stable in reducing atmospheres at high temperatures and its thermal expansion coefficient is close to that of YSZ-electrolyte. The cermet both reduces/prevents thermal mismatch between the nickel and the YSZ and produces a large three phase's boundary. A difficulty caused by the use of the cermets is the nickel sintering over time that reduces the active surface of the electrode (Kilbride 1996). However, this can be minimized by control of the grain size and microstructure of the cermet. The Ni/YSZ cermets, which display excellent catalytic properties for fuel oxidation and good current collection, but do exhibit disadvantages, such as low tolerance to sulphur and carbon deposition when using hydrocarbon fuels, and poor redox cycling causing volume instability (Tao & Irvine 2003). Zhu & Deevi (2003) have reviewed the status of anode materials for solid oxide fuel cells. Some alternate cermet anodes have been developed to solve the problems existing in the state-of-the SOFCs. Materials with the composition $(\text{Ba/Sr/Ca/La})_{0.6}\text{M}_x\text{Nb}_{1-x}\text{O}_{3-\delta}$ ($\text{M} = \text{Mg, Ni, Mn, Cr, Fe, In, or Sn}$) were proposed as alternate anodes for SOFCs because they exhibit considerable electronic conductivity and might additionally show some ionic contribution (Irvine & Sauvet 2001; Holtappels 2011). Slater & Irvine (1999) have proposed niobate based tungsten bronze materials as novel anodes since these materials are also reasonably stable in both oxidizing and reducing atmospheres. Also, the unique feature of mixed conductivity imparts these materials the ability to accelerate the electrode gas reaction. However, it was found that rare earth doped CeO_2 is a viable anode material for LT-SOFC due to its advantageously high electro-catalytic activity that enables the direct oxidation of low hydrocarbon gases, unfortunately, the occurrence of pronounced ionic conductivity along with mechanical degradation in reducing atmospheres poses a great concern for its practical applications (Zhu & Deevi 2003).

Yttria-doped ceria (YDC) and samaria-doped ceria (SDC) were proposed as potential anodes for intermediate temperature SOFCs. The common feature of these two candidate materials is, in reducing atmosphere typical of anode environment, they exhibit characteristic of mixed ionic-electronic conductivity. Since YDC shows greater electronic conductivity than SDC and comparable ionic conductivity with YSZ, the anode reaction can be appreciably enhanced (Chunwen & Ulrich 2007). Similar to Ni/YSZ cermet anode, Ni/doped ceria cermet has also been formulated and tested for use as potential anode in intermediate temperature SOFCs (Ormerod *et al.* 1999). Yang Nai-Tao *et al.* (2006) have proposed new $\text{Ni-Ce}_{0.8}\text{Gd}_{0.2}\text{O}_{1.9}$ (CGO) cermet anodes of IT-SOFCs. They found that NiO in the

anodes can be reduced to Ni completely by the mixture of 20%H₂ ~ 80%He at 700°C without the phase transformation of CGO. The competitiveness of ternary component anode consisting of Cu, CeO₂ and YSZ on direct activation of dry hydrocarbon gases is evaluated by Seungdoo *et al.* (2000) by performing a short-term single cell test at 700°C. Their results are encouraging since Cu/CeO₂/YSZ anode demonstrates an excellent activity towards direct electrochemical oxidation of a variety of hydrocarbon gases.

Recently, a variety of composite anodes was proposed for the LT-SOFC application. Composite electrodes based on Cu_{0.16}Ni_{0.27}Zn_{0.37}Ce_{0.16}Gd_{0.04}O_{2-δ} (CNZGC) have been successfully synthesized by solid state reaction method as anode material for LT-SOFC. Electrical conductivity of 4.14 S/cm was obtained for the above composite electrode at a temperature of 550°C, which makes the material suitable for LT-SOFC application (Abbas *et al.* 2012). Nano composite materials such as ZnO / NiO (Raza *et al.* 2011) and Zn_{0.6}Fe_{0.1}Cu_{0.3}/GDC (Raza *et al.* 2010) were proposed as alternate anode materials for LT-SOFC operating below 500°C. It was found that nano composite based anodes can exhibit good catalytic activity, high electronic and ionic conductivity in turn which may help to achieve high power output.

4. Choice of Cathodes

In SOFCs, the cathode functions as the site for the electrochemical reduction of oxygen. To this effect, the cathode must have: (1) high electronic conductivity (preferably more than 100 S cm⁻¹ under oxidizing atmosphere); (2) a matched thermal expansion coefficient (TEC) and chemical compatibility with the electrolyte and interconnect materials; (3) adequate porosity to allow gaseous oxygen to readily diffuse through the cathode to the cathode/electrolyte interface; (4) stability under an oxidizing atmosphere during fabrication and operation; (5) high catalytic activity for the oxygen reduction reaction (ORR); and (6) low cost. In addition, the choice of cathode materials is largely dependent on the electrolyte materials used. Hence, care should be taken to match thermal expansion coefficients and avoid undesirable interface reactions.

Perovskite materials - particularly of the LaMO₃, type, where M is typically a transition metal - have in increasing numbers been found to possess mixed ionic-electronic conductivity. The presence of mixed ionic-electronic conductivity in oxides has been found to be highly beneficial for their use as cathodes in fuel cells. Therefore, considerable efforts have been directed towards the development of this type of cathode. The performance of the cathode material is of fundamental importance to the operation of these devices. In recent years a significant amount of time has been expended

on the development of these perovskite materials, identifying new mixed conductors and improving the operational performance of existing materials through the development of improved cell designs. Sr - doped LaMnO₃ (LSM) (Huang *et al.* 1996; Heuveln *et al.* 1997; Jiang *et al.* 2002) is the state of the art cathode material for SOFCs. The chemical compatibility between LSM cathode and YSZ electrolyte has been studied thoroughly (Van Roosmalen & Cordfunke 1992; Taimatsu *et al.* 1996; Wiik *et al.* 1999). The reaction proceeds by interdiffusion of mainly Mn and La into YSZ, which leads to the formation of La₂Zr₂O₇, while Y and Zr ions remain in YSZ. Hence, the interdiffusion and formation of secondary phases at the cathode/electrolyte interface will, over time, reduce the performance of SOFCs. As well as, the electrical properties of manganite-based perovskite compounds are not sufficient for operation of SOFC at temperatures below 800°C. The absence of oxygen vacancies in LSM restricts the reduction of oxygen to the three-phase boundary regions. This limitation is the primary reason why LSM does not have acceptable performance at lower temperatures. Usually, two approaches have been taken to improve the performance of LSM cathodes so that they may be used at lower temperatures (Ralph *et al.* 2001). The cathodic over potentials of manganite cathodes can be modified greatly by replacing different rare-earth cations at the A site. Ishihara *et al.* (1994) systematically studied the cathodic over potentials of Ln_{0.6}Sr_{0.4}MnO₃ (LnSM) (Ln = La, Pr, Nd, Sm, Gd, Yb or Y). The majority of work performed on the lanthanide manganite materials has concentrated on the cases where the A site is Sr-doped. In terms of chemical compatibility and electrical conductivity, however, Ca-doped ones have proven more promising.

Apart from LnSM (Sr-doped lanthanide manganite), perovskite materials based on cobaltite and ferrite were proposed as alternate cathode materials for IT-SOFC / LT-SOFC operation. The use of lanthanum cobaltite materials as possible cathodes has been widely investigated in the past years (Godickemeier *et al.* 1996; Tu 1997; Adler 1998; van Doorn & Burggraff 2000; Nesaraj *et al.* 2007). Usually, cobalt-based materials display higher ionic and electronic conductivities than other cathode materials. Therefore, the use of cobalt-containing cathode materials should result in a decreased cathode polarization resistance. La_{1-x}Sr_xCoO_{3-δ} cathode materials have good electrode activity due to high oxygen diffusivity and high dissociation ability of oxygen molecules (Takeda *et al.* 1986). Doping Cu into the Co site can further enhance the ionic conductivity and catalytic activity of (La, Sr)CoO_{3-δ}, although the electrical conductivity of (La,Sr)(Co,Cu)O_{3-δ} (LSCC) was lower (Yasumoto *et al.* 2002). For Mn doping at the B-site, Chen *et al.* (2003) observed that La_{0.6}Sr_{0.4}Co_{0.8}Mn_{0.2}O_{3-δ} has the lowest cathodic overpotential among the tested Ln_{0.6}Sr_{0.4}Co_{0.8}Mn_{0.2}O_{3-δ} (Ln = La, Gd, Sm, or Nd) compounds at 500–800°C. Sr-

doped samarium cobaltite ($\text{Sm}_{1-x}\text{Sr}_x\text{CoO}_3$, SSC) is another widely studied cathode material for IT-SOFCs showing a higher electrical conductivity. The electrical conductivity increases with Sr doping and a maximum conductivity is usually observed at $x=0.5$. The electrical conductivity of this composition shows metallic-like behavior and reaches up to 103 S cm^{-1} in the temperature range of $800\text{--}1100^\circ\text{C}$ (Ralph *et al.* 2003).

Lanthanum ferrite (LaFeO_3) is expected to be more stable than cobaltite perovskites because the Fe^{3+} ion has a stable electronic configuration $3d^5$. Sr-doped LaFeO_3 based cathodes have shown good performance with respect to the power density and stability at 750°C . In iron-based cathodes, reactivity with YSZ electrolyte is significantly reduced (Simner *et al.* 2003). Simner *et al.* (2002) have found that an anode-supported cell consisting of $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$ cathode, YSZ electrolyte and NiO-YSZ anode exhibited a power density as high as about $0.9\text{--}0.95 \text{ W cm}^{-2}$ at 750°C and 0.7 V and exhibited excellent stability over a 300-h test period. $\text{La}_{1-x}\text{Sr}_x\text{Fe}_{1-y}\text{Co}_y\text{O}_3$ (LSCF) shows good electrical conductivity, a high oxygen surface exchange coefficient, and a good oxygen self-diffusion coefficient between 600 and 800°C (Steele 1996; Dusastre & Kilner 1999). At lower operation temperatures, LSCF-based

cathodes are superior to LSM-type cathodes due to a lower area specific resistance. However, LSCF-type perovskites are generally incompatible with YSZ electrolytes due to undesirable interface reactions. Therefore, a Gd_2O_3 doped CeO_2 diffusion barrier layer is used to prevent the formation of low conductive compounds without negatively affecting the electrochemical performance (Haanappel *et al.* 2006; Uhlenbruck 2009). Nanocomposite based cathode materials compatible for LT-SOFCs are being developed. Homogeneous mixture of $\text{Ce}_{0.8}\text{Gd}_{0.2}\text{O}_{1.9}$ and $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$ (nanocomposite) cathode was developed recently by Shen *et al.* (2011) for LT-SOFC. Raza *et al.* (2012) have developed nanocomposite material based on $\text{La}_{0.3}\text{Sr}_{0.2}\text{Mn}_{0.1}\text{Zn}_{0.4}\text{O}_{3-\delta}$ - $\text{Sm}_{0.2}\text{Ce}_{0.8}\text{O}_{1.9}$ for application as alternate cathode materials for LT-SOFC with ceria-based composite electrolyte. Tamara *et al.* (2008) have reported a novel nanocomposite material, $\text{La}_{0.8}\text{Sr}_{0.2}\text{Fe}_{0.6}\text{Ni}_{0.4}\text{O}_{3-\delta}$ / $\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_{2-\delta}$ as cathode for IT-SOFC with improved performance. However, nanocomposite materials with improved characteristics need to be developed for application in LT-SOFC and which is a thematic research area at present in SOFC systems. Various compositions of SOFC cathode materials and their properties are indicated in Table 1.

Table 1

Various compositions of SOFC cathode materials and their properties (Chunwen *et al.* 2010)

S.No.	Composition	TEC ($\times 10^{-6}\text{K}^{-1}$)	T ($^\circ\text{C}$)	σ_e (Scm^{-1})	σ_i (Scm^{-1})	References
1	$\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$	11.8	900	300	5.93×10^{-7}	Jiang 2002
2	$\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$	11.7	800	240	-	Yamamoto <i>et al.</i> 1987
3	$\text{La}_{0.6}\text{Sr}_{0.4}\text{MnO}_3$	13	800	130	-	Kenjo & Nishiyama 1992
4	$\text{Pr}_{0.6}\text{Sr}_{0.4}\text{MnO}_3$	12	950	220	-	Ishihara <i>et al.</i> 1995
5	$\text{La}_{0.8}\text{Sr}_{0.2}\text{CoO}_3$	19.1	800	1,220	-	Tietz <i>et al.</i> 2006
6	$\text{La}_{0.6}\text{Sr}_{0.4}\text{CoO}_3$	20.5	800	1,600	0.22	Ullmann <i>et al.</i> 2000
7	$\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$	12.2	750	155	-	Simner <i>et al.</i> 2002
8	$\text{La}_{0.5}\text{Sr}_{0.5}\text{FeO}_3$	-	550	352	-	Bongio <i>et al.</i> 2005
9	$\text{La}_{0.6}\text{Sr}_{0.4}\text{FeO}_3$	16.3	800	369	0.205	Patrakeev <i>et al.</i> 2003
10	$\text{Pr}_{0.5}\text{Sr}_{0.5}\text{FeO}_3$	13.2	550	129	5.6×10^{-3}	Ullmann <i>et al.</i> 2000
11	$\text{Pr}_{0.8}\text{Sr}_{0.2}\text{FeO}_3$	12.1	800	300	-	Ullmann <i>et al.</i> 2000
12	$\text{La}_{0.7}\text{Sr}_{0.3}\text{Fe}_{0.8}\text{Ni}_{0.2}\text{O}_3$	13.7	750	78	-	Ullmann <i>et al.</i> 2000
13	$\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	20.1	600	290	-	Simner <i>et al.</i> 2002
14	$\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	15.4	600	1,050	-	Jinhua <i>et al.</i> 2007
15	$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Mn}_{0.2}\text{O}_3$	18.1	500	125	-	Tai <i>et al.</i> 1995
16	$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	21.4	800	1,400	-	Chen <i>et al.</i> 2003
17	$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	15.3	600	269	2.2×10^{-3}	Tai <i>et al.</i> 1995
18	$\text{La}_{0.4}\text{Sr}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	16.8	600	330	4×10^{-2}	Ullmann <i>et al.</i> 2000
19	$\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	14.8	800	-	-	Ishihara <i>et al.</i> 1995
20	$\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	19.3	800	87	1.5×10^{-3}	Ullmann <i>et al.</i> 2000
21	$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.9}\text{Cu}_{0.1}\text{O}_3$	19.2	700	1,000	4.4×10^{-5}	Ullmann <i>et al.</i> 2000
22	$\text{Pr}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$	12.8	800	1,400	-	Yasumoto <i>et al.</i> 2002
23	$\text{Pr}_{0.7}\text{Sr}_{0.3}\text{Co}_{0.2}\text{Mn}_{0.8}\text{O}_3$	11.1	800	76	-	Ullmann <i>et al.</i> 2000
24	$\text{Pr}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	19.69	550	950	-	Meng <i>et al.</i> 2008
25	$\text{Pr}_{0.4}\text{Sr}_{0.6}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	21.33	550	600	-	Meng <i>et al.</i> 2008
26	$\text{Pr}_{0.7}\text{Sr}_{0.3}\text{Co}_{0.9}\text{Cu}_{0.1}\text{O}_3$	-	700	1236	-	Zhu <i>et al.</i> 2008
27	$\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$	20	500	30	-	Wei Bo <i>et al.</i> 2006
28	$\text{Sm}_{0.5}\text{Sr}_{0.5}\text{CoO}_3$	20.5	700-900	>1,000	-	Ishihara <i>et al.</i> 1998
29	$\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$	11.4	800	580	-	Chiba <i>et al.</i> 1999
30	$\text{Sr}_{0.9}\text{Ce}_{0.1}\text{Fe}_{0.8}\text{Ni}_{0.2}\text{O}_3$	18.9	800	87	0.04	Ullmann <i>et al.</i> 2000

5. Choice of Interconnectors

Substituted LaCrO_3 is considered as a state-of-the-art interconnect material for high temperature solid oxide fuel cell working at 1000°C (Nesaraj 2010). Interconnector is necessary to connect several cells in series to produce a stack. A typical representation of interconnector is indicated in Fig. 3 (Steele 2001). The interconnectors are critical elements of SOFC stack, both providing electrical connections between each cell and gas flow routes for fuel and air. Fully dense structure of interconnect prevents direct mixing of fuel and oxidant gases. The main problem of the chromites is related to their rather modest catalytic activity towards hydrocarbon oxidation. Preliminary studies in this type of materials, with a Ca-substituted lanthanum chromite, $\text{La}_{0.7}\text{Ca}_{0.3}\text{CrO}_{3-\delta}$ (LCC), reveals an interesting performance under humidified pure hydrogen, approximately $110\text{mW}/\text{cm}^2$, in a thick electrolyte-based cell, at 950°C . However, the performance under methane was rather modest, i.e., $25\text{mW}/\text{cm}^2$ at 950°C , possibly due to two factors: firstly, the poor catalytic activity of simple chromites towards hydrocarbon oxidation. The second factor could be a very poor microstructure (Ruiz-morales 2008). Also, the traditional LaCrO_3 -based interconnect has difficulties such as machining, failure due to mechanical properties during cell operation, availability of matching sealants and the cost of chromium. Because of these limitations of ceramic interconnects, metal-based interconnects have been introduced in the anode supported thin film electrolyte structure which operates in the temperature range $700\text{--}800^\circ\text{C}$. The necessity to operate the ceramic fuel cell much below 1000°C (preferably below 750°C) has pushed the researchers to search for suitable metals or alloys. The metals have a number of advantages over ceramic interconnects. For more than a decade, a number of alloys have been attempted, but the major interest for development of such metallic interconnect started only when SOFC developers started using metallic interconnects for SOFC operation, preferably $< 750^\circ\text{C}$.

While doped LaCrO_3 is used as ceramic interconnects for high temperature SOFC, the Cr-based alloys and ferritic steels are the choice for metallic interconnects for SOFC working at reduced temperature. Zhu *et al.* (2007) have evaluated Fe-Co

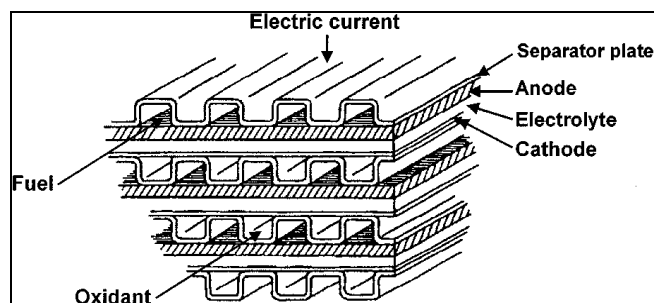


Fig. 3 Schematic representation of an interconnector (Samson Nesaraj, 2010) in SOFC

-Ni alloys as interconnect material for reduced-temperature SOFC application. Bastidas (2006) has studied variety of interconnects such as Cr-based alloys, ferritic stainless steels, austenitic stainless steels, Fe-Ni based super alloys and Ni-Fe based alloys for lower temperature SOFC. The reported properties of some alloy groups for SOFC applications are indicated in Table 2. Ceramic Fuel Cells in Australia (Yamamoto 2003) has developed a 5 kW planar type SOFC with stainless steel interconnects. However, it was found that the metallic interconnect forms a thin protective oxide which might be a most important lifetime limiting factors for SOFC. Recently, Froitzheim & Svensson (2010) have applied nano-coating of reactive elements (RE) over metallic interconnects of SOFC and they have reported that the application of such coatings can reduce the corrosion rates substantially and thus increase the lifetime of the fuel cell stack. Hence, still research work is in progress to develop alternate interconnect materials for application in SOFC working at low / reduced temperature.

6. Choice of Fuels

SOFCs require only a single partial oxidation reformer to pre-process their fuel, which can be gasoline, diesel, natural gas, etc. The nature of the emissions from the fuel cell will vary correspondingly with the fuel mix. Using hydrocarbons, for which a supply infrastructure is currently available, offers a variety of advantages over using hydrogen. First of all, hydrocarbons are much easier to transport and to store because they are in a stable state which requires no processing before use.

Table.2

Properties of some alloy groups for SOFC applications. Matrix structures are (bcc) body-centered-cubic and (fcc) face-centered cubic (Bastidas 2006)

Material	Matrix structure	Coefficients of Thermal Expansion $\times 10^{-6} \text{K}^{-1}$	Oxidation resistance	Mechanical Strength
Cr - based alloys (CrBA)	bcc	11.0-12.5	Good	High
Ferritic stainless steels (FSS)	bcc	10.5-14.0	Good	Low
Austenitic stainless steels (ASS)	Fcc	16.2-20.0	Good	High
Fe - Ni based superalloys (FeBSA)	Fcc	15.0-20.0	Good	High
Ni - Fe based superalloys (NiBSA)	Fcc	14.0-19.0	Good	High

They are also more efficient at producing energy. Methane for example yields eight electrons per molecule whereas hydrogen only yields two electrons energy. This advantage could be magnified with the use of more complex hydrocarbons, such as pentane (Boudghene & Traversa 2002). Recently, Michael *et al.* (2011) have studied the performance of SOFC with methanol and ethanol. Hence, it was found that if the operating temperature of SOFC is reduced (<500°C), liquid fuels such as methanol / ethanol can be effectively used in SOFC systems.

7. Conclusions

Different strategies adopted by the researchers for lowering the operation temperature of SOFC are dealt with in this review article. Lowering the operation temperature of SOFCs is the only option to commercialize SOFC systems in the world market. The diminishment of the operation temperature in SOFCs is essential for improving the materials compatibility, reducing energy consumption and start-up time and extending the durability. Lowering the operation temperature of SOFC systems can be carried out viably by adopting recent technological advancements like nanotechnology. In short, SOFCs with nanocomposites based cell components and metallic interconnectors can utilize liquid fuels such as methanol and ethanol for delivering power at low temperature.

Acknowledgement

ASN thanks Karunya University for promoting high temperature fuel cell based research activity in the Department of Chemistry.

References

- Abbas, G., Chaudhry, A., Raza, M.R., Liu, Q., Qin, H. and Zhu, B. (2012) Study of CuNiZnGdCe-nanocomposite anode for low temperature SOFC. *Nanoscience and Nanotechnology Letters*, 4, 389 – 393.
- Adler, S.B. (1998) Mechanism and kinetics of oxygen reduction on porous $\text{La}_{1-x}\text{Sr}_x\text{CoO}_{3-\delta}$ electrodes. *Solid State Ionics*, 111, 125 – 134.
- Bastidas (2006) High temperature corrosion of metallic interconnects in solid oxide fuel cells. *Revista De Metalurgia*, 42, 425 – 443.
- Bo, W., Zhe, L., Xiqiang, H., Jipeng, M., Xueing, S., Xianshuang, X. and Wenhui, S. (2006) Crystal structure, thermal expansion and electrical conductivity of perovskite oxides $\text{Ba}_x\text{Sr}_{1-x}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ ($0.3 \leq x \leq 0.7$). *Journal of European Ceramic Society*, 26, 2827 – 2832.
- Bongio, E.V., Black, H., Raszewski, F.C., Edwards, D., McConville, C.J. and Amarakoon, V.R.W. (2005) Microstructural and high-temperature electrical characterization of $\text{La}_{1-x}\text{Sr}_x\text{FeO}_{3-\delta}$. *Journal of Electroceramics*, 14, 193 – 198.
- Boudghene, S.A. and Traversa, E. (2002) Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews*, 6, 433–455.
- Chen, W.X., Wen, T., Nie, H. and Zheng, R. (2003) Study of $\text{Ln}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.8}\text{Mn}_{0.2}\text{O}_{3-\delta}$ (Ln = La, Gd, Sm or Nd) as the cathode materials for intermediate temperature SOFC. *Materials Research Bulletin*, 38, 1319 – 1328.
- Chiba, R., Yoshimura, F. and Sakurai, Y. (1999) An investigation of $\text{LaNi}_{1-x}\text{Fe}_x\text{O}_3$ as a cathode material for solid oxide fuel cells. *Solid State Ionics*, 124, 281 – 288.
- Datta, P. (2009) Doped LaGaO_3 based solid oxide fuel cell materials and their sintering aspects: an overview. *Materials Science Forum*, 624, 109-137.
- Dusastre, V. and Kilner, J.A. (1999) Optimisation of composite cathodes for intermediate temperature SOFC application. *Solid State Ionics*, 126, 163 – 174.
- Froitzheim, J. and Svensson, J.E. (2010) Nanocoatings for SOFC Interconnects - Mitigating Chromium Volatilization and Improving Corrosion Properties. *Materials Science Forum*, 696, 412 – 416.
- Fuentes, R.O. and Baker, R.T. (2008) Synthesis and properties of Gadolinium-doped ceria solid solutions for IT-SOFC electrolytes. *International Journal of Hydrogen Energy*, 33, 3480-3484.
- Godickemeier, M., Sasaki, K., Gauckler, L.J. and Reiss, I. (1996) Perovskite cathodes for solid oxide fuel cells based on ceria electrolytes. *Solid State Ionics*, 86-88, 691-701.
- Goodenough, J.B. (2000) Oxide-ion conductors by design. *Nature*, 404, 821 – 823.
- Gort, R.J. and Vohs, J.M. (2003) Novel SOFC anodes for the direct electrochemical oxidation of hydrocarbons. *Journal of Catalysis*, 216, 477–486.
- Haanappel, V.A.C., Mertens, J. and Mai, A. (2006) Performance Improvement of $(\text{La,Sr})\text{MnO}_3$ and $(\text{La,Sr})(\text{Co,Fe})\text{O}_3$ -Type Anode-Supported SOFCs. *Journal of Fuel Cell Science and Technology*, 3, 263 – 270.
- Heuveln van, F.H., Bouwmeester, H.J.M. and Berkel van F.P.F (1997) Electrode properties of Sr-doped LaMnO_3 on yttria-stabilized zirconia I: Three-phase boundary area. *Journal of Electrochemical Society*, 144, 126-133.
- Holtappels, P., Bradley, J., Irvine, J.T.S., Kaiserm A. and Mogensen, M. (2001) Electrochemical characterization of ceramic SOFC anodes. *Journal of Electrochem Society*, 148, A 923 – A 929.
- Huang, K., Feng, M., Goodenough, J.B. and Schmerling, M. (1996) Characterization of Sr-Doped LaMnO_3 and LaCoO_3 as Cathode Materials for a Doped LaGaO_3 Ceramic Fuel Cell. *Journal of Electrochemical Society*, 143, 3630 – 3636.
- Inaba, H. and Tagawa, H. (1996) Ceria-based solid electrolyte: review. *Solid State Ionics*, 83, 1 – 16.
- Irvine, J.T.S. and Sauvet, A. (2001) Improved oxidation of hydrocarbons with new electrodes in high temperature fuel cells. *Fuel Cells*, 1, 205 – 210.
- Ishihara, T., Honda, M., Shibayama, T., Minami, H., Nishiguchi, H. and Takita, V. (1998) Intermediate temperature solid oxide fuel cells using a new LaGaO_3 based oxide ion conductor - I. Doped SmCoO_3 as a new cathode material. *Journal of Electrochemical Society*, 145, 3177 – 3183.
- Ishihara, T., Kudo, T., Matsuda, H. and Takita, Y. (1994) Doped perovskite oxide, PrMnO_3 , as a new cathode for solid-oxide fuel cells that decrease the operating temperature. *Journal of American Ceramic Society*, 77, 1682 – 1684.
- Ishihara, T., Kudo, T., Matsuda, H. and Takita, Y. (1995) Doped PrMnO_3 Perovskite Oxide as a new cathode of solid oxide fuel cells for low temperature operation. *Journal Electrochemical Society*, 142, 1519 – 1524.
- Ishihara, T., Matsuda, H. and Takita, Y. (1994) Doped LaGaO_3 perovskite type oxide as a new oxide ionic conductor. *Journal of American Chemical Society*, 116, 3801 – 3803.
- Jiang, S.P. (2002) A comparison of O_2 reduction reactions on porous $(\text{La,Sr})\text{MnO}_3$ and $(\text{La,Sr})(\text{Co,Fe})\text{O}_3$ electrodes. *Solid State Ionics*, 146, 1-22.
- Jiang, S.P., Love, J.G. and Ramprakash, Y. (2002) Electrode behaviour at $(\text{La,Sr})\text{MnO}_3/\text{Y}_2\text{O}_3\text{-ZrO}_2$ interface by electrochemical impedance spectroscopy. *Journal of Power Sources*, 110, 201 – 208.
- Jinhua, P., Sun, K., Zhang, N., Chen, X., Xu, S. and Zhou, D. (2007) Preparation and characterization of $\text{Pr}_{1-x}\text{Sr}_x\text{FeO}_3$ cathode material for intermediate temperature solid oxide fuel cells. *Journal of Power Sources*, 172, 633-640.
- Kamruddin, M., Ajitkumar, P.K., Nithya, R., Tyagi, A.K. and Raj, B. (2004) Synthesis of nanocrystalline ceria by thermal

- decomposition and soft-chemistry methods. *Scripta Materialia*, 50, 417 – 422.
- Kenjo, T. and Nishiya, M. (1992) LaMnO₃ air cathodes containing ZrO₂ electrolyte for high temperature solid oxide fuel cells. *Solid State Ionics*, 57, 295 – 302.
- Kesapragada, S.V., Bhaduri, S.B., Bhaduri, S. and Singh, P. (2003) Densification of LSGM electrolytes using activated microwave sintering. *Journal of Power Sources*, 124, 499 – 504.
- Ketzial, J.J. and Nesaraj, A.S. (2010) Preparation of nano-ceramic composite electrolyte materials for low temperature solid oxide fuel cell application. *International Journal of Nanoscience and Nanotechnology*, 6, 179 – 190.
- Kharlamova, T., Smirnova, A., Sadykov, V., Zarubina, V., Krieger, T., Batuev, L., Ishchenko, A., Salanov, A. and Uvarov, N. (2008) Intermediate temperature solid oxide fuel cells based on nano-composite cathode structures. *ECS Transactions*, 13, 275 – 284.
- Kilbride, P. (1996) Preparation and properties of small diameter tubular solid oxide fuel cells for rapid start-up. *Journal of Power Sources*, 61, 167 – 171.
- Kumar, M., Nesaraj, A.S., Arul Raj, I. and Pattabiraman, R. (2004) Synthesis and characterization of La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-δ} electrolyte for Intermediate Temperature Solid Oxide Fuel Cells. *Ionics*, 10, 93 – 98.
- Kuščer, D., Holc, J., Hrovat, M., Bernik, S., Samardžija Z. and Kolar, D. (1995) Interactions between a thick film LaMnO₃ cathode and YSZ SOFC electrolyte during high temperature ageing. *Solid State Ionics*, 78, 79 – 85.
- Lee, J.H., Kim, K.M., Son, J.W., Kim, J.S., Kim, B.K., Lee, H.W. and Moon, J.H. (2012) An investigation of the interfacial stability between the anode and electrolyte layer of LSGM-based SOFCs. *Journal of Materials Science and Engineering*, 42, 1866 – 1871.
- Liu, W., Liu, Y., Li, B., Sparks, T.D., Wei, X. and Pan, W. (2010) Ceria (Sm³⁺, Nd³⁺) / carbonates composite electrolytes with high electrical conductivity at low temperature. *Composites Science and Technology*, 70, 181–185.
- Lokurlu, A., Grube, T., Hohlein, B. and Stolten, D. (2003) Fuel cells for mobile and stationary applications – cost analysis for combined heat and power stations on the basis of fuel cells. *International Journal of Hydrogen Energy*, 28, 703–711.
- Lu, X.C. and Zhu, J.H. (2008) Effect of Sr and Mg Doping on the property and performance of the La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-δ} Electrolyte. *Journal of Electrochemical Society*, 155, B494-B503.
- Matović, B., Bošković, S., Živković, L., Vlajić, M.D. and Krstić, V.D. (2005) Lattice parameters of Gd-doped ceria electrolytes. *Materials Science Forum*, 494, 175 – 180.
- Meng, X.W., Lu, S.Q., Wei, T. and Zhang, Y.L. (2008) Characterization of Pr_{1-x}Sr_xCo_{0.8}Fe_{0.2}O_{3-δ} (0.2≤x≤0.6) cathode materials for intermediate - temperature solid oxide fuel cells. *Journal of Power Sources*, 183, 581 – 585.
- Menzler, N.H., Tietz, F. and Uhlenbruck, S. (2010) Materials and manufacturing technologies for solid oxide fuel cells. *Journal of Materials Science*, 45, 3109–3135.
- Mogensen, M., Sammes, N.M. and Tompsett, G.A. (2000) Physical, chemical and electrochemical properties of pure and doped ceria. *Solid State Ionics*, 129, 63 – 94.
- Nesaraj, A.S. (2010) Recent developments in solid oxide fuel cell technology – A review. *Journal of Scientific and Industrial Research* 69:169 – 176.
- Nesaraj, A.S., Arul Raj, I. and Pattabiraman, R. (2007) Synthesis and characterization of LaCoO₃ based cathode and its chemical compatibility with CeO₂ based electrolyte in intermediate temperature solid oxide fuel cells (ITSOFC). *Indian Journal of Chemical Technology*, 14, 154 – 160.
- Nesaraj, A.S., Arul Raj, I. and Pattabiraman, R. (2010) Preparation and characterization of ceria based electrolytes for intermediate temperature solid oxide fuel cells (IT-SOFC). *Journal of Iranian Chemical Society*, 7, 564 – 584.
- Nomura, K., Mizutani, Y., Kawai, M., Nakamura, Y. and Yamamoto, O. (2000) Aging and Raman scattering study of scandia and yttria doped zirconia. *Solid State Ionics*, 132, 235 – 239.
- Ormerod, R.M. (1999) Internal reforming in solid oxide fuel cells. *Studies in Surface Science and Catalysis*, 22, 35 – 46.
- Park, S., Gorte, R.J. and Vohs, J.M. (2000) Applications of heterogeneous catalysis in the direct oxidation of hydrocarbons in a solid-oxide fuel cell. *Applied Catalysis A: General*, 200, 55–61.
- Patrakeev, M.V., Bahteeva, J.A., Mitberg, E.B., Leonidov, I.A., Kozhevnikov, V.L. and Poepelmeier, K.R. (2003) Electron/hole and ion transport in La_{1-x}Sr_xFeO_{3-δ}. *Journal of Solid State Chemistry*, 172, 219 – 231.
- Petric, A., Huang, P. and Tietz, F. (2000) Evaluation of La-Sr-Co-Fe-O perovskite for solid oxide fuel cells and gas separation membranes. *Solid State Ionics*, 135, 719 – 725.
- Pomfret, M.B., Steinhurst, D.A. and Owrutsky, J.C. (2011) Methanol and ethanol fuels in solid oxide fuel cells: A thermal imaging study of carbon deposition. *Energy Fuels*, 25, 2633–2642.
- Ralph, J.M., Rossignol, C. and Kumar, R. (2003) Cathode materials for reduced-temperature SOFCs. *Journal of Electrochemical Society*, 150, A 1518 -A 1522.
- Ralph, J.M., Schoeler, A.C. and Krumpelt, M. (2001) Materials for lower temperature solid oxide fuel cells. *Journal of Materials Science*, 36, 1161 – 1172.
- Rambabu, B., Ghosh, S., Zhao, W. and Jena, H. (2006) Innovative processing of dense LSGM electrolytes for IT-SOFCs. *Journal of Power Sources*, 159, 21 – 28.
- Rampon R, Toma FL, Bertrand G and Coddet C (2006) Liquid plasma sprayed coatings of yttria-stabilized zirconia for SOFC electrolytes. *Journal of Thermal Spray Technology* 15: 682-688.
- Raza, R., Abbas, G., Liu, Q., Patel, I. and Zhu, B. (2012) La_{0.3}Sr_{0.2}Mn_{0.1}Zn_{0.4} oxide-Sm_{0.2}Ce_{0.8}O_{1.9} (LSMZ-SDC) nanocomposite cathode for low temperature SOFCs. *Journal of Nanoscience and Nanotechnology*, 12, 4994-4997.
- Raza, R., Fransson, T. and Zhu, B. (2010) Zn_{0.6}Fe_{0.1}Cu_{0.3}/GDC composite anode for low temperature SOFC (300-600)°C. *Journal of Fuel Cell Science and Technology*, 8, 031010 – 031014.
- Raza, R., Gao, Z., Singh, T., Singh, G., Li, S. and Zhu, B. (2011) LiAlO₂-LiNaCO₃ composite electrolyte for solid oxide fuel cells. *Journal of Nanoscience and Nanotechnology*, 11, 5402 – 5407.
- Raza, R., Liu, Q., Nisar, J., Wang, X., Ma, Y. and Zhu, B. (2011). ZnO/NiO nanocomposite electrode for low temperature solid oxide fuel cells. *Electrochemistry Communication*, 13, 917-920.
- Ruiz-morales, J.C., Canales-vázquez, J., Lincke, H., Peña-martínez, J., Marrero-lópez, D., Pérez-coll, D., Irvine, J.T.S. and Núñez, P. (2008) Potential electrode materials for symmetrical solid oxide fuel cells. *Boletín de la Sociedad Española de Cerámica y Vidrio*, 47, 183 – 188.
- Simner, S.P., Bonnett, J.F., Canfield, N.L., Meinhardt, K.D., Sprinkle, V.L. and Stevenson, J.W. (2002) Optimized lanathanum ferrite-based cathodes for anode-supported SOFCs. *Electrochemical and Solid-State Letters*, 5, A173-A175.
- Simner SP, Shelton JP, Anderson MD and Stevenson JW (2003) Interaction between La(Sr)FeO₃ SOFC cathode and YSZ electrolyte. *Solid State Ionics* 161:11 – 18.
- Singhal, S.C. and Mizusaki, J. (2005) *Solid oxide fuel cells* – IX (The Electrochemical Society, Inc, New Jersey), Pennington, NJ, USA.
- Slater, P.R. and Irvine, J.T.S. (1999) Niobium based tetragonal tungsten bronzes as potential anodes for solid oxide fuel cells: synthesis and electrical characterization. *Solid State Ionics*, 120, 125 – 134.
- Steele, B.C.H. (1996) Survey of materials selection for ceramic fuel cells II. Cathodes and anodes. *Solid State Ionics*, 86 – 88, 1223 – 1234.
- Steele, B.C.H. (2000) Appraisal of CGO electrolytes for IT-SOFC operating at 500 °C. *Solid State Ionics*, 129, 95-110.
- Steele, B.C.H. (2001) Materials science and engineering: The enabling technology for the commercialization of fuel cell systems. *Journal of Materials Science*, 36, 1053 – 1068.
- Sun, C., Hui, R. and Roller, J. (2010) Cathode materials for solid oxide fuel cells: a review. *Journal of Solid State Electrochemistry*, 14, 1125-1144.
- Sun, C. and Stimming, U. (2007) Recent anode advances in solid oxide fuel cells. *Journal of Power Sources*, 171, 247 – 250.
- Tai, L.W., Nasrallah, M.M., Anderson, H.U., Sparlin, D.M. and Sehnlin, S.R. (1995) Structure and electrical properties of La_{1-x}Sr_xCo_{1-y}Fe_yO₃.

- Part 1. The system. $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{1-y}\text{Fe}_y\text{O}_3$. *Solid State Ionics*, 76, 259 – 271.
- Taimatsu, H., Wada, K., Kaneko, H. and Yamamura, H. (1992) Mechanism of reaction between lanthanum manganite and yttria-stabilized zirconia. *Journal of American Ceramic Society*, 75, 401 – 405.
- Takeda, Y., Kanno, R., Noda, M. and Yamamoto, O. (1986) Perovskite electrolytes for high temperature solid electrolyte fuel cells. *Bulletin of the Institute for Chemical Research*, 64, 157 – 169.
- Tao, S. and Irvine, J.T.S. (2003) A redox-stable efficient anode for solid-oxide fuel cells. *Nature Materials*, 2, 320 – 323.
- Tietz, F., Arul Raj, I., Zahid, M. and Stöver, D. (2006) Electrical conductivity and thermal expansion of $\text{La}_{0.8}\text{Sr}_{0.2}(\text{Mn,Fe,Co})\text{O}_{3-\delta}$ perovskites. *Solid State Ionics*, 177, 1753 – 1756.
- Tu, H.Y., Takeda, Y., Imanishi, N. and Yamamoto, O. (1997) $\text{Ln}_{1-x}\text{Sr}_x\text{CoO}_3$ (Ln= Sm, Dy) for the electrode of solid oxide fuel cells. *Solid State Ionics*, 100, 283 – 288.
- Uhlenbruck, S., Moskalewicz, T., Jordan, N., Penkalla, H.J. and Buchkremer, H.P. (2009) Element interdiffusion at electrolyte-cathode interfaces in ceramic high-temperature fuel cells. *Solid State Ionics*, 180, 418 – 423.
- Ullmann, H., Trofimenko, N., Tietz, F., Stöver, D. and Ahmad-Khanlou, A. (2000) Correlation between thermal expansion and oxide ion transport in mixed conducting perovskite-type oxides for SOFC cathodes. *Solid State Ionics*, 138, 79 – 90.
- Van Doorn, R.H.E. and Burggraaf, A.J. (2000) Structural aspects of the ionic conductivity of $\text{La}_{1-x}\text{Sr}_x\text{CoO}_{3-\delta}$. *Solid State Ionics*, 128, 65 – 78.
- Van Roosmalen, J.A.M. and Cordfunke, E.H.P. (1992) Chemical reactivity and interdiffusion of $(\text{La,Sr})\text{MnO}_3$ and $(\text{Zr,Y})\text{O}_2$ solid oxide fuel cell cathode and electrolyte materials. *Solid State Ionics*, 52, 303-312.
- Wang, Y., Mori, T., Drennan, J., Li, J.G. and Yajima, Y. (2004) Low-temperature synthesis of 10 mol% Gd_2O_3 -doped CeO_2 ceramics and its characterization. *Journal of Ceramic Society of Japan*, 112, S 41 – S 45.
- Wang, Y., Mori, R., Li, J.G. and Yajima, Y. (2003) Low temperature fabrication and electrical property of 10 mol% Sm_2O_3 – doped CeO_2 ceramics. *Science and Technology of Advanced Materials*, 4, 229 – 238.
- Wiik, K., Schmidt, C.R., Faaland, S., Shamsili, S., Einarsrud, M.A. and Grande, T. (1999) Reactions between strontium-substituted lanthanum manganite and yttria stabilized zirconia. I. Powder samples. *Journal of American Ceramic Society*, 82, 721 – 728.
- Yamamoto, O. (2000) Solid oxide fuel cells: fundamental aspects and prospects. *Electrochimica Acta*, 45, 2423 – 2435.
- Yamamoto, O., Takeda, Y., Kanno, R. and Noda, M. (1987) Perovskite-type oxides as oxygen electrodes for high temperature oxide fuel cells. *Solid State Ionics*, 22, 241 – 246.
- Yan, S., Almeida Veronica Alexandra, B. and François, G. (2011) Preparation of nanocomposite GDC/LSCF cathode material for IT-SOFC by induction plasma spraying. *Journal of Thermal Spray Technology*, 20, 145 – 153.
- Yang Nai-Tao, Meng Xiu-Xia, Tan Xiao-Yao and Li Zheng-Min. (2006) Anode of intermediate temperature solid oxide fuel cells. *Journal of Inorganic Materials* 21: 409-414.
- Yasumoto, K., Inagaki, Y., Shiono, M. and Dokiya, M. (2002) An $(\text{La,Sr})(\text{Co,Cu})\text{O}_{3-\delta}$ cathode for reduced temperature SOFCs. *Solid State Ionics*, 148, 545 – 549.
- Ying, Ma. (2009) Ceria-based nanocomposite electrolyte for low temperature solid oxide fuel cells. Licentiate thesis. Rolyal Institute of Technology, Stockholm.
- Zang, T.S. Ma, J. Chan, S.H. Hing, P. and Kilner, J.A. (2004) Intermediate temperature conductivity of ceria-based solid solutions as a function of gadolinia and silica contents. *Solid State Sciences*, 5, 565 – 572.
- Zhu, B. (2006) Next generation fuel cell R&D. *International Journal of Energy Research*, 30, 895-903.
- Zhu, C.J. Liu, X.M. Xu, D. Yan, D.T. Wang, D.Y. and Su, W.H. (2008) Preparation and performance of $\text{Pr}_{0.7}\text{Sr}_{0.3}\text{Co}_{1-y}\text{Cu}_y\text{O}_{3-\delta}$ as cathode material of IT-SOFCs. *Solid State Ionics*, 179, 1470 – 1473.
- Zhu, J.H. Geng, S.J. and Ballard, D.A. (2007) Evaluation of several low thermal expansion Fe-Co-Ni alloys as interconnect for reduced-temperature solid oxide fuel cell. *International Journal of Hydrogen Energy*, 32, 3682 – 3688.
- Zhu, W.Z. and Deevi, S.C. (2003) A review on the status of anode materials for solid oxide fuel cells. *Materials Science and Engineering*, A 362, 228 – 239.