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Investigation on cobalt-free anodes and cathodes for solid oxide fuel cell

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Abstract

Generally, global warming raised by greenhouse gas emissions is a great threat. New technologies are evolving that can reduce carbon emissions significantly, one of them is fuel cell. Fuel cell combines hydrogen and oxygen to produce electricity through an electrochemical reaction. Because the by products are only water and heat, there are no carbon emissions and as generation continues to shift away from coal and towards natural gas, fuel cells will not only dramatically reduce CO_2 emissions but also combine with power plants burning a less carbon-intensive fuel. Cathodes that have Cobalt are known for their ability to act under high-temperature conditions in solid oxide fuel cells (SOFCs). In this paper, the investigation of results and effects are presented for various studies on the cobalt-free anode and cobalt-free nanofiber cathode development. The polarization resistance of SOFC cathodes, which is one of the important characters in determining the cathodic performance, revealed the importance of nanofiber for this process in this investigation.

Keywords: cobalt-free, nanofiber, fuel cells, cathodes.

1. Introduction

Fuel cell's prime advantage is that it converts the chemical energy of fuels directly into electrical energy. As a result, fuel cells exhibit much higher efficiency unlike other energy conversion devices going through multiple conversion steps. The direct energy conversion in fuel cells occurs at triple-phase boundaries, so-called TPBs where fuels, electrodes, and electrolytes meet simultaneously [1]. Therefore, augmenting domains of TPBs leads to an enlargement of the reaction zone, which is directly linked to the decrease in activation loss. As one device for reducing carbon emissions and use energy efficiently, solid oxide fuel cells (SOFCs) have absorbed wide attention [2].

SOFC is one of the most promising energy conversion devices because of being high efficiency, environmental friendliness, easy scale up and economic competitiveness for fuel cell. However, the required high operating temperature (800–1000 °C) to attain the reasonable ionic conductivity of electrolyte materials induces many practical difficulties such as long-term stability, sealing, material selection, and slow start-stop cycle, limiting their expeditious commercialization [3]. Fabrication of a high-performance cathode has been critical for development of SOFCs operating at reduced temperatures [4].

Recently, nanofibers have attracted significant attention as an alternative electrode structure because of their high specific surface area, facile gas diffusion, and continuous charge transport path with high aspect ratio. Generally, the low-temperature solid oxide fuel cells cause to increases reducing of the cell performance because of losses in the SOFCs. Despite their superior structural properties, nanofiber-based SOFCs have been rarely reported with few exceptions: Lee et al. reported that $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$-$Gd_{0.1}Ce_{0.9}O_{1.95}$ based low-temperature solid oxide fuel cells with nanocomposite anode functional layers showed high current density at 2 W/cm^{-2} at 550 °C conditions [5]. Chen et al. reported performance of the fabrication of hollow nanofibers as cathodes for high-performance and durable intermediate-temperature fuel cells (ITFCs) and found the single cells with intact hollow fiber cathodes showed high performance, peak power density of 1.11 W cm^{-2}, and excellent stability, 0.95 W cm^{-2} at 0.6 V for 260 h, at 550 °C when using humidified H_2 as fuel and ambient air as oxidant [4]. Zhi et al. reported performance of the fuel cell with the monolithic lanthanum strontium cobalt ferrite (LSCF) nanofiber cathode exhibits a power density of 0.90 W cm^{-2} at 1.9 A cm^{-2} at 750 ^{o}C. They showed that when improved infiltration of 20 wt% of gadolinia-doped ceria (GDC) into the LSCF

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nanofiber, the fuel cell with the LSCF–20% GDC composite cathode showed a power density of 1.07 W cm^{-2} at 1.9 A cm^{-2} at 750 °C [3].

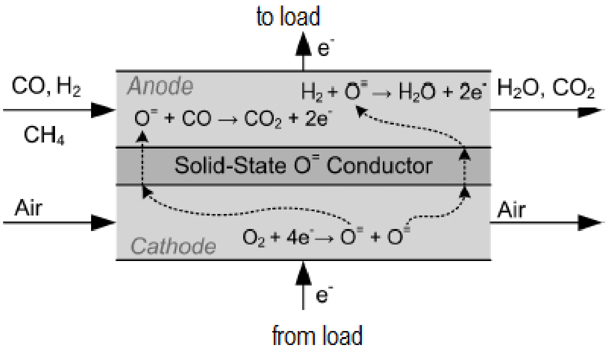

Figure 1. Schematic of reactions on a solid oxide fuel cell.

Among the various fuel cells, ceramic fuel cells have various attractive advantages, including the potential to directly use hydrocarbon fuels, such as fuel flexibility, and do not require high efficiency and precious metal catalysts [6-9]. However, the itria stabilized zirconia based solid oxide fuel cell (SOFCs) which is first generation results in high costs and material compatibility difficulties at high operating temperatures, 700°- 1000 °C [10]. Second generation of SOFCs based on newer oxygen ion conductive electrolytes (such as samarium doped ceria) (SDC)) reduced operating temperatures to about 600 °C [11-12]. Third generation which is nanostructured SOFCs rare earths such as Eu or Ru and ultra-fine multilayer electrolytes or core shell nanofiber composite electrodes from 450-600 °C, but performance drops rapidly and falls temperature because of high activation energy with oxygen ion conduction [13-14]. The performance of SOFC generations is shown in Figure 2 as the power density versus temperature. Performance of power density, also means current, on first-generation (YSZ-based), second-generation (SDC, GDC, and LSGM-based) and third generation (PCFCs vs.) compare with each other on figure 2. PCFC shows good promise in the intermediate and low-temperature regime (350° to 600°C) [6].

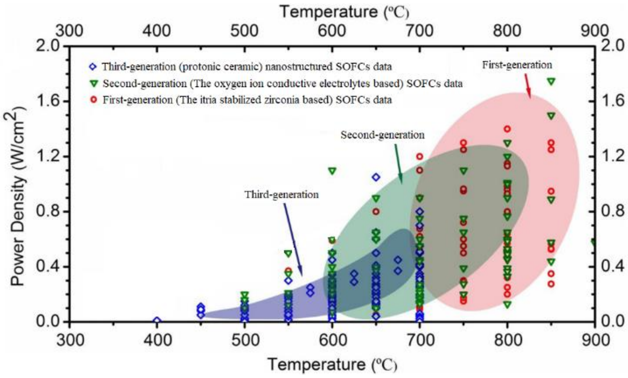

Figure 2. SOFCs performance of generations types.

2. 2. Cobalt-free anode materials of SOFCs

Solid oxide fuel cell (SOFC) anode materials has been changed rapidly reduction of the operating temperature and improvement of the performance. SOFCs are mostly constructed by using ceramic materials due to it is function optimally at high temperatures and operating temperature range of the electrolyte. High temperatures causes significant thermal stresses and effect of SOFC efficient with some metallic. fuel cell performance can be calculated by using the Nernst equation added losses of actual cell by from various electrochemical processes in shown as following equation.

$$V = E_0 - IR - \eta_{cathods} - \eta_{anods} \quad (1)$$

where E_0 is the Nernst potential of the reactants, R is the ohmic resistance, I is the current through the cell, and $\eta_{cathode}$ and η_{anode} are polarization losses of the cathodic and anodic respectively.

Anode materials are to function efficiently some important criteria should be met:

- ✓ Thermal stability
- ✓ High electronic and ionic conductivity
- ✓ Catalytic activity for fuel oxidation and combustion
- ✓ Stability on successive reducing and oxidizing cycles
- ✓ Chemical stability to contacting components
- ✓ Matched thermal expansion coefficient to contacting components

The electrolyte and operating temperature are important design of anode materials. must with which the material will operate as the thermal expansion coefficient (TEC) and chemical reactivity are electrolyte dependent. Different anode materials can be used for SOFCs. Comparison of the ionic conductivities of various oxide ion conducting electrolytes are showed Figure 3 by Kharton et al in 2004 [16].

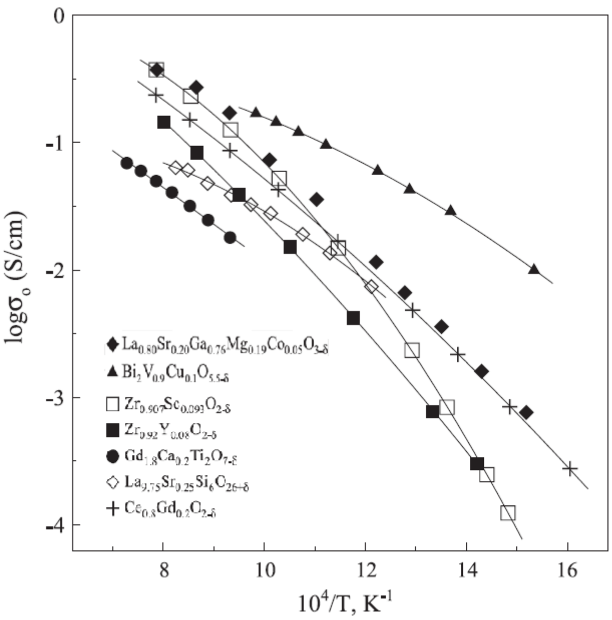

Figure 2. Oxygen ionic conductivity of various solid–electrolyte materials [16].

When designing an SOFC, there are excess of different factors to take into consideration anode material. Main considerations are electronic conduction, production of highly conducting and redox stable materials under SOFC operating conditions. There are three main categories of SOFCs anode materials which are metal-fluorite cermets, Perovskites-based and other anode materials.

Fluorite structured materials were used as both anode and cathode. These materials are optimized with usually added to a metal oxide. A metal oxide can be used to enhance the anode and increase the triple phase boundary for escape from many problems of related pure metal anodes. fluorite structured materials have focused on the based cermets, transition metal and ceria/zirconia anode materials. A cermet consisting of Ni/Yttrium stabilized zirconia, Ni-CeO_2 / Yttrium stabilized zirconia has many of the properties required for an efficient anode material. But they have multiple problems to effective implementation such as prone to carbon deposition or coking when using hydrocarbon fuels, Sulphur poisoning, nickel agglomeration upon prolonged usage and is not redox stable [17]. Samarium doped ceria with a volume percent of 50 to 60% of nickel was required for the cermet to meet requirements for anode materials based on electrical conductivity data and thermal expansion coefficient [18].

Perovskite materials have been alternative SOFC anode research. much of the research has focused on the development of the properties materials which are the lanthanum doped strontium titanate,
Yttrium doped strontium titanate and Perovskite

anode ($La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_{3-\delta}$).

The tungsten bronze, the pyrochlore structured materials and some metal vanadates, have been investigated as alternative anode materials without much success.

3. 3. Cobalt-free cathodes

Generally, the traditional SOFCs using oxygen-ion electrolyte which is work at high temperatures, leading to many technical problems. So, many studies efforts have been made to develop new architectures and materials for SOFC cathodes operated at low or intermediate temperature. Cobalt-containing cathodes have some problem that are high thermal expansion coefficient, cobalt evaporation and high price show although they relatively good performance at hydrogen fueled SOFCs [19-20]. So, cobalt-free cathodes can be used to develop high-performance.

The construction of nanofiber cathode has been proposed by some researchers. Li et al. are investigated surface exchange kinetics of Ruddlesden-Popper (R-P) phase lanthanum nickelates upon Mn doping (LNO) as an intermediate temperature solid oxide fuel cells cathode. They found that Mn-doped lanthanum nickel is excellent cobalt-free cathode material for intermediate temperature solid oxide fuel cells also they showed that the apparent activation energy for the porous Sr20Mn10 electrode is calculated as 1.57 eV as above in the literature [21]. The nickel LNF and LNO cathode materials coupled with the nanofiber structure is a promising cathode system for H-SOFCs. When compared to the prevalent Co-based perovskite cathodes, lanthanum nickelates possess mild thermal expansion coefficients which matches better with current electrolytes such as $La_{1-x}Sr_{x}Ga_{1-y}Mg_{y}O_{3-\delta}$ and cause no concerns associated with Co volatility, thus promising advantages in the dimensional and chemical stability during long-term operation [22]. Research on cobalt-free cathodes have been conducted over the past five years, with strontium ferrite oxide, $SrFeO_{3-\delta}$, as the preferred subject [23]. It should be note Strontium is a gray/silvery metal that is softer than Ca. It is even more reactive in water, and reacts on contact to produce $Sr(OH)_2$ and hydrogen gas [24].

Tang et al. [15] reported that nanofiber-structured $La_2NiO_{4+\delta}$ (LNO) and $LaNi_{0.6}Fe_{0.4}O_{3-\delta}$ (LNF) cathodes which are produced by an electrospinning technique for proton-conducting solid oxide fuel cells (H-SOFCs) to develop high-performance cobalt-free cathodes for H-SOFCs. they found that the structure of fuel cell performance was power density of 508 $mWcm^{-2}$ and 551 $mWcm^{-2}$ for LNO and LNF cathode cell at 700 °C, respectively.

Zhou et al. presented results of the cubic perovskite oxide, $SrFe_{0.9}Nb_{0.1}O_{3-\delta}$ (SFN) as cobalt-free cathode for intermediate-temperature solid oxide fuel cells. They found a maximum power density of 407 $mWcm^{-2}$ with the electrolyte $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC) at 800 ^{0}C [25]. Jiang et al. prepared cobalt-free cathodes from Sr $Nb_{0.1}Fe_{0.9}O_{3-\delta}$ (SNF) and evaluated its effect on the electrochemical performance of the fuel cell. They obtained the peak power density of the cell has 1403, 1074, and 841 $mWcm^{-2}$ at 800, 750,
and 700 8C, respectively [26].

After getting result from processing methods, powder cathode can be prepared different from by the conventional combustion method. Nanofiber cathode has the rod-like structure and three-dimensional network structure so it can be providing efficient diffusion pathways for gas transportation. Also, well electro-catalytic activity and much three-phase reaction sites can be obtained in nanofiber structured cathode. for cobalt-free materials, the performance enhancement of H-SOFCs can be obtained by using nanofabrication techniques.

4. Results and discussion

Cobalt-based cathodes have showed higher electro-catalytic performance than that of the conventional the Strontium-doped lanthanum manganite cathodes. These cobalt-based cathodes often come upon some problems such as high thermal expansion coefficient, poor stability and high cost of cobalt element. So, the cobalt-free cathodes with good electro-catalytic activity for SOFCs have being improved by a lot of researcher. The cubic perovskite oxide, $SrFe_{0.9}Nb_{0.1}O_{3-\delta}$ (SFN) with pure H_2 as cobalt-free cathode for intermediate-temperature solid oxide fuel cells is highest power density, 1403 mW/cm^2 in Table1. This designates that the SFN oxide has a high electro-catalytic activity and it shows a promising candidate as a cathode material for SOFCs.

Table 1. Fuel cell performance of cobalt-free anode and cathodes.

Anode composition		**Electrolyte/ Cathode**	**Temperature (ºC)**	**Fuel**	**Maximum Power Density (mW/cm ^{2})**	**Reference**
metal- fluorite cermet based	Ni-$Sc_{0.1}Ce_{0.01}Zr_{0.89}O_{1.95}$	YSZ/LSM-YSZ	800	H_2O saturated H_2	980	27
	$Fe_{0.1}Ni_{0.9}$ /YSZ	YSZ/LSM-YSZ	800	3% H_2O-H_2	960	28
	Cu-CeO_2 -YSZ/Ni-ScSZ	ScSZ/PCM	800	H_2/O_2 50%, H_2O-C_2H_5OH/O_2	604, 438	9
	2 wt% $Gd_{0.2}C_{0.8}O_2$-Ni-ScSZ	ScSZ/PCM	800	3% H_2O-H_2 /O_2	602	30
	10% Cu- 90% $Ce_{0.8}Zr_{0.2}O_2$ /Ni-CeO_2 /Ni-YSZ	ScSZ/PCM	800	H_2/O_2 50%, H_2O-C_2H_5OH/O_2	601, 519	31
	25 wt% Ni- 10wt% CeO_2 – 65 wt% YSZ	YSZ/Pt	800	3% H_2O-H_2	530	32
	Ni-YSZ	8YSZ/LSM-8YSZ	850	3% H_2O-NH_3, 3% H_2O-H_2	526, 530	33
	10% Cu- 90% CeO_2 /Ni-YSZ	ScSZ/PCM	800	H_2/O_2 50%, H_2O-C_2H_5OH/O_2	520, 410	34
	NiO-YSZ	8YSZ/LSM-8YSZ	800	3% H_2O-H_2	500	35
	Ni–$Gd_{0.1}Ce_{0.9}O_{1.95}$	GDC/Bi2V0.9Cu0.1O5.35 –Ag	800	H_2 (3% H_2O)	443	36
	CuO-SDC-CeO_2	YSZ/LSM-YSZ	800	H_2, C_3H_7OH	350, 220	37
	25% Cu- 75% CeO_2 /Ni-YSZ	ScSZ/PCM	800	H_2/O_2 50%, H_2O-C_2H_5OH/O_2	450, 380	38
	Ni-ScSZ	ScSZ/PCM	800	3% H_2O-H_2/O_2	466	40
	NiO-$BaZr_{0.1}Ce_{0.7}Y_{0.2}O_{3-\delta}$	LNO / LNF	700		508, 551	15
Sr -based	5% CeO_2 –0.5% Pd–45% $La_{0.3}Sr_{0.7}TiO_3$ –65% $Y_{0.08}Zr_{0.92}O_2$	YSZ/LSF-YSZ	800	Humidified H_2	780	41
	YSZ–Ni	$SrNb_{0.1}Fe_{0.9}O_{3-\delta}$ (SNF)	800, 750, 700	Pure H_2	1403, 1074, 841	26
	NiO-SDC	$SrFe_{0.9}Nb_{0.1}O_{3-\delta}$ (SFN)	800	dry H_2	407	25
$L_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ -based	2wt% Ag–6wt% Ni–32% $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ -60%$Y_{0.08}Zr_{0.92}O_2$	YSZ/LSM	850	Dry H_2, Dry CH_4	1302, 769	42
	37wt% (NiO-$La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$)–63wt% $Y_{0.08}Zr_{0.92}O_2$	YSZ/LSM	800	Dry H_2, Dry CH_4	1151, 704	43
	Ni -$Sm_{0.2}Ce_{0.8}O_2$ –$La_{0.75}Sr_{0.25}Cr_{0.5}Fe_{0.5}O_3$ –$Y_{0.08}Zr_{0.92}O_2$	YSZ/LSM-SDC	800	Dry H_2, Dry CH_4 Dry C_2H_5OH	960, 744, 406	44
	8.9wt% Ni–5.8%wt CeO_2 –$La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$	YSZ/LSM	800	Dry H_2, Dry CH_4	948 197	45
	35% $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ –65% $Y_{0.08}Zr_{0.92}O_2$ YSZ/LSM	YSZ/LSM	850	Dry H_2, Dry CH_4	567 561	46
	$La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ –$Gd_{0.2}Ce_{0.8}O_2$	YSZ/LSM-YSZ	800	Humidified H_2 Humidified CH_4	419 158	43
	0.5% Pd–5% CeO_2 –45% $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ –$Y_{0.08}Zr_{0.92}O_2$	YSZ/LSF-YSZ	700	Humidified H_2	520	47
	Cu–$La_{0.7}Sr_{0.3}Cr_{0.5}Mn_{0.5}O_3$ –$Y_{0.08}Zr_{0.92}O$	Ni-YSZ/Ni-ScSZ/ScSZ/PCM	800	H_2 2:1 mixture CH_3CH_2OH-H_2O	534 384	48

Abbreviations: YSZ:Yttrium stabilised zirconia, LSM: Strontium-doped lanthanum manganite, ScSZ: Scandia-stabilized zirconia PCM: Proton-conducting membrane, SDC: Samarium-doped ceria, LSF: Strontium-doped lanthanum metal.

Cobalt-free perovskites are suggested for use as cathode material, seeing their excellent long-term stability and compatibility. Nickel, molybdenum, and iron are the more promising nominees for replacing cobalt. Between these elements, the cost of iron is the lowest, and iron-containing perovskites yield favorable electro-catalytic activity on the oxygen reduction reaction. Furthermore, the cell performance would be more enhanced through optimizing cathode microstructures.

5. Conclusions

The development of cobalt-free cathodes for intermediate temperature SOFCs has good potential. Besides the reduction in thermal expansion coefficient difference between cathode and electrolyte, cobalt-free cathodes also show acceptable polarization resistance in electrochemical impedance spectroscopy (EIS) analysis. This paper investigations various studies on cobalt-free anodes and cathodes with/without nanofiber development including the important characters in determining performance of SOFCs as shown in Table 1. The polarization resistance of SOFC cathodes also importance of cobalt-free anodes and cathodes for this process.

References

[1] O'Hayre R., Cha S.W., Colella W.G., Prinz FB. Fuel Cell Fundamentals. John Wiley&Sons Inc., Hoboken, NJ, USA, 2016.

[2] Shao Z., Haile S.M. A high-performance cathode for the next generation of solid-oxide fuel cells, Nature, 431, 2004, 170-173.

[3] Zhi M., Lee S., Miller N., Menzler N.H., Wu N. An intermediate-temperature solid oxide fuel cell with electrospun nanofiber cathode. Energy Environmental Sci., 5, 2012, 7066-7071.

[4] Chen Y., Bu Y., Zhao B., Zhang Y., Ding D., Hu R., Wei T., Rainwater B., Ding Y., Chen F., Yang C., Liu J., Liu M. A durable, high-performance hollow-nanofiber cathode for intermediate-temperature fuel cells. Nano Energy, 26, 2016, 90-99.

[5] Lee J.G., Park J.H., Shul Y.G. Tailoring gadolinium-doped ceria-based solid oxide fuel cells to achieve 2Wcm-2 at 550 oC. Nature Communications, 2014, 1-10.

[6] Duan, C., Tong, J., Shang, M., Nikodemski, S., Sanders, M., Ricote, S., Almansoori, A., O'Hayre, R. Readily processed protonic ceramic fuel cells with high performance at low temperatures. Science, 349, 2015, 1321-1326.

[7] Murray E.P., Tsai T., Barnett S.A. A direct-methane fuel cell with a ceria-based anode. Nature, 400, 1999, 649–651.

[8] Park S., Vohs J.M., Gorte R.J. Direct oxidation of hydrocarbons in a solid-oxide fuel cell. Nature, 404, 2000, 265–267.

[9] Hibino T., Hashimoto A., Inoue T., J. Tokuno, Yoshida S., Sano M., A low-operating temperature solid oxide fuel cell in hydrocarbon-air mixtures. Science, 288, 2000, 2031–2033.

[10] Adams T.A., Nease J., Tucker D., Barton P.I. Energy conversion with solid oxide fuel cell systems: A review of concepts and outlooks for the short- and long-term. Ind. Eng. Chem. Res., 52, 2012,3089– 3111.

[12] Jacobson A.J. Materials for solid oxide fuel cells. Chem. Mater. 22, 2009, 660–674.

[13] Choi S., Yoo S., Kim J., Park S., Jun A., Sengodan S., Kim J., Shin J., Jeong H.Y., Choi Y., Kim G., Liu M. Highly efficient and robust cathode materials for low-temperature solid oxide fuel cells: PrBa0.5Sr0.5Co2-xFexO5+δ. Scientific Reports, 3, 2426, 2013, 1-6.

[14] Lee J.G., Park J.H., Shul Y.G. Tailoring gadolinium-doped ceria-based solid oxide fuel cells to achieve 2 W cm-2 at 550 °C. Nature Communications. 5, 2014, 4045.

[15] Tang,H., Jin Z., Wu Y., Liu W., Bi L. Cobalt-free nanofiber cathodes for proton conducting solid oxide fuel cells. Electrochemistry Communications, 100, 2019, 108-112.

[16] Kharton V.V., Marques F.M.B., Atkinson A. Transport properties of solid oxide electrolyte ceramics: a brief review. Solid State Ionics. 174, 2004, 135-149.

[17] Cowin P.I., Petit C.T.G., Lan R., Irvine J.T.S., Tao S. Recent Progress in the Development of Anode Materials for Solid Oxide Fuel Cells. Advanced Energy Materials, 1, 2011, 314–332.

[18] Chen M., Kim B.H., Xu Q., Nam O.J, Ko J.H. Synthesis and performances of Ni–SDC cermets for IT-SOFC anode. Journal of the European Ceramic Society, 28, 2008, 2947–2953.

[19] Zhua Z., Guoa E., Weia Z., Wang H. Tailoring Ba3Ca1.18Nb1.82O9-δ with NiO as electrolyte for proton-conducting solid oxide

fuel cells. Journal of Power Sources, 373, 2018, 132-138.

[20] Wang B., Bi L., Zhao X.S., Liquid-phase synthesis of SrCo0.9Nb0.1O3-δ cathode material for proton-conducting solid oxide fuel cells. Ceramics International, 44, 2018, 5139-5144.

[21] Li W., Guan B., Yan J., Zhang N., Zhang X., Liu X. Enhanced surface exchange activity and electrode performance of La2_2xSr2x)(Ni1_xMnx)O4-δ cathode for intermediate temperature solid oxide fuel cells. Journal of Power Sources, 318, 2016, 178-183.

[22] Tsipis E.V.. Kharton V.V., Electrode materials and reaction mechanisms in solid oxide fuel cells: a brief review. J Solid State Electrochem 12, 2008, 1367–1391.

[23] Molin S., Lewandowska-Iwaniak W., Kusz B., Gazda M., Jasinski P. Structural and electrical properties of Sr(Ti,Fe)O3-δ materials for SOFC cathodes. J Electroceramics, 28,2012, 80-87.

[24] Ropp R.C., Chapter 1 - The Alkaline Earths as Metals. Encyclopedia of the Alkaline Earth Compounds, 2013, Elsevier.

[25] Zhou Q., Zhang L., He T. Cobalt-free cathode material SrFe0.9Nb0.1O3−δ for intermediate-temperature solid oxide fuel cells. Electrochemistry Communications, 12, 2010, 285-287.

[26] Jiang, S., Zhou W., Niu, Zhu Z., Shao, Z. Phase transition of a cobalt-free perovskite as a high-performance cathode for intermediate-temperature solid oxide fuel cells, ChemSusChem, 5, 2012, 2023-2031.

[27] Zhang Y., Huang X., Lu Z., Liu Z., Ge X., Xu J., Xin X., Sha X., Su W. Ni–Sm0.2Ce0.8O1.9 anode-supported YSZ electrolyte film and its application in solid oxide fuel cells. Journal of Alloys and Compounds, 428, 2007, 302-306.

[28] Ding J., Liu J., Guo W. Fabrication and study on Ni1−xFexO-YSZ anodes for intermediate temperature anode-supported solid oxide fuel cells. Journal of Alloys and Compounds, 480, 2009, 286-290.

[29] Ye X.F., Wang S.R., Hu Q., Chen J.Y., Wen T. L., Wen Z.Y., Improvement of Cu–CeO2 anodes for SOFCs running on ethanol fuels. Solid State Ionics. 180, 2009, 276-281.

[30] Huang B., Ye X.F., Wang S.R., Nie H.W., Liu R.Z., Wen T.L., Performance of Ni/ScSZ cermet anode modified by coating with Gd0.2Ce0.8O2 for a SOFC. Materials Research Bulletin, 42, 2007, 1705-1714.

[31] Ye X.F., Wang S.R., Hu Q., Wang Z.R., Wen T.L., Wen Z.Y. Improvement of multi-layer anode for direct ethanol Solid Oxide Fuel Cells. Electrochemistry Communications, 11, 2009, 823–826.

[32] Qiao J. , Sun K., Zhang N., Sun B., Kong J., Zhou D. Ni/YSZ and Ni–CeO2/YSZ anodes prepared by impregnation for solid oxide fuel cells. Journal of Power Sources, 169, 2007, 253-258.

[33] Ma Q., Ma J., Zhou S., Yan R., Gao J., Meng G. A high-performance ammonia-fueled SOFC based on a YSZ thin-film electrolyte. Journal of Power Sources, 164,2007, 86-89.

[34] Bozza F., Polini R., Traversa E. High performance anode-supported intermediate temperature solid oxide fuel cells (IT-SOFCs) with La0.8Sr0.2Ga0.8Mg0.2O3−δ electrolyte films prepared by electrophoretic deposition Electrochemistry Communications, 11, 2009, 1680-1683.

[35] Storjohann D., Daggett J., Sullivan N.P., Zhu H., Kee R.J., Menzer S., Beeaff D. Fabrication and evaluation of solid-oxide fuel cell anodes employing reaction-sintered yttria-stabilized zirconia. Journal of Power Sources, 193, 706-712.

[36] Xia C.R., Liu M.L. Novel Cathodes for Low-Temperature Solid Oxide Fuel Cells. Advanced Materials, 2002, 14, 521–523.

[37] Zhan Z., Lee S.I. Thin film solid oxide fuel cells with copper cermet anodes. Journal of Power Sources, 195, 2010, 3494-3497.

[38] Ye X.F., Wang S.R., Hu Q., Wang Z.R., Wen T.L., Wen Z.Y. Improvement of multi-layer anode for direct ethanol Solid Oxide Fuel Cells, Electrochem. Commun., 11 2009, 823–826.

[40] Huang B., Ye X.F., Wang S.R. , Nie H.W., Liu R.Z., Wen T.L. Performance of Ni/ScSZ cermet anode modified by coating with Gd0.2Ce0.8O2 for a SOFC. Materials Research Bulletin, 42, 2007, 1705-1714.

[41] Blennow P., P. Hagen P., Hansen K.K., Wallenberg L.R., Mogensen M. Defect and electrical transport properties of Nb-doped SrTiO3P Blennow, A Hagen, KK Solid State Ionics, 179, 2008, 2047-2058.

[42] Chen X. J., Liu Q.L., Khor K.A., Chan S.H. High-performance (La,Sr)(Cr,Mn)O3/ (Gd,Ce)O2−δ composite anode for direct oxidation of methane. J. Power Sources 165, 2007, 34-40.

[43] Zhu X., Lu Z., Wei B., Zhang Y., Huang X., Su W. A comparison of La0.7Sr0.25Cr0.5Mn0.5O3−δ and Ni

impregnated porous YSZ anodes fabricated in two different ways for SOFCs. Electrochem.Solid-State Lett. 2010, 3932-3938.

[44] Ye X.F., Wang S.R., Wang Z.R., Hu Q., Sun X. F., Wen T.L., Wen Z.Y., Use of La0.7Sr0.25Cr0.5Mn0.5O3 materials in composite anodes for direct ethanol solid oxide fuel cells. J. Power Sources 2008 , 183 , 512-517.

[45] Lu X.C., Zhu J.H. Cu(Pd)-impregnated La0.75Sr0.25Cr0.5Mn0.5O3−δ anodes for direct utilization of methane in SOFC. Solid State Ionics, 2007, 178 , 1467-1475.

[46] Chen X.J., Liu Q.L. , Khor K.A., Chan S. H. J. High-performance (La,Sr)(Cr,Mn)O3/ (Gd,Ce)O2−δ composite anode for direct oxidation of methane Power Sources 2007 ,165 , 34-40.

[47] Zhu X., Lü Z., Wei B., Chen K. , Liu M., Huang X., Su W. Fabrication and performance of membrane solid oxide fuel cells with La0.75Sr0.25Cr0.5Mn0.5O3-δ impregnated anodes. J. Power Sources 2010, 195, 1793-1798.

[48] Zhu X., Lü Z., Wei B., Chen K. , Liu M., Huang X., Su. J. Enhanced performance of solid oxide fuel cells with Ni/CeO2 modified La0.75Sr0.25Cr0.5Mn0.5O3-δ anodes Power Sources, 2009, 190, 326-330.