Open Access Journal

Journal of Power Technologies 91 (2) (2011) 82–92

journal homepage:papers.itc.pw.edu.pl

Determination of electronic conductance of solid oxide fuel cells

Łukasz Nikonowicz*, Jarosław Milewski

Institute of Heat Engineering, Warsaw University of Technology
21/25 Nowowiejska Street, 00-665 Warsaw, Poland

Abstract

This work considers electronic conductance in solid oxide fuel cells and consequences of its existence. Various types of electrolyte are analyzed. The voltage characteristics of cells show differences between a theoretical maximum circuit voltage and open circuit voltage (OCV). A relationship is assumed between the OCV value and electronic conductance. Based on experimental measurements an appropriate mathematical model was created. The model is used to calculate the temperature dependence of electronic conductance for the most popular types of electrolytes: GDC (Gadolinia-Doped Ceria), ScSZ (Scandia Stabilized Zirconia), LSGMC (Cobalt, Strontium, and Magnesium Doped Lanthanum Gallate), YSZ (Yttria-Stabilized Zirconia).

The obtained results point to the possible existence of a very tight relationship between the electronic conductance and the open circuit voltage. This relationship enables OCV to be calculated when electronic conductance is known. Appropriate formulae can be determined.

Temperature is one of the factors which influences the value of electronic conductance. Other influencing factors also exist but their impact on OCV is not well know. This article mentions some of them.

1. Introduction

While the volume of literature on fuel cells grows ever greater, some aspects are still unexplained. One is the difference between voltage values: theoretical maximum voltage and open circuit voltage, to be precise. This article attempts to find an explanation for this phenomenon.

This issue is assumed to be a consequence of the existence of electronic conductance in electrolytes. While ionic conductance has been tested quite well and widely described, electronic conductance is yet to be thoroughly examined.

The main aim of the work presented in this article is to define electronic conductance and to determine the temperature dependence of electronic conductance for the following materials: $(Ce_2)_{0.8}(GdO_{0.5})_{0.2}$ – GDC, $(ZrO_2)_{0.9}(Sc_2O_3)_{0.1}$ – ScSZ, $(ZrO_2)_{0.9}(Y_2O_3)_{0.1}$ – YSZ. These materials are the ones most often used as electrolytes in SOFC and therefore attention is given to them in this article. They each have a particular molar composition, as is shown, e.g. the molar fraction of gadolinium oxide in GDC is 80 %. This molar composition varies according to electrolyte.

The obtained results are presented in the form of graphs. All calculations were done on the assumption of 0 D theory. A 1 D or 3 D approach is unnecessary since the calculations are based on discrete values.

This article considers the electronic conductance

---

*Corresponding author

Email addresses: `lukasz.nikonowicz@gmail.com` (Łukasz Nikonowicz*), `milewski@itc.pw.edu.pl` (Jarosław Milewski)

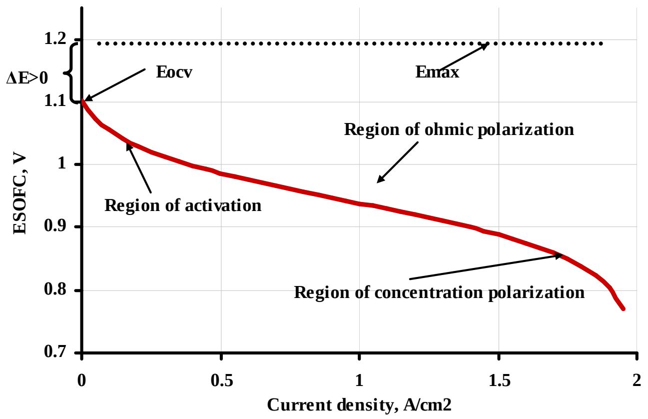

Figure 1: Voltage-current characteristics of the fuel cell

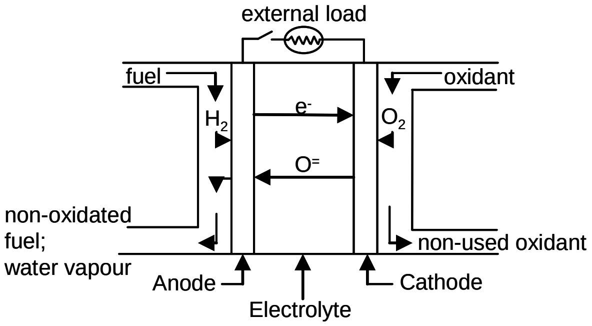

Figure 2: Schematic diagram of a working fuel cell when the external circuit is open

of LSGMC and the influence of various factors on its electronic conductance.

The calculations were based on data taken from [1–8]. Those articles present results of experimental measurements which contain OCV values in various operating temperatures of SOFC.

For each considered material data from at least two different articles are collected. This is done because it enables the received values to be compared and it affords an opportunity to perform a correlation to check if the results are more or less collinear.

The only exception is LSGMC. Since the authors could not find appropriate measurement results for the second sample, it was impossible to carry out the correlation test for this material or verify the results.

2. Theory

An example of the voltage-current characteristic of the fuel cell is shown in Fig. 1. The curve shows the current density dependence of the potential difference in external circuit. This makes it possible to compare different fuel cells without taking into consideration the geometrical construction of each cell. Dividing the current which flows through the external circuit by the area of the fuel cell, it is possible to compare the performance of each cell irrespective of whether the cell area is 1 cm^2 or 10 cm^2.

The graph charts the theoretical maximum voltage (the dotted line) and OCV. For $i=0$ A/cm^2 the difference between the calculated maximum voltage (E_{max}) and the measured E_{ocv} ($\triangle E = E_{max} - E_{ocv} > 0$) is observed. The OCV is lower than the calculated theoretical voltage. The difference between both can be very little, but sometimes it reaches a considerable value (up to 20 % of E_{max}). This great range of difference motivated the work presented in this article.

The principle underpinning the operation of fuel cells is well known. If the external circuit is open, theoretically, the fuel cell will not work – the current will not flow through it. In fact, this sentence is contrary to the real state which is mentioned above because of $\triangle E$ existence. It would not been observed if fuel cell did not work at all. And in such case E_{ocv} and E_{max} would be equal.

There are two possible explanations. The first is that the electrolyte is a high-density solid body with a micro-porosity structure. This porosity is not as great as at the anode or cathode but it still exists in the micro scale. The internal leakages of substance from one side of the electrolyte to the other are possible through this porous body until fuel and oxidant approach a state of thermodynamic equilibrium. The second explanation is based on the fact that the electrolytes form a crystal lattice which is wide enough to transmit ions and electrons. For those two types of particles the crystal lattice can be viewed as a porous material. Some of the oxygen ions always move from the cathode to the anode across the electrolyte layer. On the anode layer they react with fuel and electrons appear as a result. If there is a lack of electrons on the cathode layer and an excess of them on the anode layer, a movement of electrons across the electrolyte will take place. In consequence, the current flows in an ‘internal’ circuit of electrolyte. The electrolyte is not an ideal insulator as it has an unlimited electronic

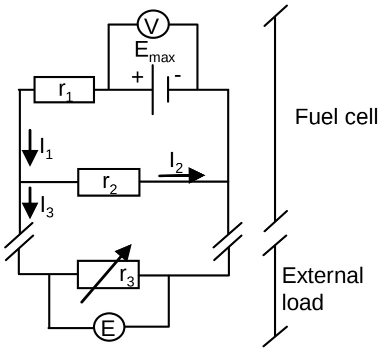

Figure 3: Equivalent electric circuit of the cell (after [9])

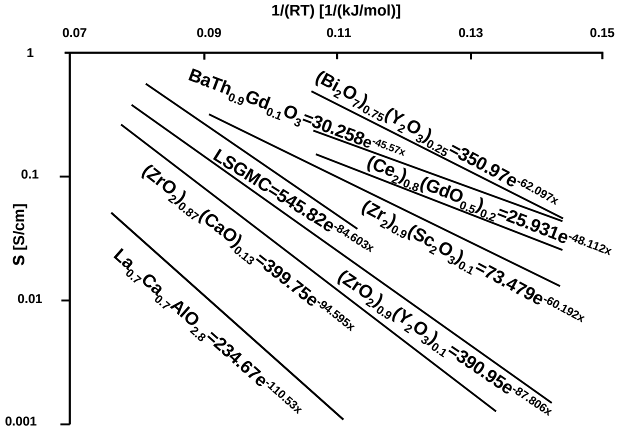

Figure 4: Temperature dependence of ionic conductance for various types of solid oxide electrolytes

resistance. This phenomenon is illustrated in Fig. 2.

It is assumed however that the external circuit is open and the fuel cell works. This is caused by the internal current flow across the electrolyte layer. The oxygen ions move from the cathode to the anode. The electrons overcome resistance and move through the electrolyte in the opposite direction at the same time. Part of the fuel is oxidized in spite of the open external circuit.

Fig. 3 presents an equivalent electric circuit of the cell. There are two samples of conductance (resistance) in the fuel cell: ionic r_1 and electronic r_2. Both are connected with electrolyte. Resistance r_3 represents an external load which can be changed by the SOFC operator. If the limb of circuit with r_2 did not exist, the internal current flow would not appear. In that situation equilibrium would occur between E_{max} and E_{ocv}. This proposition comes clearly from electric circuit theory. The assumption that only ionic conductance is present in the fuel cell seems to be wrong.

The existence of resistance r_2 in the crosswise limb of the circuit causes internal current flow in spite of the open external circuit. This explains the phenomenon of the voltage drop from E_{max} to E_{ocv}.

Analytic functions which describe the current density dependence of voltage can be found in the literature. Substituting *j=0* into those equations, the voltage goes to infinity.

The presented further line of thought gives the methodology of finding the analytic relationship for electronic conductance in electrolytes.

The appropriate mathematical model is presented below.

The basis for further calculation is the ionic conductance chart presented in Fig. 4 (after [9]). It shows the temperature dependences of ionic conductance for various types of SOFC electrolytes.

Based on this data the ionic resistance of electrolyte can be calculated by the equation

$$r_1 = \frac{\delta}{\sigma_1} \tag{1}$$

where: δ– electrolyte thickness [cm]; σ_1– ionic conductance for solid oxide electrolyte [S/cm].

Ionic conductance for solid oxide can be described by the following relationship

$$\sigma_1 = \sigma_0 exp^{\frac{-E}{RT}} \tag{2}$$

where: σ_0 [S/cm]; E [kJ/mol] – factors depending on type of used material.

The maximum voltage of a single cell is represented by

$$E_{max} = \frac{RT}{4F} ln \frac{p_{O_{2cathode}}}{p_{O_{2anode}}} \tag{3}$$

where: T – absolute temperature [K]; R – universal gas constant (R=8.314 J/mol/K); $p_{O_{2cathode}}$– oxygen partial pressure at cathode inlet [bar]; $p_{O_{2anode}}$ – oxygen partial pressure at anode inlet [bar]; F – constant of Faraday (F=96485 C/mol). Hysys software is used to calculate appropriate values of partial pressure of oxygen. Calculations are based on Peng-Robinson thermodynamic functions and minimization of Gibbs free energy.

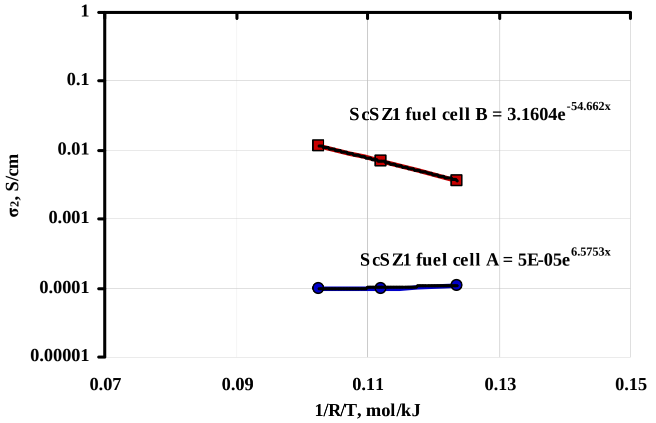

Figure 5: Temperature dependence of electronic conductance in ScSZ electrolyte (for A and B electrolytes)

The second type of resistance occurring in electrolyte is electronic resistance – r_2 (Fig. 3). The temperature and electrolyte thickness dependence of this kind resistance is still not well known.

The values of solid oxide electrolyte ionic conductance vary across a broad range. The influence of this conductance is inconsiderable when the fuel cell is operating. In this situation the fuel conversion factor achieves a high value.

Electronic resistance has a particular impact on the OCV value. The value of electronic resistance from experimental data can be estimated.

Assuming that the fuel conversion factor equals 0, OCV can be calculated by an equation which joins the values of both types of resistance

$$E_{ocv} = \frac{E_{max}}{\frac{r_1}{r_2} + 1} \tag{4}$$

The difference between OCV and maximum theoretical voltage is shown in Fig. 1.

$$\triangle E = E_{max} - E_{ocv} \tag{5}$$

For given values r_1 (from Fig. 5 – when temperature is determined), E_{max} (value calculated using eq. 3) and E_{ocv} (from experimental data) the value of electronic conductance can be presented by the equation

$$\sigma_2 = \sigma_1 \left(\frac{E_{max} - E_{ocv}}{E_{ocv}} \right) \tag{6}$$

where: σ_2 – electronic conductance of electrolyte [S/cm].

The value of electronic conductance calculated using eq. 6 is the first approximation of real value. An iteration process is required to find a value which is very close to the real value. This routine is demanded because of oxygen ion transmission through the electrolyte layer. The partial oxygen value modification on the anode site is caused by that transmission. All this impacts on E_{max}. In consequence the new value of σ_2 must be determined.

The value of electronic resistance can be calculated by

$$r_2 = \frac{\delta}{\sigma_2} \tag{7}$$

Having r_1, r_2, and $\triangle E$ it is possible to obtain the value of the internal current flowing through the electrolyte layer when the fuel cell is fed by fuel and oxidant and the external circuit is open

$$I_{INTERNAL} = \frac{\Delta E}{(r_1 + r_2)} A \tag{8}$$

where: A – effective surface of fuel cell [cm^2].

The $p_{O_{2anode}}$ and $p_{O_{2cathode}}$ values can be calculated by entering the appropriate data into the HYSYS software.

Oxygen is observed on both sides of the electrolyte layer. On the cathode side oxygen pressure equals the oxygen partial pressure in the oxidant. On the anode side the $p_{O_{2anode}}$ value is minimal. It can attain 10^{-23} and vary by a couple orders of magnitude. In spite of the small value, changes in it have a major influence on E_{max} and ionic conductance (due to the presence of this value in the denominator of the logarithm in eq. 3).

The state of thermodynamic balance must be achieved on both sides of the electrolyte in a considered fuel cell. This balance relates to the transmission of oxygen ions through the electrolyte layer. Once again the iteration process is necessary during the calculation. If the value of E_{max} (value calculated using eq. 3) does not change in the following steps of iteration, the iteration stops. If no difference appears between the old and the new value of E_{max} this means that the state of thermodynamic balance has

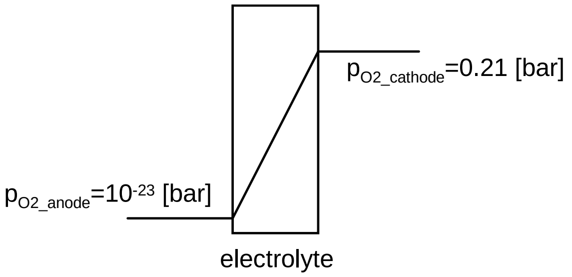

Figure 6: Schematic graph of oxygen pressure in the electrolyte layer

been achieved and the correct value of σ_2 can be calculated.

The presence of oxygen on the anode side is the consequence of thermodynamic balance between the anode and cathode layers. Oxygen ions are transmitted even when the external circuit is open. Chemical reactions are observed between oxygen ions and hydrogen on the anode-electrolyte boundary. Free electrons are products of those reactions. They move from anode to cathode and cause internal current flow. This is the fundamental assumption in the work.

In the chemical reaction

$$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \tag{9}$$

It is clearly observed that one hydrogen mole needs half an oxygen mole. So equality between hydrogen and oxygen flows will occur when

$$n_{H_2} = 2n_{O_2} \tag{10}$$

Then the stoichiometric reaction will take place.

The current generated from this reaction is

$$I_{INTERNAL} = 2 \cdot F \cdot n_{H_2} \tag{11}$$

where: n_{H_2} – molar flow of reacting hydrogen with oxygen which is transmitted from the cathode layer [mol/s].

Connecting formulae 10 and 11, the equation for the amount of oxygen ions moving across the electrolyte is achieved (external circuit is open)

$$n_{O_2} = \frac{I_{INTERNAL}}{4 \cdot F} \tag{12}$$

This value is used by HYSYS software to model the transmission of oxygen from the cathode to the anode layer.

The algorithm presented below is used to find the appropriate values of electronic conductance. The following steps are:

- define the type of electrolyte;
- find in articles information about thickness of electrolyte, effective area of cathode, type and amount of supplied fuel and oxidant;
- determine the temperature at which all calculations are done;
- determine the ionic conductance for the electrolyte using formula 2 and Fig. 5;
- calculate ionic resistance r_1;
- input the data into HYSYS software and calculate $p_{O_{2anode}}$, $p_{O_{2cathode}}$ values;
- calculate E_{max} using formula 3;
- take E_{ocv} from the article for determined temperature;
- determine r_2 and σ_2 using formulae 6 and 7;
- calculate internal current using formula 11;
- calculate oxygen molar flow using formula 12;
- modify values of fuel and oxidant flows (new values) in HYSYS. The new oxidant flow is lower than previously by the value of calculated n_{O_2}. The fuel flow is now enriched by n_{O_2} value ;
- take new $p_{O_{2anode}}$, $p_{O_{2cathode}}$ values and calculate the new value of E_{max} (value calculated using eq. 3) ;
- check the difference between the old and the new values of E_{max}. Repeat iteration when necessary using new $p_{O_{2anode}}$, $p_{O_{2cathode}}$, r_2 and n_{O_2} values.

The iterations process stops when the difference between the old and the new E_{max} value is less than 0.001.

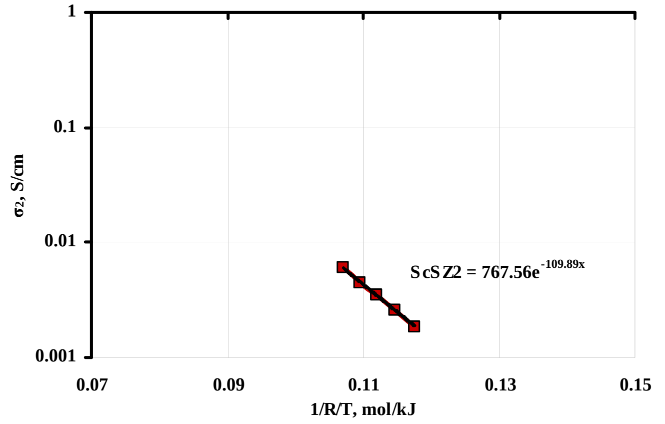

Figure 7: Electronic conductance in function of temperature for the ScSZ electrolyte in symmetric SOFC

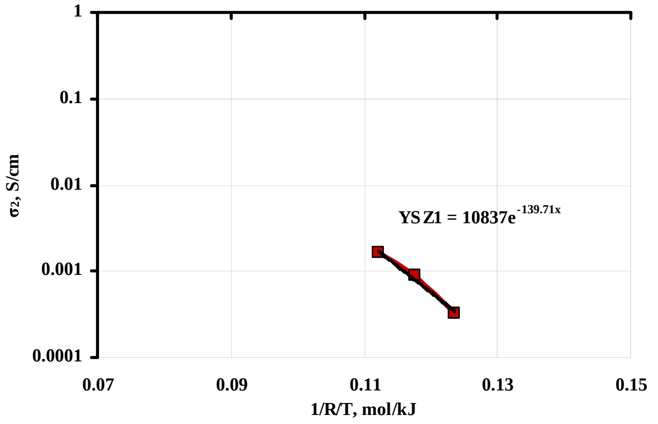

Figure 8: Temperature dependence of electronic conductance (based on data from [7])

3. Results

3.1. ScSZ

The ionic conductance of ScSZ electrolyte can be described by the following equation

$$\sigma_{ScSZ} = 73.479e^{-60.192x} \tag{13}$$

where: x=1/RT [1/(kJ/mol)].

The results of calculations for three different ScSZ electrolytes are presented below. The first two electrolytes were almost the same from the construction point of view. They were subjected to laboratory testing in similar environment conditions. The construction elements of both cells consisted of the same types of materials. The only difference was in the size of powder used to manufacture the anode and electrolyte layers. For more details, please see [1].

The achieved results of electronic conductance for ScSZ electrolyte are shown in Fig. 5.

For verification purposes, another cell with ScSZ electrolyte was considered. The construction and experiment conditions are set out in [6]. Fig. 7 shows the result of the calculation.

3.2. YSZ

The ionic conductance of YSZ is given by the following relationship

$$\sigma_{YSZ} = 390.95e^{-87.806x} \tag{14}$$

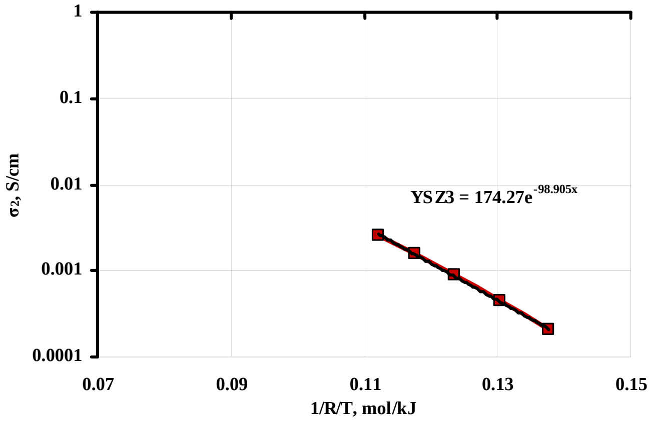

Figure 9: Temperature influence on electronic conductance of YSZ (based on data from [2])

The results of electronic conductance of SOFC with an YSZ electrolyte layer are presented below. All used examples of cells contained an NiO-YSZ anode layer, YSZ electrolyte layer and LSM-YSZ cathode layer. This enables a comparison of the obtained results with special attention in hopes of repeatability in fuel cells which share the same structure.

Based on data from [2, 7, 8] appropriate calculations were made. The results are shown in Figures 8–9.

3.3. GDC

Using the equation below, the ionic conductance of GDC electrolyte might be calculated

$$\sigma_{GDC} = 25.931e^{-48.112x} \tag{15}$$

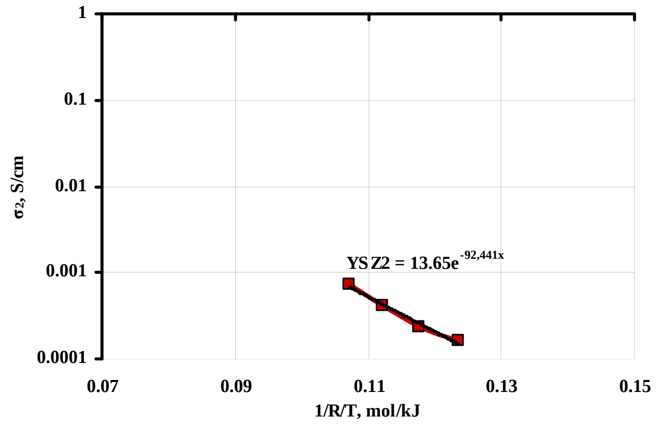

Figure 10: Electronic conductance graph of YSZ electrolyte (based on data from [8])

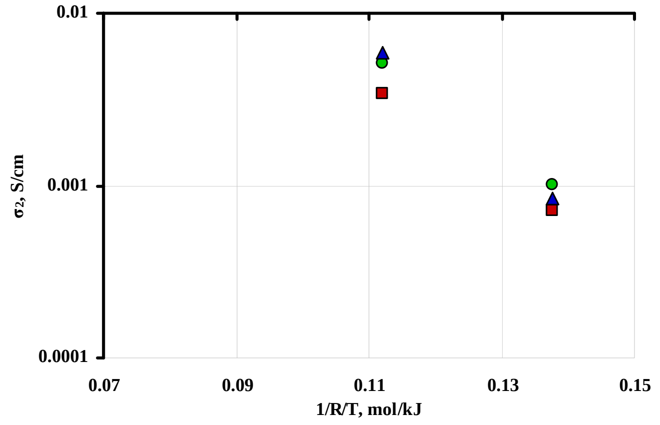

Figure 11: The electronic conductance of LSGMC electrolyte achieved for various thicknesses of electrolyte at 600°C and 800°C (thickness: ▲ – 180 μm; •– 275 μm; ■ – 500 μm)

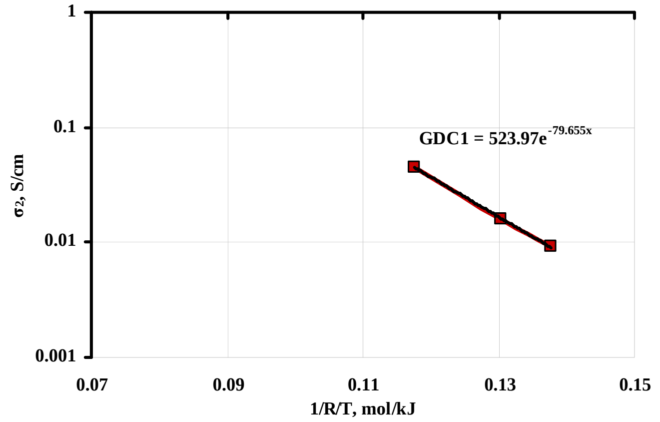

Figure 12: Temperature dependence of electronic conductance in the SOFC (based on an experiment with the LSCV-GDC-NiO/GDC/LSCF-GDC fuel cell [4])

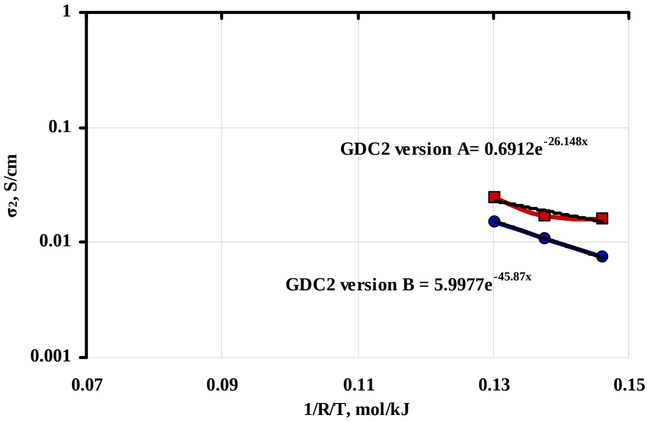

Figure 13: The electronic conductance in NiO-GDC/GDC/LSC-GDC fuel cells (the thickness of electrolyte layer: version A – 15 μm, version B – 25 μm)

In this part the electronic conductance of GDC electrolyte is presented. Based on data from two different experiments [4, 5] the results of the calculation were shown in the following figures (Fig. 12 and Fig. 11).

Considerable differences were noticed between theoretical maximum circuit voltage and open circuit voltage during the calculations. Those differences were more significant here than in previous examples.

Fig. 12 shows the results of the first considered examples. The others are presented in Fig. 11, where two fuel cells are compared. The first (version A) has a 15 μm thick electrolyte layer and the second (version B) has a 25 μm thick electrolyte. The other components and conditions were the same for both.

3.4. LSGMC

The ionic conductance of LSGMC can be described by the following equation

$$\sigma_{LSGMC} = 545.82e^{-44.603x} \tag{16}$$

The calculations for LSGMC electrolyte are based on data from [3]. The electrolyte thickness dependence of electronic conductance was analyzed. The influence on electronic conductance of the used oxidant was considered too.

Fig. 14 presents the calculation results. They were obtained for a cell fed by pure oxygen and air as the oxidant during the tests.

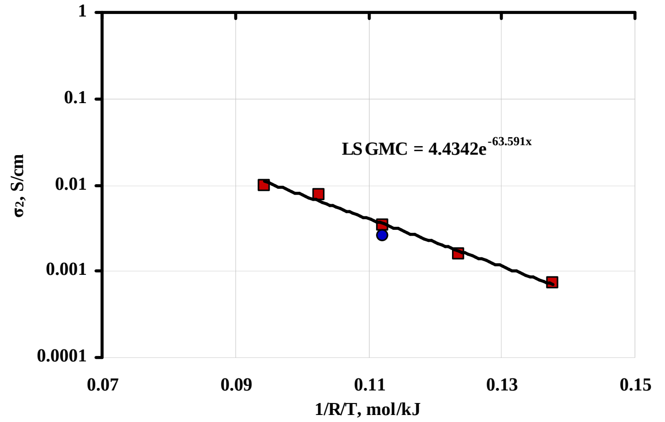

Figure 14: Graph of temperature and used oxidant dependence of electronic conductance for LSGMC electrolyte, ■ – electronic conductance for pure oxygen, • – electronic conductance for air (at t = 800°C)

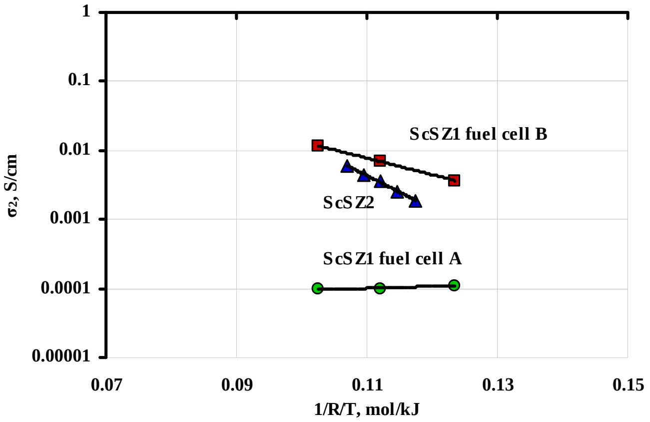

Figure 15: Comparison of ionic conductance in ScSZ electrolytes

Further calculations were done with electrolyte thickness as a variable factor. Fig. 11 shows the discrete values of electronic conductance for three different thickness at 600°C and 800°C temperature.

4. Discussion

The article demonstrates how to obtain the temperature dependence of electronic conductance for various types of electrolytes used in SOFC.

The electrolytes used in the work were YSZ, ScSZ, GDC and LSGMC.

The central concept was to select comparable data for each electrolyte so as to determine whether the achieved analytic dependences are repeatable. A second target was to find out if temperature is the only factor which influences electronic conductance. While it is possible to find the temperature dependence for each electrolyte, the obtained results illustrate that analytic equations are tightly connected with the particular electrolyte. There is no simple transfer from the results of one electrolyte type to other results of that same electrolyte type. The achieved results for one type of material are not coherent, which means that some differences between results are observed for the same sort of electrolyte, e.g. in YSZ electrolytes. This non-repeatability of results must be caused by different factors; not only temperature influences on electronic dependence. In addition to temperature, other factors can probably influence electronic conductance as well: the construction of the fuel cell, technology of manufacture, used oxidant.

For ScSZ 3 types of fuel cells were considered. Two of them concerned the fuel cell manufactured in the same way. Only the grain size of the used powder was different for both - 0.56 μm and 0.60 μm. These powders were used in the manufacture of electrolytes. The third type of fuel cell considered was a symmetrical fuel cell.

The achieved results present the lack of electronic conductance coherence for the considered ScSZ electrolyte examples.

Fig. 15 presents the calculation results. It is clearly shown that the differences in values for electrolyte ScSZ1 are significant. It is all the more surprising because the test conditions were the same for ScSZ1 – fuel cells A and B. The influence of grain size is bigger than previously thought. This fact confirms that other factors impact on electronic conductance. The explanation of this phenomenon is likely to be found in the crystal lattice – the different grain size seems to cause this big divergence in results.

The OCV drop in ScSZ1 is caused by changes in the structural properties of materials. The change of grain size influenced general fuel cell performances.

A difference is observed too in results between ScSZ1 and ScSZ2. But in this case the fuel cells have a susbstantially different built-structure – not only in terms of the electrolyte but generally the materials used and manner of manufacture. Different materi-

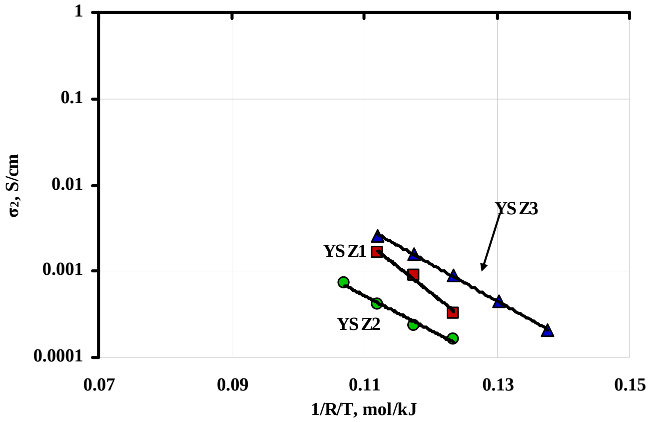

Figure 16: Comparison results for YSZ electrolytes

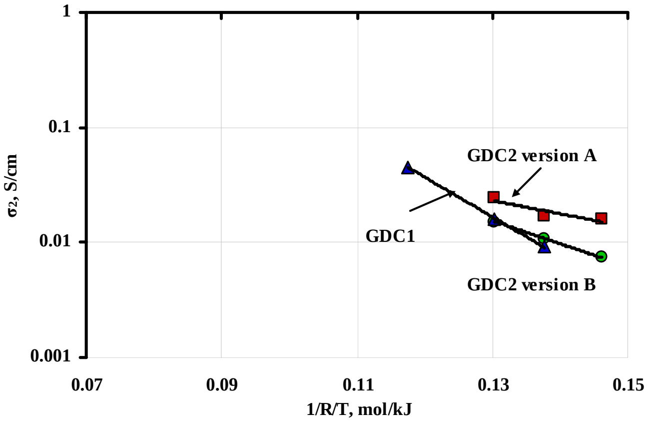

Figure 17: Comparison results of electronic conductance for GDC

als were used in the construction of ScSZ2. It can also be assumed that the type of connected material layers influence the achieved results.

The next considered material was YSZ. A table with data taken from experiments for YSZ can be found in [2]. In those tests fuel cells were used which had NiO–YSZ as the anode and YSZ as the electrolyte (spray coated on the anode). This table shows that fuel cells operating at the same temperature but with a different electrolyte layer thickness have different OCV. In formula 4 OCV is a function only of E_{max}, r_1, r_2. But electrolyte thickness appeared in the mathematical model and it influences oxygen flow transmitting through the electrolyte layer. This is in keeping with the laws of physics. The lower the electrolyte thickness, the more oxygen transmits to the anode through the electrolyte.

The article shows the results for several cases with YSZ as electrolyte. They are different for the same type of material used. Every examined fuel cell had an NiO-YSZ anode and YSZ electrolyte.

Fig. 16 presents collected results of calculations. The difference between particular results is noticed. The reason for this fact should be found in the structure of particular elements. One possible reason might be the different molar proportions of substrates in the anode. A second reason might be the different way the anode is manufactured. Each of the fuel cells considered had a different sort of cathode.

The molar composition of each YSZ electrolyte is very important. But in the considered cases based on 8 %YSZ and 10 %YSZ it does not greatly influence the results. The explanation of that fact can be found in [10].

GDC is the next type of material considered. 3 fuel cells containing GDC electrolyte are described in this article. Two of them were tested under the same supply conditions. The materials in each electrolyte layer were the same for both but the electrolyte thickness were 15 and 25 μm respectively.

Fuel cells with GDC electrolyte typically have a much lower OCV than cells with other materials. The authors of the articles on which the researchers' own calculation were based explained the lower OCV as being due to the existence of a path for electrons in GDC electrolyte. The path is present because of the conductance in ceria. This point of view is similar to the one presented in this article.

The results in this case are not convergent either. Moreover, there is a visible difference between electronic conductance of the GDC2–version A and GDC2–version B fuel cells. This must be effect of electrolyte thickness since all other factors remained the same for the two fuel cells. The tests were performed under the same conditions.

LSGMC is the last case considered. The experimental data gave an opportunity to perform the calculation and once more check the influence of electrolyte thickness on electronic conductance. It was possible to check the influence of the type of oxidant on electronic conductance at 800°C – air was one oxidant, the second being pure oxygen.

During calculation the observation was made that the type of oxidant influenced the result.

Electronic conductance in a fuel cell at 800°C is σ_2= 0.00256414 S/cm when it was supplied with air, which is less than the value for pure oxygen. This can be explained by different oxygen partial pressure in the oxidants. The bigger difference in oxygen pressure between the anode and cathode side, the more oxygen is transported through the electrolyte. In consequence, the amount of reacting hydrogen is greater when pure oxygen is used as the oxidant. This implies more current in the internal circuit. It is very possible that the type of oxidant used has an impact on the results obtained.

Calculations were made to check the influence of electrolyte thickness on electronic conductance. The appropriate values are shown in Fig. 11.

As previously, here the influence of electrolyte thickness is observed too.

Fig. 11 throws up an interesting quirk: at 600°C 180 μm thick electrolyte has the highest electronic conductance, but at 800°C it does not have the highest value.

5. Conclusion

The work presented in this article focused on electronic conductance in materials used in manufacturing SOFC. The presented model and results sought reasons for differences between E_{max} and E_{ocv} when the external circuit of the fuel cell is open. The calculations performed give a partial answer. Electronic conductance exists and is responsible for the drop in voltage. The attempt of explanation this gave approximated results. Other factors which may have influenced the obtained results were not taken into consideration: electrolyte thickness, manufacturing technology, grain size in the powders, used type of oxidant etc.

To check the results obtained calculations for relative error were made, i.e. the difference between the values calculated using eq. 4 and the experimental values. The maximum error was 3.8 %.

The putative mistakes could have been various in origin. They might be the result of limited machine word length, mistakes by digitalization of graphs from articles and of course mean error by measurements. All this make cumulated error which can cause deviations in calculations.

The obtained approximated relationships make it possible to calculate electronic conductance. But they can be used only for specified types of fuel cells with a determined structure (types of: anode, electrolyte and cathode). General analytic relationships have not been determined.

Here only specified functions $\sigma_2 = f(T)$ for several types of ScSZ, YSZ, GDC and LSGMC are presented.

It seems that electronic conductance is the function of different variables. The presented approach is an attempt to explain the phenomenon of voltage difference between E_{max} and E_{ocv}.

Better dependences would be obtained if the fuel cell were examined very precisely by changing only one factor at a time. Then, step by step, the changes in electronic conductance could be checked. This issue deserves further investigation. From the results of the experiments conducted, it is not possible to obtain dependences of ‘pure’ electronic conductance.

References

[1] Z. Cai, T. N. Lan, S. Wang, M. Dokiya, Supported Zr(Sc)O2 SOFCs for reduced temperature prepared by slurry coating and co-firing, Solid State Ionics (2002) 152–153.

[2] J. Ding, J. Liu, An anode-supported solid oxide fuel cell with spray-coated yttria-stabilized zirconia (YSZ) electrolyte film, Solid State Ionics 179.

[3] T. Ishihara, T. Shibayama, M. Honda, H. Nishiguchi, Y. Takita, Solid oxide fuel cell using Co doped La(Sr)Ga(Mg)O3 perovskite oxide with notably high power density at intermediate temperature, Chem. Commun.

[4] B. D. Madsen, S. A. Barnett, Effect of fuel composition on the performance of ceramic-based solid oxide fuel cell anodes, Solid State Ionics 76.

[5] H. C. Park, A. Virkar, Bimetallic (Ni–Fe) anode-supported solid oxide fuel cells with gadolinia-doped ceria electrolyte, Journal of Power Sources 186.

[6] Z. Yao, R. R. Z. Chunming, R. Cai, Z. Shao, D. Farrusseng, A new symmetric solid-oxide fuel cell with La0.8Sr0.2Sc0.2Mn0.8O3-δ perovskite oxide as both the anode and cathode, Acta Materialia 57.

[7] D. Young, A. M. Sukeshini, R. Cummins, H. Xiao, M. Rottmayer, T. Reitz, Ink-jet printing of electrolyte and anode functional layer for solid oxide fuel cells, Journal of Power Sources 184.

[8] W. Zhou, H. Shi, R. Ran, R. Cai, Z. Shao, W. Jin, Fabrication of an anode-supported yttria-stabilized zirconia thin

film for solid-oxide fuel cells via wet powder spraying, Journal of Power Sources 184.

[9] J. Milewski, A. Miller, A. Dmowski, P. Biczel, The control strategy for a solid oxide fuel cell hybrid system, ASME Turbo EXPO 2009, GT2009-59050.

[10] J. V. Herle, A. J. McEvoy, K. R. Thampi, Conductivity measurements of various yttria-stabilized zirconia samples, Journal of Materials Science 29.