The Electrochemical Behavior 
of the LaSrCuO$_{4-\delta}$/Ce$_{0.9}$Gd$_{0.1}$O$_{2-\delta}$ Interface$^1$

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Abstract—The electrochemical behavior of the LaSrCuO$_{4-\delta}$/Ce$_{0.9}$Gd$_{0.1}$O$_{2-\delta}$ interface is studied by impedance spectroscopy and cyclic voltammetry methods. By analyzing the dependence of the impedance frequency spectra on the oxygen partial pressure, the rate-determining stages of oxygen exchange are determined in the temperature interval of 500–900°C. For temperatures above 700°C, the adsorption of oxygen molecules and their dissociation to oxygen atoms are shown to make a substantial contribution to the polarization resistance of the overall electrode process, besides the charge-transfer resistance.

Keywords: lanthanum-strontium cuprates, screen printing technology, electrode/electrolyte interface, impedance spectroscopy, cathodic material, SOFC

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INTRODUCTION

Oxide materials with the high mixed electronic-ionic conductivity find wide application in various electrochemical devices such as solid-oxide fuel cells (SOFC), oxygen separation membranes, oxygen pumps and sensors [1–3]. Among traditional perovskite materials, the oxides with the structure of the K$_2$NiF$_4$ type formed by perovskite blocks grown together with NaCl-type blocks [4] attracted keen attention due to their high mixed electronic-ionic conductivity. Such materials include strontium-substituted lanthanum cuprates La$_{3-x}$Sr$_x$CuO$_{4-\delta}$, which due to the anionic sublattice disordering induced by heterovalent alloying exhibit the high oxygen mobility (the oxygen-ionic conductivity for LaSrCuO$_{4-\delta}$ (LSCO) $\sigma_{179\text{K}} = 3.8 \times 10^{-3}$ S/cm [5]). The total conductivity of LSCO at 500°C was ca. 10 S/cm in air and 1 S/cm in argon (the conduction was of the metal nature in the temperature range of 500–900°C) [6]. Studies of the LaSrCuO$_{4-\delta}$/Ce$_{0.9}$Gd$_{0.1}$O$_{2-\delta}$ interface [7], which was prepared according to screen printing technology by depositing the electrode material on the surface of Ce$_{0.9}$Gd$_{0.1}$O$_{2-\delta}$ (CGO) solid electrolyte, demonstrated its high reversibility with respect to oxygen (the exchange current in the temperature range of 500–900°C varied from $1 \times 10^{-3}$ to $3.5 \times 10^{-2}$ A/cm$^2$). Furthermore, it was shown that after the thermal treatment at 900°C for 400 h, no new phases were formed in the LSCO/CGO contact zone within the limits of sensitivity of the X-ray spectral microanalysis. Hence, LSCO may be considered as the promising cathodic material for SOFC. However, no information was published on the mechanism and the main limiting stages in the oxygen exchange kinetics for this system.

This work was aimed at the systematic investigation of the electrochemical behavior of a porous LSCO-based electrode applied on the CGO surface by the screen printing technology, as a function of the partial oxygen pressure and the temperature.

EXPERIMENTAL

The LSCO powder was synthesized by the sol-gel method. As the starting reagents, we used La$_2$O$_3$ and SrCO$_3$ of the analytical grade; copper oxide was prepared by the decomposition of malachite (CuOH)$_2$CO$_3$ at 300°C. To remove the adsorbed gases (water vapors and carbon dioxide), the lanthanum oxide and strontium carbonate were annealed for 4 h at 800 and 400°C, respectively, prior to taking their weighed portions. The required amounts of strontium carbonate and lanthanum and copper oxides were dissolved in the equimolar amount 30% HNO$_3$ solution. To the resulting nitrate solution, polyvinyl alcohol was added in the 10 : 1 mass ratio. The thus prepared colloid solution (sol) was boiled and then evaporated to obtain a gel. The air-dried residue was heated to 600°C up to the complete decomposition of nitrates and then annealed at 900°C for 8 h. The phase composition of samples was controlled by the X-ray diffraction (XRD)
analysis by using a Guinier-de-Wolf focusing camera-monochromator of high resolution FR-552 (CuK_{\alpha 1} radiation) manufactured by Enraf Nonius Delft (Netherlands). The composition was identified using the XRD database JCPDS PDF-2. Diffraction patterns were processed using the Powder 2 software package.

The formation of symmetrical electrochemical cells LaSrCuO_{4-\delta}/Ce_{0.9}Gd_{0.1}O_{2-\delta}/LaSrCuO_{4-\delta} used in studying the electrochemical behavior of the electrode/electrolyte interface involved several stages. In the first stage, degassed CGO pellets were prepared from commercial reagent (Tosoh\textsuperscript{\textregistered}, Japan). The average density of prepared samples was 94\% of the values calculated based on X-ray data. Layers of LSCO cuprate were applied on the preliminarily polished surfaces of sintered CGO pellets. For this purpose, we prepared a suspension of the LSCO powder mixed with a special organic binder (Heraeus\textsuperscript{\textregistered}, Germany) in the mass ratio 1 : 1. The suspension was applied according to the screen printing technology by using fabric meshes VS-Monoprint PES HT PW 100/40 (100 is the number of threads per cm, 40 in the thread thickness in \( \mu \)m). The resulting cells were dried at 150\°C for 30 min and then subjected to two-step annealing at 600\°C for 30 min and at 900\°C for 3 h. Immediately before the measurements, the pellet surface was covered with platinum past, dried at 100\°C for 2 h, and then annealed at 900\°C for 3 h for the complete removal of organic components of the paste.

The electrochemical measurements were carried out in the two-electrode circuit mode by the methods of impedance spectroscopy and cyclic voltammetry (CVA) in the temperature range of 500–900\°C and the oxygen partial pressure range of 2.8–2.1 \times 10^4 \text{ Pa}. The impedance measurements were carried out using a Z-500P impedance meter (Elinis, Russia) in the frequency range from 0.014 to 45.5 kHz with the signal amplitude of 10 mV. Cyclic voltammograms were recorded using a PS-7 potentiostat (Elinis, Russia) with the potential scan rates of 20 and 400 mV/s in the voltage range from –800 to 800 mV. The sample temperature was controlled by a Pt–Pt/Rh thermocouple placed near the sample. The oxygen partial pressure was determined by a potentiometric sensor based of stabilized zirconium dioxide.

**RESULTS AND DISCUSSION**

According to the XRD data, the LSCO powder synthesized by the sol-gel method was single-phase. The lattice parameters, the oxygen nonstoichiometry index, the size distribution of particles in the prepared sample and also the results of studying the LSCO/CGO interface can be found in \[7\]. The present study was focused on the systematic analysis and the elucidation of peculiarities in the electrochemical behavior of the LSCO/CGO interface.

Figure 1 shows impedance spectra of a symmetrical cell LSCO/CGO/LSCO, studied in the temperature range of 500–900\°C as a function of the oxygen partial pressure \( (P_{O_2}) \). The studies were carried out in a two-electrode cell in the open-circuit emf mode. The presented spectra (Figs. 1b, 1c) indicate the presence of at least two different limiting oxygen exchange stages. The changes in the hodograph shape with the increase in the temperature indicated the changes in the contributions of these stages to the overall electrode process.

To describe the frequency dependences of impedance, we used an equivalent circuit (EC) (Fig. 1a) that included a resistor \( (R_{el}) \) connected in series with two circuits each formed by a resistor and a constant phase element connected in parallel \( (R_{1}\text{-CPE}_1, R_{2}\text{-CPE}_2) \). The \( R_{el} \) magnitude corresponded to the electrolyte...
resistance determined from the high-frequency cutoff and did not change with variations in the oxygen partial pressure. The CPE impedance can be represented as follows:

\[ Z_{\text{CPE}} = \frac{1}{A(j\omega)^P} \]  

where \( A \) is the proportionality factor, \( P \) is the exponent associated with the phase shift [8]. Table 1 shows the impedance components for the LSCO/CGO interface, obtained using the EC shown in Fig. 1a.

Below 700°C, the hodographs (Fig. 1b) consisted of high- and low-frequency circular arcs. The high-temperature arc (1–500 kHz) closely approximated a \( RC \) circuit. As seen from Table 1, the exponent \( P_1 \) was close to 1 and the apparent capacitance \( A_1 \) depended weakly on the variations in the oxygen partial pressure. Moreover, the resistance \( R_1 \) determined in the high-frequency arc approximation was also virtually independent of the oxygen partial pressure. Considering the resistance \( R_2 \) that corresponded to the low-frequency arc (0.01–1000 Hz) showed that the resistance increased with the decrease on \( p_{O_2} \). The low-frequency arc was sagged towards the real resistance axis and corresponded to the exponent \( P_2 \approx 0.5 \), which pointed to the presence of transport (diffusion) limitations in the overall electrode process. The proportionality factor \( A_2 \) increased insignificantly with a decrease in the oxygen partial pressure.

Above 700°C, the hodograph changed its shape as follows (Fig. 1c): the high-frequency arc disappeared; which was accompanied by the appearance (in the region of low frequencies from 0.01 to 1 Hz) of a circular arc corresponding to a \( RC \) circuit (the exponent \( P_2 \) approached 1, Table 1). For the enhanced oxygen content (above 6.4 kPa), no low-frequency arc was observed. Its appearance became noticeable only when \( p_{O_2} \) dropped below 0.79 kPa. The efficient capacitance \( A_2 \) showed no clear dependence on \( p_{O_2} \). The high-frequency arc (from 1 Hz to 500 kHz) was convincingly observed to sag towards the real resistance axis and the exponent \( P_1 \) was close to 0.5, which also indicated the presence of transport limitations.

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To gain insight into the processes on the electrode/electrolyte interface and determine the limiting stages of oxygen exchange, we analyzed the resistances \( R_1 \) and \( R_2 \) and also the specific polarization resistance \( R_\eta \), which was determined by the following equation

\[ R_\eta = \frac{(R_1 + R_2)}{2} S_A, \]  

\( S_A \) is the electrode surface, as a function of the oxygen partial pressure and temperature.

Figure 2 shows the dependences of the logarithm of reciprocal \( R_1, R_2, \) and \( R_\eta \) on the logarithm of the oxygen partial pressure. The dependences were linear and

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<th>( A_1 )</th>
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the logarithm of reciprocal resistance increased according to the relationship

\[ 1/R \propto p_{O_2}^n, \quad (3) \]

where \( n \) determined the reaction order of the corresponding limiting stage of the overall electrode process [9–13].

The overall process of oxygen reduction on the cathode can be described by the following quasichemical reaction:

\[ O_2(g) + 4e + 2V^\infty_o \rightleftharpoons 2O^x_o, \quad (4) \]

where \( V^\infty_o \) is the oxygen vacancy, \( O^x_o \) is the oxygen ion in its regular position in the lattice. Reaction (4) can be conditionally divided into three elementary stages each having its own reaction order \( (n) \)

\[ O_2(g) \rightleftharpoons O_{2,ad} \quad (n = 1), \quad (5) \]

\[ O_{2,ad} \rightleftharpoons 2O_{ad} \quad (n = 1/2), \quad (6) \]

\[ O_{ad} + 2e + V^\infty_o \rightleftharpoons O^x_o \quad (n = 1/4), \quad (7) \]

where \( O_{2,ad} \) and \( O_{ad} \) are the adsorbed oxygen molecule and atom, respectively. These stages also involved the following processes: diffusion of \( O_2 \) molecules from the gas phase to the active reaction sites, adsorption of \( O_2 \) molecules on the electrode surface (Eq. (5)), dissociation of oxygen molecules to atoms (Eq. (6)), surface diffusion of oxygen species, charge transfer to oxygen species before and after the dissociation, and incorporation of oxygen ions into the lattice vacancies of the electrode material (Eq. (7)), bulk transfer of \( O^{2-} \) through the electrode to the electrode/electrolyte interface, and the transfer of \( O^{2-} \) ions across the electrode/electrolyte interface [9–11].

Our analysis of the dependences of the logarithm of reciprocal \( R_1 \), \( R_2 \), and \( R_\eta \) on the logarithm of the oxygen partial pressure at different temperatures started from the temperature range of 500–700°C (Fig. 2). At temperature below 700°C, \( R_1 \) decreased with the increase in temperature and was virtually independent of \( p_{O_2} \). The similar behavior was also observed for a perovskite \( La_{0.5}Ba_{0.5}CoO_{3-\delta} \) cathode [11]. The authors of [11] associated this with the fact that the process was limited by the transport of oxygen ions through the electrode material bulk to the electrode/electrolyte interface and their transfer across this interface

\[ O^{x-} (\text{electrode}) \]

\[ \rightleftharpoons O^{x-} (\text{electrode/electrolyte interface}), \quad (8) \]

\[ O^{x-} (\text{electrode/electrolyte interface}) \rightleftharpoons O^{-} (\text{electrolyte}). \quad (9) \]

Insofar as in our case we dealt with the \( RC \) circuit \( (P_1 \) was close to 1), the limiting stage was most probably associated with the transfer of oxygen ions across the electrode/electrolyte interface (Eq. (9)). Below 700°C, \( R_2 \) decreased with the increase in the temperature. In the process, the slope of concentration surface corresponded to \( n \) close to 1/4, which in turn meant that the charge transfer process (Eq. (7)) was the limiting stage. Thus, in this temperature range, the resistance \( R_1 \) can be considered as a volume process (the
transport of oxygen ions through the electrode material bulk to the electrode/electrolyte boundary and their transfer across this boundary (the rate-determining stage) and \( R_2 \) can be associated with a surface process (diffusion of adsorbed oxygen atoms over the electrode surface and their subsequent discharge).

As follows from the changes in the hodograph shape (Fig. 1c), at temperatures above 700°C, the physical meaning of resistance \( R_1 \) and \( R_2 \) apparently changed. The resistance \( R_1 \) decreased with the increase in the temperature, and \( n \) approached 1/4 (Fig. 2a). This suggested that in the high-frequency interval, the charge transfer was the rate-determining process (Eq. (7)). The resistance \( R_2 \) (Fig. 2b) became independent of temperature and \( n \) decreased to ~3/4. In this case, apparently, both the adsorption of molecular oxygen on the electrode surface (Eq. (5), \( n = 1 \)) and its dissociation to oxygen atoms (Eq. (6), \( n = 1/2 \)) contributed to the rate-determining process. The similar behavior was observed for cathodes based on ferrites and manganites [9]. Thus, in the temperature range of 700–900°C, the resistances \( R_1 \) and \( R_2 \) could apparently be associated with superficial rate-determining processes, i.e., \( R_1 \) with the diffusion of adsorbed oxygen atoms over the electrode surface followed by their discharge and \( R_2 \) with the adsorption of oxygen molecules on the electrode surface followed by their dissociation to oxygen atoms.

The analysis of the specific polarization resistance \( R_\eta \) vs. \( p_{O_2} \) dependence (Fig. 2c) has shown that as the temperature increased, \( n \) gradually increased from ~1/4 (below 700°C) to ~1/2 (above 700°C). Moreover, such substantial change in the reaction order of the rate-determining stage was observed only at temperatures above 700°C and low oxygen concentrations. The slope of \( R_\eta \) curves at temperatures below 700°C (\( n \sim 1/4 \)) was predominantly determined by the \( R_2 \) contribution to the overall polarization resistance, because the slopes of curves in Figs. 2b and 2c were comparable in the magnitude. Therefore, the charge transfer on the electrode (Eq. (7)) can be assumed to be the rate-determining stage of the overall electrode process below 700°C. Quite a different situation was observed at temperatures above 700°C, where the slope of \( R_\eta \) curves became equal to ~1/2. Apparently, the charge transfer process (Fig. 2a, \( n \sim 1/4 \)) and the processes of adsorption and dissociation that involved the oxygen molecules and atoms (Fig. 2b, \( n \sim 3/4 \)) made a comparable contribution into the rate-determining stage of the overall electrode process, especially at low oxygen concentrations.

The correctness of our conclusions on the physical meaning of resistances \( R_1 \) and \( R_2 \) involved in the equivalent circuit (Fig. 1a) is well confirmed by the temperature dependences shown in Fig. 3.

Figure 3 demonstrates the data on the low-frequency resistance \( R_2 \) at temperatures below 700°C and also on the high-temperature resistance \( R_1 \) at higher temperatures. From our point of view, the circular arcs in impedance spectra (\( n \sim 1/4, P \sim 0.5 \)), corresponding to these resonances describe one and the same electrochemical process, namely, the surface diffusion of adsorbed oxygen atoms followed by their discharge. It is quite reasonable that these resistances lie on the same straight lines.

At the same time, the high- and low-frequency \( RC \) circuits (\( P = 1 \)) for temperatures below and above 700°C, respectively, corresponded to different rate-determining processes (Fig. 3b).

Furthermore, the changeover of the rate-determining process was indicated by the smooth variation in the slope of temperature dependences of \( R_\eta \) for the temperature ~700°C (Fig. 3c). This phenomenon was the most pronounced at low \( p_{O_2} \).

Table 2 shows the calculated apparent activation energies \( E_a \) of temperature dependences of \( R_1, R_2, \) and \( R_\eta \) at different oxygen partial pressures. In the temperature range of 500–700°C, the average activation energy \( E_a(\eta) \) associated with the transfer of oxygen ions across the electrode/electrolyte interface (Eq. (9)) was \( 1.37 \pm 0.07 \) eV. The average \( E_a \) associated with the surface diffusion of adsorbed oxygen atoms followed by their discharge was \( 1.46 \pm 0.04 \) eV in the whole temperature range tested (500–900°C). Above 700°C, the dependence of the reciprocal resistance \( R_2 \) on the temperature was not thermoactivated (the

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<th>( p_{O_2}, \text{Pa} )</th>
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* The calculations were carried out in the temperature range of 500–900°C for all points (Fig. 3a); the calculation error ±(3–5)%.
resistance remained virtually unchanged with the temperature for all \( p_0 \).

Considering the specific polarization resistance in the range of 500–700°C, it was concluded that \( E_a \) values were sufficiently close to one another and virtually independent of \( p_0 \) (\( E_a (\text{av}) = 1.51 \pm 0.07 \text{ eV} \)). Moreover, the average activation energies of temperature dependences of \( R_2 \) and \( R_\eta \) corresponded to one another within the experimental error. This was apparently associated with the fact that the charge-transfer processes (Eq. (7)) were the major rate-determining stage of the overall electrode process in this temperature range. In the temperature interval of 700–900°C, as the partial oxygen pressure decreased, the \( E_a \) value decreased more than two-fold from 1.37 eV to 0.66 eV. Such a change in the activation energy for \( R_\eta \) also confirmed that the overall electrode process was determined by a combination of different rate-determining stages. Moreover, with the decrease in \( p_0 \), the effect of molecular oxygen adsorption (Eq. (5)) and its dissociation to oxygen atoms (Eq. (6)) became the most significant because depended directly on the concentration of oxygen involved in the exchange interaction. It should be noted that the obtained values agreed with the literature data for perovskite-based cathodic materials [9–11].

Figure 4 shows polarization \( i \) vs. \( \eta \) curves of the LSCO/CGO interface in air as a function of the voltage scan rate and the temperature. The overall electrode overvoltage (\( \eta \)) was calculated according to the following equation:

\[
\eta = U - i R_{el},
\]

where \( U \) is the voltage, \( i \) is the current taken from CVA; \( R_{el} \) is the electrolyte resistance determined from impedance data as the high-frequency cutoff on the impedance hodograph. In the low overvoltage range from –20 to +20 mV, the \( i \) vs. \( \eta \) dependences were linear and passed through the origin (Fig. 4a, insert). Moreover, for small polarization values, the voltage scan rate did not virtually affect the shape of polarization curves.

The overall polarization resistance \( R^\approx_\eta \) was calculated based on the slope of the \( i \) vs. \( \eta \) curve according to the equation

\[
\frac{1}{R^\approx_\eta} = \frac{i}{\eta}. \tag{11}
\]

The obtained data were recalculated to the \( R_\eta \) value that took into account the electrode surface \( S_e \):

\[
R_\eta = \frac{R^\approx_\eta}{2} S_e. \tag{12}
\]

Table 3 shows the \( R_\eta \) values calculated from CVA data in the range of low polarizations and found by impedance measurements in air. Insofar as the mea-

---

**Table 3**

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>( \log(1/R) ) [S/cm²]</th>
<th>( 1000/T ) [K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>800</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>700</td>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>600</td>
<td>4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

For different oxygen partial pressures, \( p_0 \): (1) \( 2.1 \times 10^4 \), (2) 6400, (3) 790, (4) 135, (5) 28. Exponent \( P \): (a) 0.5, (b) 1.
measurements were carried out in the two-electrode mode, the calculations were performed only for high oxygen partial pressures, i.e., in the absence of substantial diffusion limitations. The obtained values agreed sufficiently well with one another.

Figure 5 shows the typical shape of polarization curves of the LSCO/CGO interface as a function of the partial oxygen pressure. As $p_{O_2}$ dropped, the contribution of diffusion limitations to the overall electrode process became more significant, which manifested itself in the appearance of a hysteresis loop in CVA curves.

To test the effect of high temperatures on the resistance of the electrode/electrolyte interface, the electrochemical cells were cycled for 5 days in the temperature interval of 500–900°C for 5 days. The average $R_\eta$
obtained at a temperature of \((875 \pm 5)\)°C based on impedance data was equal to \(1.6 \pm 0.1\) \(\Omega\) cm\(^2\) and remained unchanged in time. The fact that no substantial changes in the specific electrode resistance were observed pointed to the stability of the electrode/electrolyte interface.

Comparing the \(R_n\) values for LSCO with the latest literature data for SOFC cathodes showed that the values obtained were higher compared with manganites (~ by 1 order of magnitude) \([14, 15]\) and lanthanum cobaltites (1–2 orders of magnitude) \([10, 11]\) alloyed with strontium. It deserves mention that when comparing \(R_n\) values with the literature data, it should be borne in mind that the electrode properties may depend on numerous technological parameters, for example, the method of deposition, the electrode shape, and the cell geometry. This is why, it was sufficiently difficult to assess whether the worst electrode characteristics were associated with the poorest development of technologies of the electrode layer formation on the solid electrolyte surface or with substantial differences in the electrical properties of tested materials. In our case, as compared with LSCO, both manganites and cobaltites exhibited the high electronic conductivity (higher by 1 and 2 orders of magnitude, respectively) \([9, 16–20]\). Moreover, cobaltites had the higher oxygen-ionic conductivity (by 1–2 orders of magnitude) \([18–20]\) and manganites exhibited the lower oxygen-ionic conductivity (by an order of magnitude) \([20]\). These differences together with the underdeveloped procedure of deposition could also be the reason for somewhat lower working characteristics of the tested LSCO electrodes.

### Table 3. Comparison of \(R_n\) values calculated based on CVA data in the low polarization interval (the voltage scan rate was 20 mV/s) with the impedance data in air

<table>
<thead>
<tr>
<th>(T, ) °C</th>
<th>((\partial \eta/\partial \eta)_{\text{CVA}}, ) (\Omega) cm(^2)</th>
<th>(R_n,\text{ imp}, ) (\Omega) cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>875</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>770</td>
<td>6.3</td>
<td>6.8</td>
</tr>
<tr>
<td>660</td>
<td>35</td>
<td>39</td>
</tr>
<tr>
<td>545</td>
<td>630</td>
<td>590</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

The electrochemical behavior of the LSCO electrode deposited by the screen printing technology on the surface of a CGO solid electrolyte was studied in the temperature interval of 500–900°C and for oxygen partial pressures of \(28–2.1 \times 10^4\) Pa. The impedance measurements have shown that in the system tested, at least two oxygen exchange limiting stages can be singled out. According to the analysis of the logarithmic dependences of the reciprocal \(R_n, R_\eta,\) and \(R_\eta\) values, for the temperature of 700°C, the changeover of the rate-determining stages of the overall electrode process was observed. Below 700°C, the charge transfer was the main rate-determining stage, whereas above 700°C, the adsorption of molecular oxygen and its dissociation to oxygen atoms began to make a contribution comparable with that made by the charge transfer into the rate-determining stage of the overall electrode process, especially at low oxygen concentrations. A comparison of \(R_n\) values calculated based on the CVA data at low overpotentials with the data of impedance spectroscopy in air has shown that the obtained results were self-consistent throughout the temperature interval studied. Monitoring \(R_n\) of the electrode material under conditions of cycling in the temperature interval of 500–900°C for 5 days has shown the presence of substantial changes, which pointed to the stability of the electrode/electrolyte interface.

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### REFERENCES


