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Transport and Kinetics Properties of LaF₃ in FLiNaK Molten Salt Determined by Electrochemical Methods

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Graphical abstract



Highlights

- 1. Fundamental properties of LaF_6^{3-} in FLiNaK molten salt was explored.
- 2. Diffusion coefficient of LaF_6^{3-} in FLiNaK molten salt was obtained from chronopotentiometry measurements.

- 3. The relationship between diffusion coefficient and temperature was derived for the temperature range of 973 to 1023 K.
- 4. Kinetic parameters of LaF_6^{3-} in FLiNaK molten salt was achieved by potentiodynamic polarization through employing an electrode kinetics equation.

Abstract

It is found that lanthanum species can exist in the form of LaF_6^{3-} in FLiNaK (46.5 LiF-11.5 NaF-42 KF, mol%) molten salt in previous studies. The understanding of transport and reaction kinetics parameters of LaF_6^{3-} ions in FLiNaK molten salt is essential for the electrochemical separation of lanthanum from FLiNaK melt to achieve the coolant clean-up in fluoride salt cooled hightemperature reactor (FHR). Through conducting chronopotentiometry tests, the diffusion coefficients of LaF_6^{3-} ions in FLiNaK molten salt at the temperature range of 923 K to 1023 K were determined. By conducting potentiodynamic polarization measurements at different concentrations and temperatures, the exchange current density, reaction rate constant, and charge transfer coefficient were obtained. The experiment data of potentiodynamic polarization were analyzed using a non-simplified electrode kinetics equation which incorporates both mass transfer and reaction kinetics.

Keywords: Lanthanum; FLiNaK molten salt; diffusion coefficient; exchange current density; reaction rate constant

1. Introduction

FHR is a promising GEN IV reactor concept with a potential to be manufactured as a commercial power reactor [1]. FHR combines liquid molten salt coolant and graphite matrix coated-particle fuel originally proposed for High Temperature Gas-cooled Reactor (HTGR). Because of the most favorable nuclear properties such as negative void coefficient [2] and low neutron absorption cross-section [3], FLiBe (67LiF-33BeF₂, mol%) is selected as the primary coolant. FLiNaK is a candidate salt mixture for the intermediate loop and a good surrogate of FLiBe [4]. FHR has the advantages of low operating pressure and high-temperature power cycle which will enhance safety and increase output for the electricity generation of a reactor, however, one challenge presented for the application of molten fluoride salt in FHR is the acquisition of fission products from fuel leakage into the coolant during normal operation. The circulating fission products within the coolant would be a potential radioactive source for both the maintenance worker and the public [5]. Therefore, to ensure the continuous operation of the reactor and minimize the volume of salt coolant waste, it is necessary to have an online coolant clean-up system installed in FHR [6,7].

As an ionic fluid, molten salt lends itself to various chemical control applications due to its electrochemical properties. Several different chemical control methods for molten salt coolant clean-up have been proposed. For instance, applying reducing electrical currents by

electrochemical separation technique or introducing reducing agent in liquid cathode (such as Li in Bi). Among them, the electrochemical separation technique has been demonstrated as a promising option for the clean-up of molten salt coolant in FHR. In the electrochemical separation technique, a proper electrical potential or current can be applied, some of soluble fluorides of fission products in molten salt coolant will be electrodeposited as metals or metal compounds on the cathode. In that way, the fission products can be extracted out with cathode from the molten salt to realize the clean-up of the coolant in FHR.

Lanthanum is one of the abundant lanthanide fission products in nuclear reactors [8] and which is commonly taken as a model system for the electrochemical separations of fission products in molten salt. To manage the electrochemical separation of lanthanum, the understanding of its fundamental properties is significant. Massive studies have been performed for the fundamental properties of lanthanum in LiCl-KCl molten salt [9,10,11]. However, the investigation on the fundamental properties of lanthanum in molten fluoride salt is still rare. Chesser et al. [12] recently studied the diffusion coefficient of lanthanum in FLiNaK molten salt using cyclic voltammetry technique, and reported that the diffusion coefficient is much less than that in chloride salt.

Based on available studies, the deposition of La metal in FLiNaK-LaF₃ molten salt system on an inert electrode such as W is due to the deposition reaction of LaF_6^{3-}/La [6]. In addition, Dracopoulos et al [13] found the dipole-induced-dipole interaction between the La^{3+} partially shielded by the fluorides and the mobile K⁺ was enhanced, and reported La ions would predominantly exist in the form of LaF_6^{3-} in the KF-rich molten salt mixtures. At the same time, Rollet [14] pointed out the local structure of molten fluoride salt could change when LaF₃ exists and the fundamental properties of lanthanum species would change accordingly as well. Therefore, it is interesting to know the transport and kinetics properties of LaF₆³⁻ in molten salt. In the present work, the diffusion coefficients of LaF_6^{3-} in FLiNaK molten salt were studied at different concentrations and temperatures by the method of chronopotentiometry. Additionally, potentiodynamic polarization measurements at different LaF₆³⁻ concentrations and temperatures were carried out. Through using a non-simplified electrode kinetics equation as reported by Guo et al [15] to nonlinearly fit the obtained potentiodynamic polarization curves, the kinetics parameters such as exchange current density, reaction rate constant, and charge transfer coefficient for the redox reaction of LaF₆³⁻/La were determined.

2. Experimental

All the electrochemical experiments and salt preparations were performed in an argon-filled glove box manufactured by Inert Technology. The oxygen and moisture inside the glovebox were maintained below 5 ppm and 0.5 ppm respectively during the normal operation. The chemicals used in this study include lithium fluoride (LiF, >99.0% purity, Sigma Aldrich), sodium fluoride (NaF, >99.0% purity, Sigma Aldrich), and potassium fluoride (KF, >99.5% purity, Sigma Aldrich). To provide lanthanum ions, lanthanum fluoride (LaF₃) with the purity of \geq 99.99% was procured from Sigma Aldrich. 50 g FLiNaK constituents were prepared by weighing LiF, NaF, and KF chemicals according to the FLiNaK composition of 46.5 mol% LiF, 11.5 mol% NaF, and 42 mol%

KF using a precision analytical balance with an accuracy of 0.0001 g (MS 105DU Mettler Toledo). The prepared FLiNaK constituents and LaF₃ chemicals were mixed inside a plastic sample bottle and then transferred to a nickel crucible (55 ml, Sigma Aldrich). The salt powder with the weight of 0.003 g was taken out for Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) sample, which was firstly dissolved into 65 wt% nitric acid. Once the salt was completely dissolved, an amount of deionized water was added to obtain a 2 v/v% nitric acid based ICP-MS sample solution. 5 identical ICP-MS samples were prepared in total and the average quantity of the salt impurity is shown in Table 1.

The present study assumed that the dominant ions of La is LaF_6^{3-} , therefore, the concentration (mol/cm³) of LaF_6^{3-} in FLiNaK is obtained based on the amount of LaF_3 added into FLiNaK salt. The unit of mol/cm³ was adopted for the concentration in this study for the convenience of calculation. The nickel crucible with an external alumina safety crucible was then placed in a muffle furnace (Thermofisher Scientific FB1315M) for which the temperature can be maintained within ± 1 °C during the experiment. The muffle furnace was customized with a lid which was equipped with a quartz assembly to fix the electrodes. The salt mixture was heated at 473 K for 24 hours to eliminate the oxygen and moisture and subsequently heated up to the target temperature for further electrochemical tests.

The electrochemical tests in this study utilized a three-electrode electrochemical cell in the furnace. The working electrodes used was a 1.6 mm diameter tungsten rod (Midwest Tungsten Service, >99.5% purity). The counter electrode was a 3.05 mm diameter graphite rod (99.9995% purity, Alfa Aesar). The reference electrode utilized was a 0.81 mm diameter platinum wire (99.99%, Surepure Chemetals) with potential associated to Pt/PtO_x/O²⁻ [16]. The bottoms of the electrodes were immersed in the FLiNaK-LaF₃ salt bath while their top ends were connected to the Gamry Interface 1000 poteniostat to perform the electrochemical measurements. The surface area of the working electrode was measured according to the submerged depth into the salt melt. Open circuit potential test was conducted before the chronopotentiometry and potentiodynamic polarization tests to check the stability of the system. The current interrupt method which is programmed in the Gamry Framework software was chosen to perform IR compensation in all the chronopotentiometry measurements.

3. Results and discussion

The electrochemical behavior of LaF₃ in FLiNaK molten salt has been studied in the previous studies [12,17] by cyclic voltammetry test as shown in Figure 1.Generally, it is believed that the electrodeposition of lanthanum is impossible in FLiNaK molten salt because of the more cathodic standard reduction potential of La³⁺/La than that of K⁺/K. However, Lanthanum predominantly exists in the species of LaF₆³⁻ instead of La³⁺ in FLiNaK molten salt [6] and the existence of LaF₆³⁻ helps shift the electrodeposition potential to a more anodic value. As a result, the electrochemical reduction of LaF₃ in FLiNaK molten salt is a one-step charge transfer process, i.e., LaF₆³⁻+3e⁻ → La+6F⁻, as reported in the previous study [6].

3.1.Determination of diffusion coefficient by chronopotentiometry

Based on the known redox reaction of LaF₃ occurring in FLiNaK molten salt, the reduction process of LaF₃ in FLiNaK melt was studied by chronopotentiometry test in the present study and then the diffusion coefficients at several temperatures were determined. Figure 2 illustrates the typical chronopotentiograms of LaF₃ (1.05×10^{-4} mol/cm³) in FLiNaK molten salt at the temperatures of 923, 973, and 1023 K when applying different currents. The first plateau shown with time evolution corresponds to the reduction of LaF₆³⁻ into La metal. After this plateau, the cathodic potential rapidly decreases to reach a limiting value which corresponds to the reduction of potassium. The transition time for the reduction of LaF₆³⁻ can be determined from chronopotentiograms using the method described in the literature [18]. Figure 3 (a) shows the relationship between the applied current and the obtained transition time for the chronopotentiometry data given in Figure 2. A fine proportional relation can be observed between *I* and $\tau^{-1/2}$, therefore, the Sand's equation is applicable for the reduction of LaF₃ in FLiNaK molten salt. The diffusion coefficient of LaF₆³⁻ can be calculated from the slope of the plot of *I* versus τ ^{1/2} based on Sand's equation [19] shown below

$$I\tau^{1/2} = 0.5nFC_0^{*}S\pi^{1/2}D^{1/2} \tag{1}$$

)

where *I* is the applied current (A), τ is the transition time (s), C_o^* is the bulk concentration (mol/cm³), *D* is the diffusion coefficient (cm²/s), *F* is the Faraday's constant, *S* is the working electrode surface area (cm²) and *n* is the electron transfer number.

In addition to the chronopotentiometry test of LaF₃ in FLiNaK molten salt at the concentration of 1.05×10^{-4} mol/cm³, the same test was performed at a higher concentration (2.25×10^{-4} mol/cm³). The relationship between the applied current *I* and the obtained transition time τ was plotted (Figure 3 (b)). The diffusion coefficients at these two different concentrations were calculated based on equation (1) and summarized in Table 2. These values are slightly smaller than the reported 9.16×10^{-7} cm²/s at 923K, 2.15×10^{-6} cm²/s at 973 K, and 4.62×10^{-6} cm²/s at 1023 K by Chesser et al [12]. However, if considering all of these values are extremely small, this discrepancy is acceptable. When comparing with the diffusion coefficient of lanthanum ion in chloride salt [9,10,11], it is found the one obtained for LaF₆³⁻ in FLiNaK molten salt is much smaller. The reason for this phenomenon was still not well understood. However, the smaller diffusion coefficient of LaF₆³⁻ could be attributed to the difference on the physical properties of molten fluoride salt, for example, the higher viscosity of molten fluoride salt, or different chemical forms of La in molten chloride and fluoride salts.

Based on simulations in molten salt system [20], it is reasonable to assume that the diffusion coefficient is independent of the species concentration. The average values based on the measurement values for the two concentrations at 923, 973, and 1023 K were calculated and given in Figure 4 in the Arrhenius plot. A correlation was obtained:

$$lnD = -1.5945 - 12487/T \tag{2}$$

which can be written in the form of Arrhenius equation:

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{3}$$

where E_a is the activation energy (J/mol), R is the gas constant and T is the temperature (K), the activation energy E_a was acquired with a value of 103.8 kJ/mol which is close to the value of 127 kJ/mol reported in the previous study [12]. The small difference could be attributed to the difference on experimental methods used for the estimation of diffusion coefficient and the inevitable errors existing in the experimental tests, for example, the measurement of the working electrode area.

3.2. Determination of kinetic parameters by potentiodynamic polarization

Kinetics parameters such as exchange current density and charge transfer coefficient are important to understand the reaction kinetics of LaF_6^{3-} to La metal in molten FLiNaK salt. Potentiodynamic polarization can be used to determine the values of these kinetics parameters. In potentiodynamic polarization, the electrode at zero-current potential is in fact under cathodic polarization since the measured current is the sum of charging current and faradic current [21]. Charging current comes from the continuous change of the potential during the scan process and is proportional to scan rate. Based on that the magnitude of charging current decreases with the decreasing scan rate, low scan rate is usually employed in potentiodynamic polarization to minimize the influence of charging current. The zero-current potentials at the scan rates of 0.5 and 1 mV/s are commonly believed to nearly equal to the equilibrium potential [21]. However, the potentiodynamic polarizations at 0.5 and 1 mV/s will take longer time, electrode surface may change greatly during this process and bring more noises to the curve obtained. In the present study, the potentiodynamic polarizations were first carried out at four different scan rates: 0.5, 1, 2, and 5 mV/s. Figure 5 indicates the potentiodynamic polarization curves at these four different scan rates highly coincident on the curve during each scan except the distortion part. Therefore, the scan rate of 5 mV/s is sufficiently low to approach the steady state in the investigated system and will be adopted for all the following tests.

In Figure 5, the potential applied on the inert working electrode (W) was scanned from the negative overpotential to the anodic direction in the potentiodynamic polarization test. In the negative overpotential section, LaF_6^{3-} was reduced to La metal and formed a layer on the tungsten working electrode surface. A distortion on the curve, where the initial potential scan started was observed in this section, could be attributed to the initial development of the diffusion layer. In the positive overpotential section, the dissolution of the deposited La occurs and the current increased with the increase of overpotential. The irregular variation was observed when overpotential η becomes

more positive. This is due to the heterogeneous dissolution of deposited La layer which might not be uniform after negative overpotential scan [15]. Some spots of the deposited La layer might dissolve faster, which will cause the exposure of some parts of the working electrode during the anodic polarization. Thus, the coverage area of La and the measured current will drop suddenly at some points. The dissolution of La layer and the decrease of La coverage area on the electrode with time might be different at different scan rates, as a result, there is an obvious deviation on the distortion area in the positive overpotential scan section for each scan.

Figure 6 illustrates the potentiodynamic polarization curves obtained at the scan rate of 5 mV/s for FLiNaK molten salt containing different concentrations of LaF_3 at the temperatures of 923, 973, and 1023 K, respectively. The figure shows that the measured current density increases with concentration for each temperature. The surface area of the working electrode was used to convert the current to current density based on the assumption that the current is uniformly distributed on electrode surface.

In order to determine the kinetics parameters, an analysis method based on the non-simplified electrode kinetics equation was applied here. This method is verified to be more reliable than the conventional Tafel and linear polarization methods [15]. The non-simplified electrode kinetics equation for the redox reaction of lanthanum ion can be expressed as follows [15]

$$i = \frac{i_0 \left\{ exp\left[\frac{(1-\alpha)nF}{RT}\eta\right] - exp\left(\frac{-\alpha nF}{RT}\eta\right) \right\}}{1 - \frac{i_0}{i_L}exp\left(\frac{-\alpha nF}{RT}\eta\right)}$$
(4)

Where *i* is the current density (A/cm²), i_0 is the exchange current density (A/cm²), *n* is the electron transfer number, α is the charge transfer coefficient, η is the overpotential (V). i_L (A/cm²) is the limiting diffusion current density.

Equation (4) was applied to fit the experimental potentiodynamic polarization curves. The values of the various parameters that best fit the experimental data can be extracted by the least squares fitting procedure through minimizing χ^2 with respect to the 3 fitting parameters: i_0 , i_L , and α . Thus, if we refer to the parameters by a vector $m = [i_0, i_L, \alpha]$, then the Chi-square function to be minimized can be expressed by

$$\chi^{2}(m) = \left| i^{sim}(m) - i^{exp}(m) \right|^{2}$$
(5)

The non-linear least square algorithm can search this 3- dimensional parameter space to find the optimum values that minimize χ^2 . In detailed, the optimization process was performed through iterating the values of i_0 , i_L , and α in the ranges of $0 \le i_0 \le 0.1$ A/cm², -0.1 A/cm² $\le i_L \le 0$, and $0 \le \alpha \le 1$ by the step sizes of 0.00001, 0.0001, and 0.01, respectively. Due to the distortion at the both ends of the experimental polarization curve, the data in the overpotential range of -0.2 to 0.05 V was used to do the fitting. Through this way, these three parameters at which the calculated potentiodynamic polarization best fits the experimental one can be obtained. The solid lines in Figure 7 are the calculated polarization curves at the optimized values. It can be seen that the experimental data at the range (-0.2~ 0.1 V) are fitted well by the method. The optimized values for the parameters are included in Table 3. In addition to the parameters discussed previously, reaction rate constant k^0 is another key kinetics parameter for the understanding of the kinetics of the redox reaction. It is related to the exchange current density i_0 and charge transfer coefficient α by the following correlation [15,19]:

$$i_0 = nFk^0 C_0^{*(1-\alpha)} \tag{6}$$

The values of exchange current density i_0 listed in Table 3 were plotted against its corresponded concentration of LaF₃ in mol/cm³ which can be seen in Figure 8. Equation (6) was used to fit the data points in Figure 8 from which it can be known all data points agree well with the fitted power law trend line. The values of charge transfer coefficient α from the fitted process using equation (6) are 0.47 at 923 K, 0.51 at 973 K, and 0.47 at 1023 K, respectively. These numbers in fact are close to the values of α obtained from the optimization fitting of individual test results (Table 3). Table 4 lists the values of reaction rate constant k^0 determined from the fitted expression by equation (6), from which it can be known reaction rate constant k^0 increases with temperature.

4. Conclusions

The present study explored the fundamental properties of LaF_6^{3-} in FLiNaK molten salt. The diffusion coefficient of LaF_6^{3-} in FLiNaK molten salt was obtained from chronopotentiometry measurements. It is found the diffusion coefficient of lanthanum ion in fluoride salt is much less than that in chloride salt. The diffusion coefficients of LaF_6^{3-} in FLiNaK molten salt at the temperature range of 923 to 1023 K was correlated by lnD = -1.5945 - 12487/T with temperature. Other fundamental parameters including exchange current density, charge transfer coefficient, and reaction rate constant of LaF_6^{3-}/La reaction were measured via performing potentiodynamic polarization tests at three concentrations in the temperature range of 923 K to 1023 K. A non-simplified electrode kinetics equation was employed as the analysis method to nonlinearly fit the obtained potentiodynamic polarization curves through which the values of exchange current density and charge transfer coefficient were obtained. Based on the obtained exchange current density at different concentrations and temperatures, the values of reaction rate constant and charge transfer coefficient were fitted by a correlation equation. The derived reaction

state constant at different temperatures shows that they are positively related. The derived charge transfer coefficient is close to the ones achieved from non-simplified electrode kinetics equation, which indicates the reliability of the obtained results.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure 1. Cyclic voltammograms obtained in FLiNaK-LaF₃ (working electrode area= 0.673 cm^2) and pure FLiNaK molten salts at the scan rate of 100 mV/s reported in the previous study [17].





Figure 2. Chronopotentiograms of LaF₃ in FLiNaK molten salt at the temperatures of (a) 923 K, (b) 973K, and (c) 1023 K. LaF₃= 1.05×10^{-4} mol/cm³; electrode area=0.296 cm².





Figure 3. Linear relationship of *I* versus $\tau^{-1/2}$ for the chronopotentiometry test of LaF₃ in FLiNaK molten salt with the concentration of (a) LaF₃=1.05×10⁻⁴ mol/cm³ and (b) LaF₃=2.25×10⁻⁴ mol/cm³.



Figure 4. Arrhenius plot of diffusion coefficient as a function of temperature.



Figure 5. Potentiodynamic polarization curves measured at different scan rates for LaF₃ in FLiNaK molten salt. LaF₃= 1.58×10^{-4} mol/cm³; T=923K.





Figure 6. Potentiodynamic polarization curves at different concentrations for the temperatures of (a) 923 K, (b) 973 K, and (c) 1023K. Scan rate: 5 mV/s.





Figure 7. Experimental and fitted potentiodynamic polarization curves at the scan rate of 5 mV/s for LaF₃ in FLiNaK molten salt at the temperatures of 923, 973, and 1023 K. (a) LaF₃= 6.31×10^{-5} mol/cm³; (b) LaF₃= 1.58×10^{-4} mol/cm³; (c) LaF₃= 2.59×10^{-4} mol/cm³.



Figure 8. The plot of i_0 from Table 3 versus LaF₃ concentration.

Solutions Mg Al Si P Fe Ni Se Ba Blank 0.0005 0.0092 0.1126 0.0015 0.0014 0.00001 0.0009 0 LiNaK-LaF3 0.0021 0.0094 0.1677 0.0025 0.0026 0.0114 0.0015 0.0000	Solutions				Impurition	es (wt%)			
Blank solution 0.0005 0.0092 0.1126 0.0015 0.0014 0.0001 0.0009 0 LiNaK-LaF3 0.0021 0.0094 0.1677 0.0025 0.0026 0.0114 0.0015 0.000		Mg	Al	Si	Р	Fe	Ni	Se	Ba
	Blank	0.0005	0.0092	0.1126	0.0015	0.0014	0.0001	0.0009	0
Southurs and and and and and and and and	FLiNaK-LaF ₃	0.0021	0.0094	0.1677	0.0025	0.0026	0.0114	0.0015	0.0007
Journal Pression	LiNaK-LaF3	0.0021	0.0094	0.1677	0.0025	0.0026	0.0114	0.0015	0.0007

Table 1. Tr	ace impurities	in the FLiNaK-LaF	F_3 salt and blank solution.
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$C_o^* (\text{mol/cm}^3)$	1.05×10 ⁻⁴				2.25×10 ⁻⁴	
T (K)	923	973	1023	923	973	1023
$D \times 10^{7} (cm^{2}/s)$	3.47	4.92	8.14	2.24	4.76	13.4

			2							
Table 7	Diffusion	agafficienta	afIaE3	$= EI : M_{\odot} V$	molton cold	datamainad	110100.0	anotion	(1)	
rable Z	I JIIIIISION	coefficients (п гілімак	monen san	aererminea	insing e	ппапоп /	()	
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$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Concentration(mol/cm ³)	T (K)	$i_0 (A/cm^2)$	α	i_L (A/cm ²)
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		923	0.00013	0.47	-0.0058
$\frac{1023}{923} 0.00250 0.53} 0.0102 \\ \frac{923}{0.00025} 0.48 0.0049 \\ \frac{973}{0.00120} 0.50 0.0070 \\ \frac{1023}{0.00380} 0.37 0.00169 \\ \frac{923}{973} 0.00080 0.45 0.0010 \\ \frac{973}{1023} 0.000460 0.44 0.0177 \\ \frac{973}{0.00140} 0.0000 \\ \frac{973}{0.00040} 0.44 0.0177 \\ \frac{973}{0.00140} 0.0000 \\ \frac{973}{0.00000} 0.0000 \\ \frac{973}{0.0000} 0$	6.31×10 ⁻⁵	973	0.00069	0.52	-0.0065
923 0.00025 0.48 -0.0049 973 0.00120 0.50 -0.0070 1023 0.00380 0.37 -0.0169 923 0.00000 0.45 -0.0010 973 0.00180 0.52 -0.0109 1023 0.00460 0.44 -0.0177		1023	0.00250	0.53	-0.0102
1.58×10 ⁻⁴ 973 0.00120 0.50 -0.0070 1023 0.00380 0.37 -0.0169 923 0.00060 0.45 -0.0010 973 0.00180 0.52 -0.0179 1023 0.00460 0.44 -0.0177		923	0.00025	0.48	-0.0049
1023 0.00380 0.37 -0.0169 923 0.00060 0.45 -0.0010 973 0.00180 0.52 -0.0109 1023 0.00460 0.44 -0.0177	1.58×10^{-4}	973	0.00120	0.50	-0.0070
2.59×10 ⁻⁴ 923 0.00060 0.45 -0.0010 973 0.00180 0.52 -0.0109 1023 0.00460 0.44 -0.0177		1023	0.00380	0.37	-0.0169
2.59×10 ⁻⁴ 973 0.00180 0.52 -0.0109 1023 0.00460 0.44 -0.0177		923	0.00060	0.45	-0.0010
	2.59×10 ⁻⁴	973	0.00180	0.52	-0.0109
	2.39×10	1023	0.00460	0.44	-0.0177

Table 3. Optimized	parameters determined	oy non-simplified	l electrode kinetics equation	on.
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Table 4. The obtained values of reaction rate constant k^0	at different temperatures using equation
(6).	

T (K) 1023 973 923	$\begin{array}{c} k^{0} \text{ (cm/s)} \\ 7.6 \times 10^{-7} \\ 3.8 \times 10^{-7} \\ 5.9 \times 10^{-8} \end{array}$	