

# MASS TRANSFER ON ROTATING DISK BY ADSORPTION AND ELECTROCHEMICAL METHODS\*

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One of the ways to intensify the process is the use of rotating elements, which increase the mass transfer coefficients many times over. In this study, the mass transfer coefficient was determined by adsorption and electrochemical methods, using a rotating disk (RD) to study the effect of rotation on the mass transfer intensity. For adsorption method, a dilute solution of methylene blue was used, and silica gel foils on rotation disk were used as adsorbents. The measurements were performed under diffusion-controlled conditions, and the color intensity of the surface was determined using Sigma Scan Pro. The study of mass transfer by electrochemical method was performed in batch systems with a volume of 20 dm<sup>3</sup> and 0.8 dm<sup>3</sup>, using a solution of sulfuric acid and copper sulfate, and potassium ferricyanide (III), potassium ferricyanide (II), and potassium chloride. Disks with diameters of 0.8 cm, 1 cm, 2 cm, 5.6 cm, and 20 cm were used in the rotation range up to 800 rpm. After determining the operating voltage, the current intensity was measured at different rpm and the mass transfer coefficients were calculated. It was found that the mass transfer coefficient increases as the rotation speed of the RD increases, and that it does not depend on the diameter of RD. It is shown that the current density increases with the increase of the RD speed, while the diffusion layer thickness decreases. A comparative analysis of the results obtained by the adsorption and electrochemical methods was made and the results were compared with literature correlations.

**Keywords:** mass transfer, rotation disk electrode, diffusion limited current

## Introduction

Mass transfer is a phenomenon in which matter/components are transferred through one or more phases. It is caused by an imbalance in the system, i.e., by unevenly distributed components in the system. One way to intensify the process is to use rotating elements to increase the mass transfer coefficients. The rotating disk (RD) is suitable for studying the reaction under mixed activation-diffusion control because of its technical simplicity and the fact that there is an accurate mathematical model to describe the hydrodynamic system and mass transfer at the electrode. By using a rotating disk, mass transfer near the electrode surface can be controlled and determined. The main advantages of using RD are: technical simplicity, high precision and the possibility of conducting the experiment in a steady state mode [1], the possibility of easy experimental determination and control of the diffusion layer thickness [2], uniform concentration of reactants on the surface of the electrode [2], the constant mass transfer is achieved very quickly, the electrode is not limited to one

metal [2]. A rotating disk electrode (RDE) consists of a disk that can be made of platinum, nickel, copper, silver, iron, silicon, cadmium sulfide, gallium arsenide, glassy carbon, and many other materials [3].

For RD, the convective diffusion model is valid. Due to the use of rotating disk electrode in the solution, strong convection is realized that controls the thickness of the diffusion layer, while diffusion controls the rate of transport of the reactant through the diffusion layer. [4]

A major advantage of using rotating disk electrode (RDE) is that control of mass transfer is achieved in this way. Diffusion control is achieved when the current plateau is reached on the current-potential dependence diagram, that is, when the current does not depend on the potential. This means that the current is limited only by the diffusion of the reactants through the Nernst diffusion layer [5]. The diffusion limited current  $I_d$  can then be described by the Levich equation [6]:

$$I_d = 0.62 \cdot n \cdot F \cdot A \cdot D_0^{2/3} \cdot \nu^{-1/6} \cdot \omega^{1/2} \cdot c_0^0 \dots \dots \dots (1)$$

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where  $n$  is the number of electrons transferred in the reaction,  $F$  is the Faraday constant ( $96\,485\text{ C mol}^{-1}$ ),  $A$  is the electrode geometric area,  $D$  is the diffusion coefficient of the reactant,  $\nu$  is the kinematic viscosity,  $c$  is the bulk concentration of reactant, and  $\omega$  is the rotation speed given in angular velocity [5]. By dividing the diffusion limited current value by the electrode geometric area, the current density value can be obtained.

Levich's equation applies only to the laminar region of electrolyte flow and under conditions where the thickness of the hydrodynamic layer is less than the radius of the electrode. The upper limit of the disk speed for which Levich's equation is valid is determined by the value of the Reynolds number, because it is known that the turbulent flow on the RDE starts at  $Re > 10^5$ . The lower limit of the disk speed is determined by the thickness of the hydrodynamic layer [7]. The Levich's equation shows that the limiting diffusion current density depends linearly on the square root of the rotation speed of the RDE. When the reaction is controlled by activation diffusion, a curved line is obtained for the same dependence. This means that the shape of the dependence  $j_d - \omega^{1/2}$  is an indicator of the type of reaction control [4].

Systems with a rotating disk electrode are widely used to study the kinetics of reactions, which are characterized by a slow rate of mass transfer, define the mechanism of reactions on the catalyst, to evaluate the stability of the catalyst, to produce a new catalyst for oxygen reduction, and to determine the optimal operating conditions. Lee et al. [1] studied the mechanism and kinetics of oxygen reduction on Pt-dispersed carbon (Pt/C) electrodes for fuel cells using RDE. It was found that the reaction mechanism at the Pt/C electrode can be more precisely determined when the RDE technique is combined with the cathodic potentiostatic current transient technique (PCT). The advantage of using RDE is that a constant mass transfer is achieved very quickly and the advantage of the potentiostatic current transient technique is that it provides information on the contribution of diffusion and charge transfer to the kinetics of oxygen reduction [1].

Fleige et al. [5] developed and tested a system with a rotating disk electrode operating under elevated pressure (1–101 bar oxygen), and temperature conditions (140 °C) for oxygen reduction reaction on polycrystalline platinum. Fleige et al. [5] found that RDE is functional under elevated pressure and temperature conditions and that under such conditions, diffusion limited current densities increase by two orders of magnitude compared to conventional RDE setups. By using a high-pressure reactant gas, the problem of low solubility of the gas in the liquid electrolyte, which is a limitation of the use of the rotating disk electrode, is overcome [5]. It was found that at low electrode potential, the measured current densities are fully diffusion controlled, while at higher potentials, a mixed kinetic-diffusion controlled regime is observed [5].

The application of Levich's equation for defining the kinetic current is limited only to reactions in which the

mass transfer of one reactant occurs. In the work of Chen et al. [8], a method was proposed for determining the kinetics of reactions in which the mass transfer of both  $O_2$  and  $H^+$  are slow, by studying the oxygen reduction reaction at Pt in un-buffered solutions with medium pH. During the experiment, Pt single crystal working electrode was used, and Pt wire and Ag/AgCl (with saturated KCl solution) was used as counter electrode and reference electrode [8]. The rate constant for this reaction was found to increase by three orders of magnitude as the pH of the solution increased from 1 to 3. [8]

Kotb and Nasr-El-Din [9] used a system with a rotating disk to investigate the kinetics of the reaction, i.e. the flow regime of Newtonian and non-Newtonian fluids under the rotating disk and the influence of the reactor boundaries on the mass transfer to the disk and the optimal dimensions of the reactor were determined. In this paper, mass transfer in reactors of different dimensions was investigated to determine the optimum dimensions of the reactor that reduce the influence of reactor boundaries on mass transfer. It was found that the mass transfer rate is affected by the axial distance between the base of the disk and the bottom of the reactor, the diameter of the reactor, the rotation speed of the disk and the kinematic viscosity of the reacting fluid.

Asadollahzadeh et al. [10] investigated the recovery of zinc ions in such a system using a rotating disk system. It was found that the zinc yield is affected by the rotation speed of the disk as well as the flow of the organic and aqueous phases, as if the mass transfer coefficient depends on the agitation speed. It was also found that as the mixing speed and net flow rate increased, the axial dispersion coefficient also increased in addition to the mass transfer coefficient.

Martens et al. [11] found in their work that the rotating disk electrode system is suitable for the preliminary screening of fuel cell catalysts. In this paper, a carbon-based platinum reference catalyst was used and the rotating disk electrode technique was tested to compare the correlation of catalyst activity and stability obtained with this technique and other techniques. Sharma et al. [12] investigated the mass and heat transfer during the vertical movement of a rotating disk with a magnetic field that acts perpendicular to the rotation of the disk. The vertical motion of the disk increases the radial and tangential velocity, which affects the heat and mass transfer, i.e. the heat and concentration fields increase.

The aim of this paper was to experimentally determine the mass transfer coefficient from the rotating disc to the fluid by adsorption and electrochemical methods, and to determine the influence of the rotation speed and the diameter of the disk electrode on the mass transfer coefficient. Based on the measurement results, a comparison of the experimental values of the mass transfer coefficient obtained by adsorption and electrochemical methods was made. In the study, the influence of the rotation speed of the disk electrode on the current density and the thickness of the diffusion layer were also investigated.

**Material and methods**

Experimental testing of mass transfer in a rotating system was performed in a batch system with a volume of 20 dm<sup>3</sup> and 0.8 dm<sup>3</sup>. The batch system with a volume of 20 dm<sup>3</sup> contained, depending on the method, a dilute solution of methylene blue or an aqueous solution of copper sulphate to which sulfuric acid was added. A batch system with a volume of 0.8 dm<sup>3</sup> contained an aqueous solution of potassium ferrocyanide (K<sub>4</sub>Fe(CN)<sub>6</sub>), to which potassium ferricyanide (K<sub>3</sub>Fe(CN)<sub>6</sub>) and potassium chloride (KCl) were added. During the experiments, rotating disc electrodes with diameters of 0.8 cm, 1 cm, 2 cm, 5.6 cm and 20 cm were used in the range of rotation speeds up to 800 rpm. For the physical properties of the solution, the physical properties of water at a temperature of 26 °C were used [13].

The characteristics of the system used for testing mass transfer by adsorption and electrochemical methods are given in Table 1.

**Table 1.** Characteristics of the mass transfer testing system by adsorption and electrochemical methods

	System volume, dm <sup>3</sup>	Substances/materials
Adsorption method	20	Diluted solution of methylene blue c=2·10 <sup>-3</sup> g dm <sup>-3</sup>
Electrochemical method.	20	Aqueous solution: CuSO <sub>4</sub> c=0.05 mol dm <sup>-3</sup> H <sub>2</sub> SO <sub>4</sub> c=0.5 mol dm <sup>-3</sup>
	0.8	Aqueous solution: K <sub>4</sub> Fe(CN) <sub>6</sub> c=0.01 mol dm <sup>-3</sup> K <sub>3</sub> Fe(CN) <sub>6</sub> c=0.01 mol dm <sup>-3</sup> KCl c=1 mol dm <sup>-3</sup>

In the study of mass transfer in the rotating system by the adsorption method, silica gel foils were used as adsorbents, which were placed on rotating disks of different diameters and immersed in a methylene blue solution. Mass transfer was measured for 3 minutes, after which the silica gel foil was removed from the rotating disc and a new foil was placed on the disc. After the silica gel foils were dried and scanned, the images were processed using "Sigma Scan Pro 5" software and the coloration of the surface of the silica gel foil was determined. On the scanned image of the silica gel foil, a specific area was marked with the mouse pointer, for which the program then indicated the value of the average color intensity. The coloration of the silica gel foil was determined three times for the reliability of the measurement, and then the average value of the measurement was calculated, which was taken as the final value of the coloration of the silica gel foil for the given number of revolutions.

The coloration of the silica gel foil corresponds to the adsorbed amount of methylene blue [14-15].

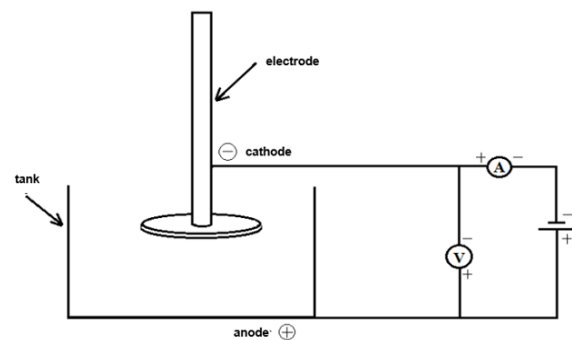
Based on the surface concentration, the mass transfer coefficient is determined according to the following equation:

$$k = \frac{c_p}{c_0 \cdot t} \dots\dots\dots(2)$$

Nešić et al. [16] used a similar method to test the sorption of methyl violet dye on mesoporous silica. The method was based on determining the coloration intensity of the samples using software and the relationship between the coloration intensity of the samples and the concentration of the dye in the aqueous solution.

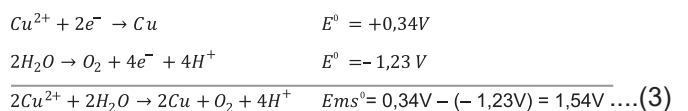
The electrochemical method is based on mass transfer during an electrochemical reaction under diffusion-controlled conditions. The electrode material is in the form of a cylinder, which is pressed into a larger cylinder of non-conductive material so that their end faces lie in one plane. The electrode is placed vertically in the solution and rotated about its vertical axis. The higher the rotation speed, the more intense the transport of the reactant to the electrode surface, the thinner the diffusion layer and the higher the measured current density [4]. The apparatus consisted of an autotransformer, a rectifier converting alternating current to direct current, a voltmeter and an ammeter, a tank containing an electrolyte solution, and an electrode connected to a variable speed-regulated motor. Another electrode made of prochromic steel was immersed in the tank containing the electrolyte solution, which acted as the anode, and the reduction took place at the rotating disk electrode, which served as the cathode.

The scheme of the experimental data system is shown in Figure 1.

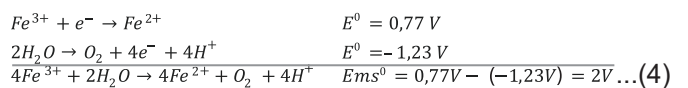


**Figure 1.** Scheme of the experimental system (electrochemical method)

The reactions at the cathode and anode during the electrolysis of the copper sulfate solution [17] are:



The reactions at the cathode and anode during the electrolysis of potassium ferricyanide, potassium ferrocyanide and potassium chloride solutions [17] are:



The current value was measured at different rotation

speeds of the electrode. For a given rotation speed value, the current was measured three times to check the reliability of the measurement, and then the mean value of the measurement was calculated, which was taken as the final value of the current for the given rotation speed.

The measurement error was  $\pm 0.3$  mA. The measurement was repeated for different numbers of revolutions (from 0 to 700 rpm) and at each number of revolutions the current was measured. The same experimental procedure was repeated for different electrode diameters for the 20 dm<sup>3</sup> and 0.8 dm<sup>3</sup> volume system. A total of 25 experiments were performed for the 20 dm<sup>3</sup> volume system and 33 experiments for the 0.8 dm<sup>3</sup> volume system, with each current measurement being performed three times to ensure the reliability of the measurement.

Based on the measured value of the current and the electrode geometric area, the experimental values of the current density were determined according to the following equation:

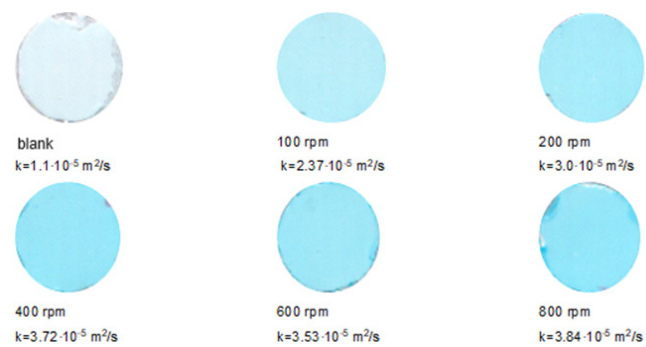
$$j_d = \frac{I_d}{A} \dots\dots\dots(5)$$

Based on the obtained value of the current density, the value of the mass transfer coefficient was determined:

$$k = \frac{j_d}{n \cdot F \cdot c_0} \dots\dots\dots(6)$$

**Results and discussion**

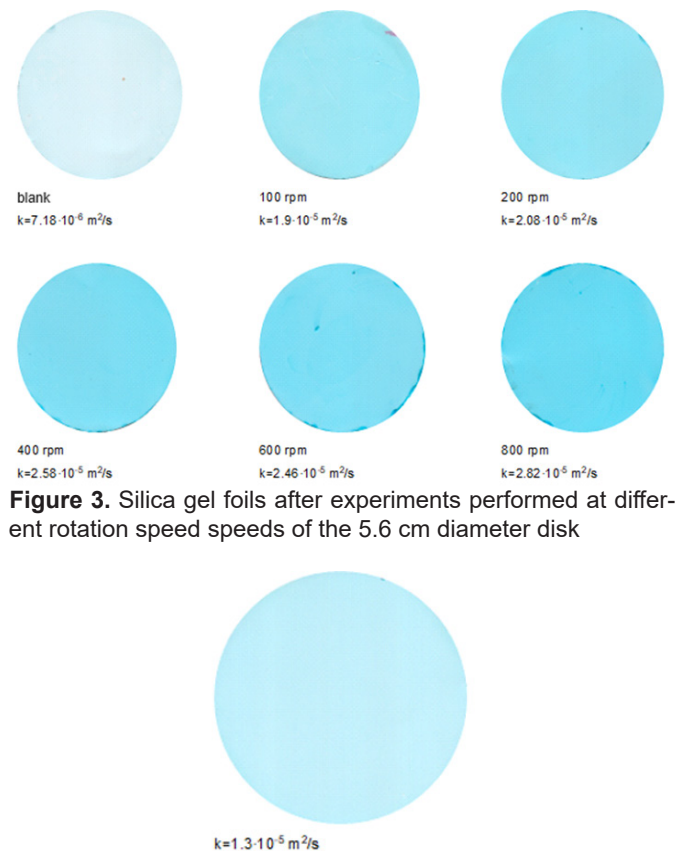
Determination of the mass transfer coefficient by the adsorption method



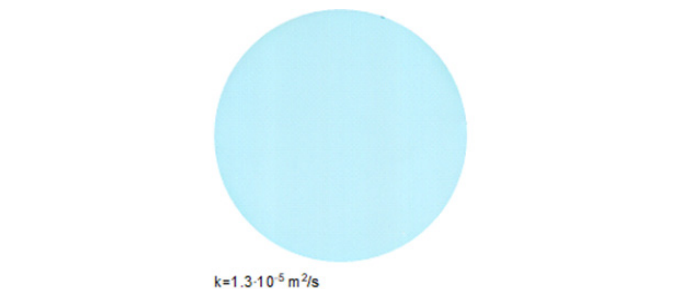
**Figure 2.** Silica gel foils after experiments performed at different rotation speeds of the 2 cm diameter disk

Figures 2, 3, and 4 show silica gel foils at different rotation speeds using rotating disk with diameters of 2 cm, 5.6 cm, and 20 cm, respectively, and the corresponding values of mass transfer coefficients obtained based on the obtained values of average color intensity. Analyzing Figures 2 and 3, it was found that the appearance of the silica gel foil depends on the rotation speed of the rotating disk electrode. As the rotation speed of the disk increases, the coloration of the silica gel film becomes more intense because better mass transfer was

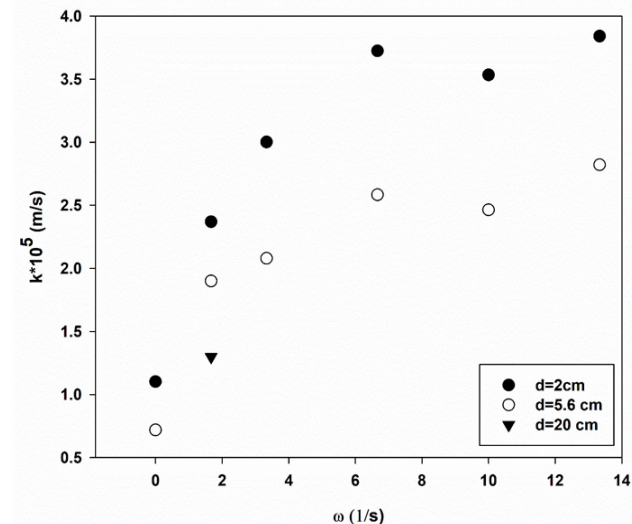
achieved. By comparing the mass transfer coefficient values, it can be found that the mass transfer coefficient is 2.43-3.93 times higher for rotating disks than for stationary disks.



**Figure 3.** Silica gel foils after experiments performed at different rotation speed speeds of the 5.6 cm diameter disk



**Figure 4.** Silica gel foil after the experiments performed at a rotation speed of 100 rpm of the 20 cm diameter disk



**Figure 5.** Dependence of the mass transfer coefficient on the rotation speed of a disc with a diameter of 2 cm, 5.6 cm and 20 cm

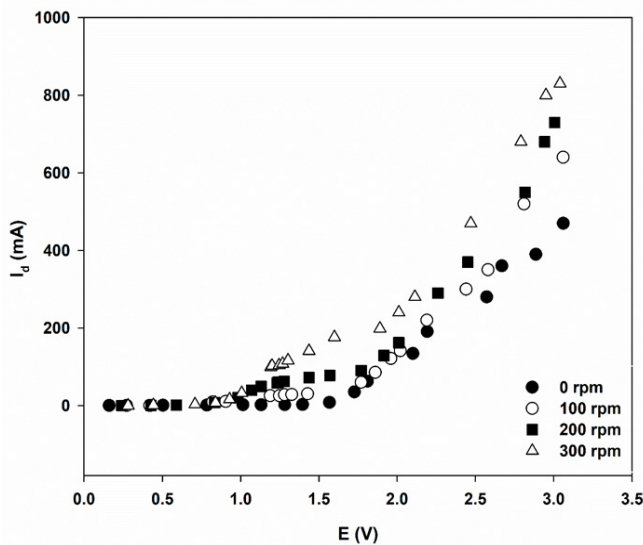
Figure 5 shows the dependence of the mass transfer coefficient on the rotation speed of a disk with different diameters. It can be observed that the value of

the mass transfer coefficient increases as the rotation speed of the disk increases. At a higher rotation speed ( $> 6 \text{ s}^{-1}$ ), the values of mass transfer coefficients change slightly and practically do not depend on the disk rotation speed. From the analysis of Figure 5, it can be seen that the highest value of mass transfer coefficient is obtained when using a disk with a diameter of 2 cm, i.e. the mass transfer coefficient decreases as the disk diameter increases.

Determination of the mass transfer coefficient by the electrochemical method

The experimental studies on mass transfer using the electrochemical method were first carried out in a batch system with a volume of  $20 \text{ dm}^3$ . First, the operating potential was determined by measuring the current for different voltages at a constant rotation speed, based on which the polarization curves were constructed. The measurement was repeated for different numbers of revolutions (0, 100, 200, and 300 rpm), and the value corresponding to the initial part of the plateau on the polarization curve was taken as the operating potential. Before reaching the operating potential, the polarization curves pass through the region where the measured current is controlled by kinetics and mass transport [5]. When the current plateau is reached on the current-potential dependence diagram, the current is limited only by the diffusion of the reactants through the Nernst diffusion layer [5].

The polarization curves for an electrode with a diameter of 0.8 cm are shown in Figure 6. It was found that as the diameter of the electrode increases, it becomes increasingly difficult to determine the operating potential as the region of limiting diffusion current decreases. Therefore, the operating potential could not be determined for the electrode with a diameter of 20 cm.



**Figure 6.** Polarization curve for an electrode with a diameter of 0.8 cm in a system with a volume of  $20 \text{ dm}^3$

Based on the polarization curves, the operating potential for electrodes with different diameters was determined and shown in Table 2.

**Table 2.** Operating potential for electrodes with different diameters in a system with a volume of  $20 \text{ dm}^3$

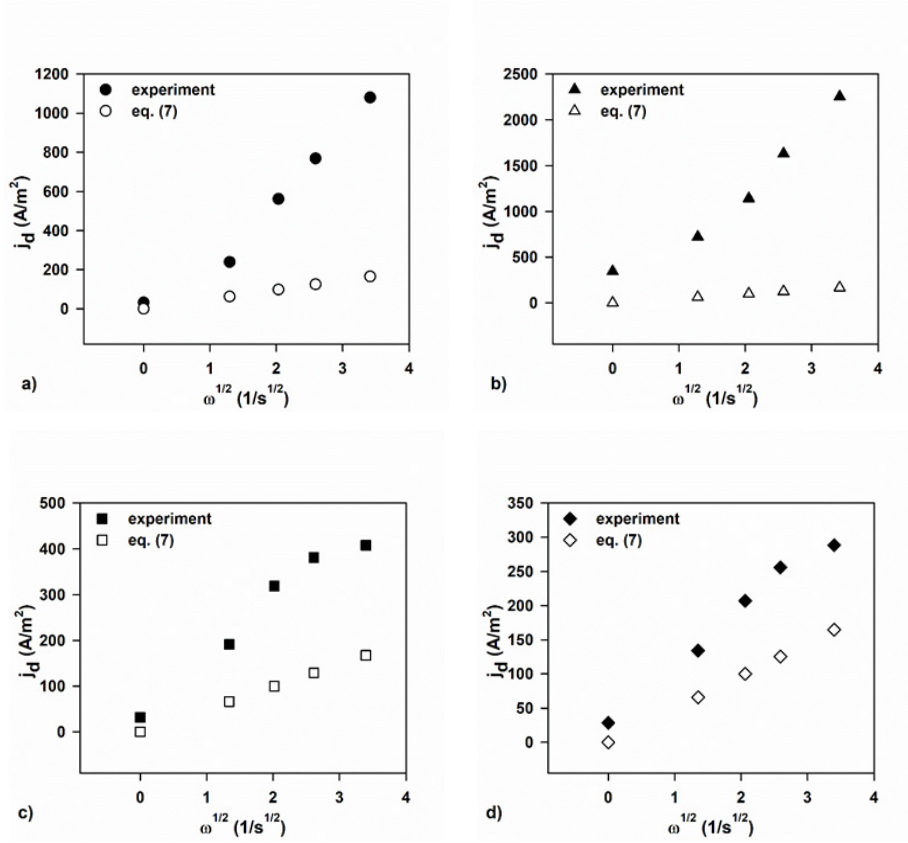
Electrode diameter, cm	Operating potential, V
0,8	1,2
1,0	1,2-1,3
2,0	1,3
5,5	1,5

After determining the operating potential, based on the measured values of the current at different rotation speeds of the electrode, an experimental value of the current density for different rotation speeds of the electrode was obtained. The obtained value of current density was compared with the theoretical value determined by Levich's equation [6]:

$$j_d = 0.62 \cdot n \cdot F \cdot D_0^{2/3} \cdot \nu^{-1/6} \cdot \omega^{1/2} \cdot c_0 \dots \dots \dots (7)$$

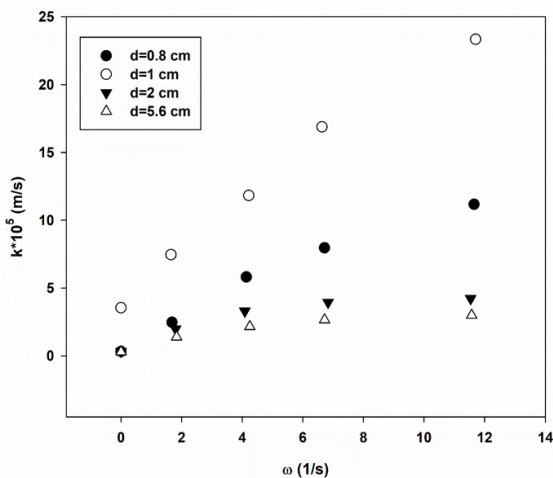
Figures 7a, 7b, 7c, and 7d show a comparison of the theoretically calculated and experimentally determined current density values as a function of rotation speed for electrodes with different diameters. The linear dependence of the experimentally determined current density values on the electrode rotation speed indicates that the reaction is controlled by diffusion. The current density increases with increasing rotation speed because due to greater centrifugal forces, strong convection is achieved, which improves the mass transfer rate [18]. It can be observed that the experimentally determined values differ from the theoretical values. This could be due to the low concentration of sulfuric acid added, making the migration currents more dominant. Parallel reactions can take place at the prochromic electrode, which also has an influence on the deviation of the experimental from the theoretical values.

Based on the experimentally measured values of the current density, the experimental value of the mass transfer coefficient was obtained (equations 5 and 6).



**Figure 7.** Comparison of experimental values of current density with values calculated by correlation (7) for electrodes with a diameter of a) 0.8 cm b) 1 cm c) 2 cm d) 5.6 cm in a system with a volume of 20 dm<sup>3</sup>

Figure 8 shows the dependence of the mass transfer coefficient on the rotation speed of electrodes with different diameters. From the analysis of Figure 8, it is clear that the influence of the electrode diameter on the value of the mass transfer coefficient cannot be accurately determined because the value of the mass transfer coefficient does not change properly with the electrode diameter.

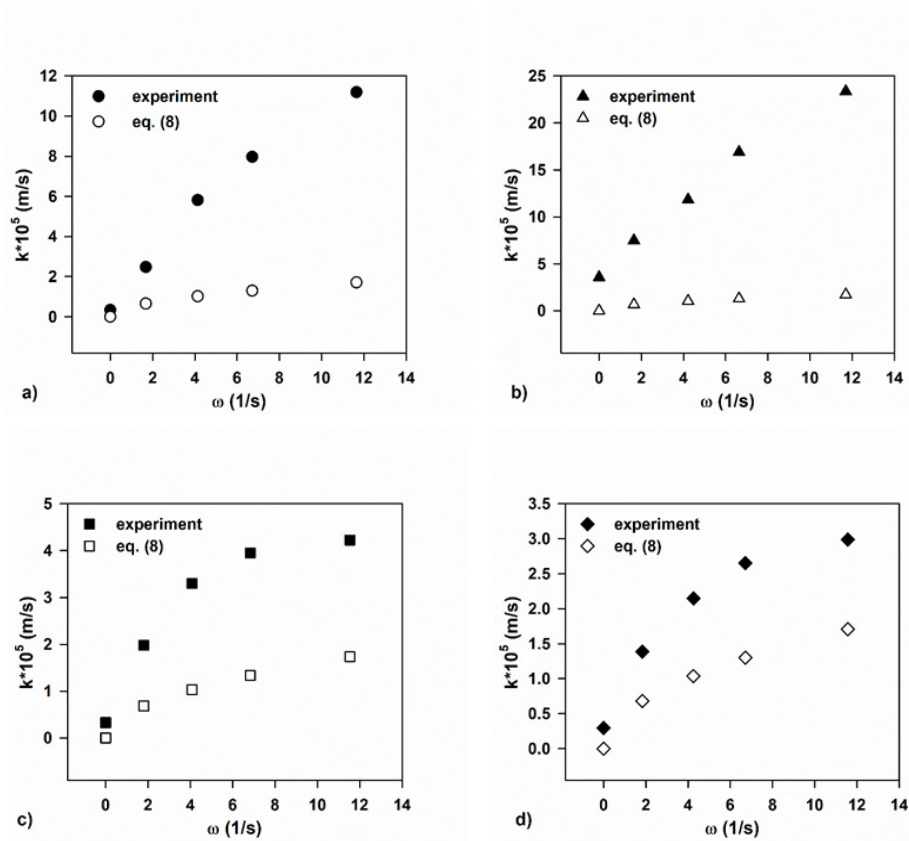


**Figure 8.** Dependence of the mass transfer coefficient on the rotation speed of electrodes with different diameters in a system with a volume of 20 dm<sup>3</sup>.

By combining equations (6) and (7), the theoretical value of the mass transfer coefficient was obtained:

$$k = 0.620 \cdot D_0^{2/3} \cdot \nu^{-1/6} \cdot \omega^{1/2} \dots \dots \dots (8)$$

Figures 9a, 9b, 9c, and 9d show a comparison of the theoretically calculated and experimentally determined values of the mass transfer coefficient as a function of rotation speed for electrodes with different diameters. The mass transfer coefficient was found to increase with increasing electrode rotation speed, but the experimentally determined mass transfer coefficient values did not show good agreement with the theoretically calculated values. The mean relative error between the experimental and theoretical mass transfer coefficient values is 34.3%. The reason for this may be a low sulfuric acid concentration, which is why mass transfer occurs not only by diffusion and convection, but also by ion migration. This leads to oscillations of the electrode and to the deviation of the experimentally determined values of the mass transfer coefficients from the theoretically calculated ones. Analyzing Figures 9a, 9b, 9c and 9d, it was observed that with the increase in the diameter of the electrode, the agreement between the experimentally obtained coefficient values and the theoretically determined ones is better.



**Figure 9.** Comparison of experimental values of the mass transfer coefficient with values calculated by correlation (8) for electrodes with a diameter of a) 0.8 cm, b) 1 cm, c) 2 cm, d) 5.6 cm in a system with a volume of 20 dm<sup>3</sup>

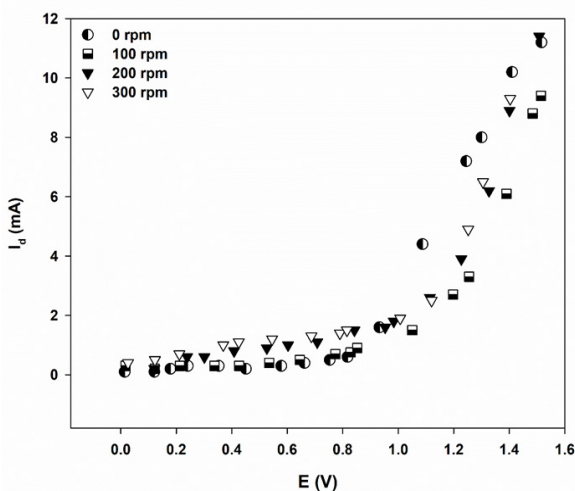
Due to the deviation of the experimentally determined values of the mass transfer coefficient from the theoretical values, the experiment was repeated in a batch system with a volume of 0.8 dm<sup>3</sup> containing an aqueous solution of potassium ferricyanide, potassium ferrocyanide, and potassium chloride. Electrodes with a diameter of 0.8 cm, 1 cm and 2 cm were used.

First, the operating potential was determined, by measuring the current for different potentials at a constant number of revolutions, on the basis of which the polarization curves were constructed. The measurement was repeated for several different numbers of revolutions (0, 100, 200 and 300 rpm) and the value corresponding to the initial part of the plateau on the polarization curve was adopted as the operating potential. The polarization curves for the electrode with a diameter of 1 cm are shown in Figure 10.

Based on the polarization curves, the operating potential for electrodes with different diameters were determined and shown in Table 3.

**Table 3.** Operating potential for electrodes with different diameters in a system with a volume of 0.8 dm<sup>3</sup>

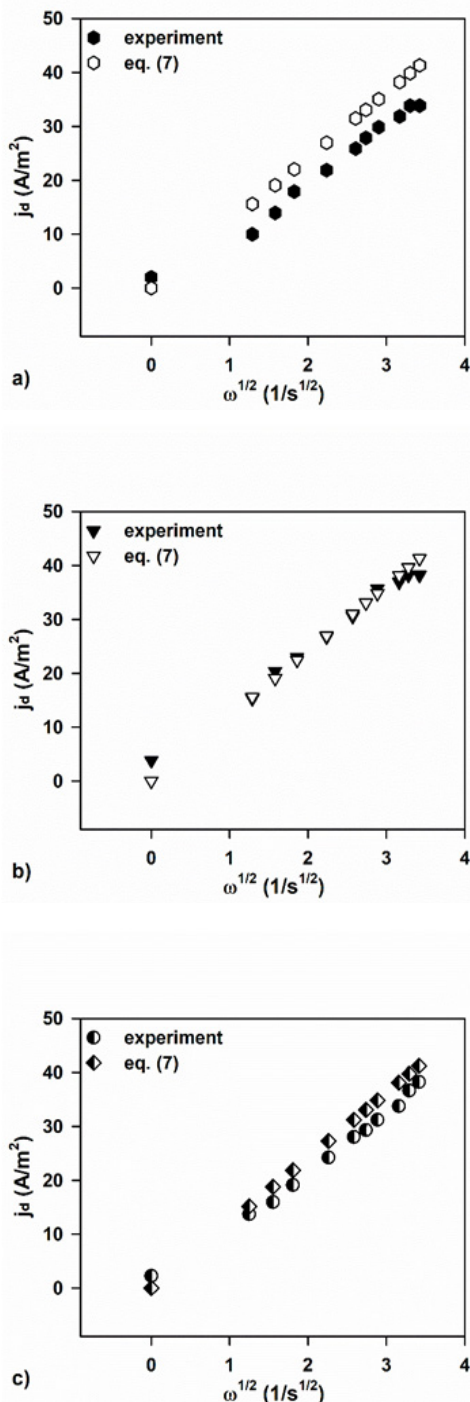
Electrode diameter, cm	Operating potential, V
0,8	0.5
1,0	0.6
2,0	0.5



**Figure 10.** Polarization curve for an electrode with a diameter of 1 cm in a system with a volume of 0.8 dm<sup>3</sup>

After determining the operating potential, the current was measured at different rotation speeds of the electrode and the experimental value of the current density was obtained based on the measured current values. A comparison was made between the experimental and

the theoretical value of the current density (obtained using equation 7).

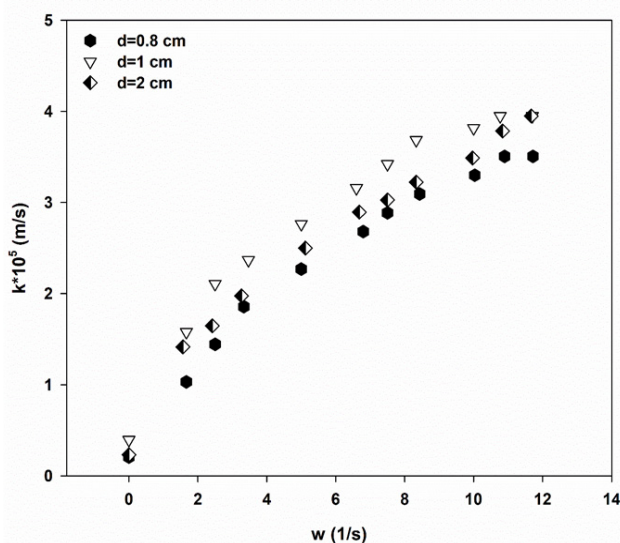


**Figure 11.** Comparison of experimental values of current density with values calculated by correlation (7) for disc electrodes with a diameter of a) 0.8 cm b) 1 cm c) 2 cm in a system with a volume of 0.8 dm<sup>3</sup>

Figures 11a, 11b and 11c show a comparison of theoretically calculated and experimentally obtained current density values depending on the rotation speed for electrodes with different diameters. By analyzing Figure 11a,

11b and 11c, a linear dependence of the current density on the rotation speed of the electrode can be observed, which proves that the reaction is diffusion controlled. The experimental data agree well with the theoretical values. It is noted that in the case of electrodes with a diameter of 0.8 cm and 2 cm, the experimentally obtained current density values are lower than the theoretical values.

Based on the experimentally measured and theoretically calculated values of the current density, the mass transfer coefficient was also calculated. Figure 12 shows the dependence of the mass transfer coefficient on the speed of rotation of electrodes with different diameters.

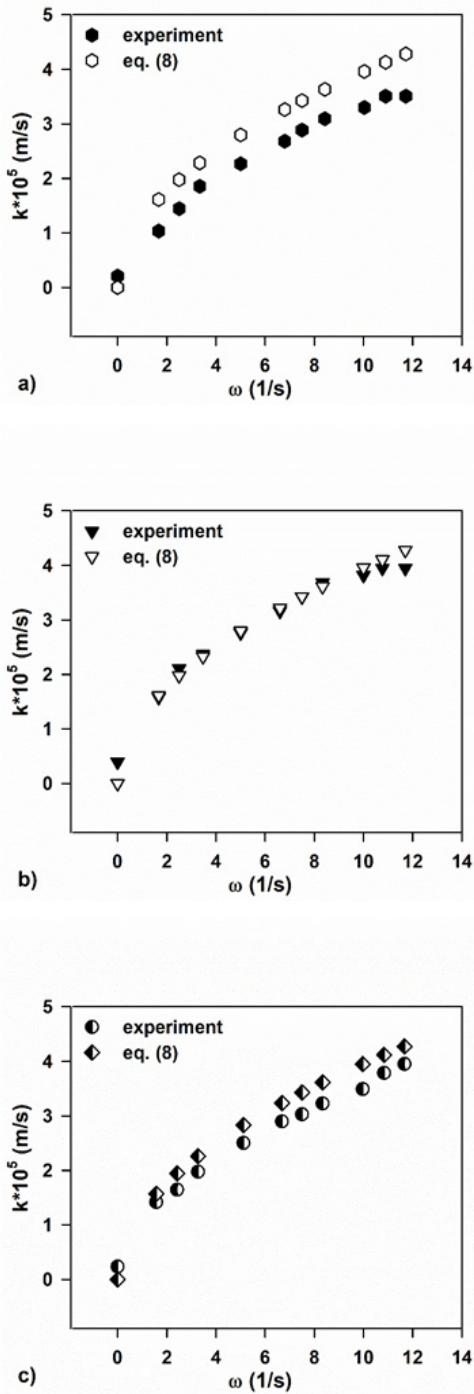


**Figure 12.** Dependence of the mass transfer coefficient on the rotation speed of electrodes with different diameters in a system with a volume of 0.8 dm<sup>3</sup>

The analysis of Figure 12 shows that the influence of the electrode diameter on the value of the mass transfer coefficient cannot be accurately determined because the value of the mass transfer coefficient does not change properly with the electrode diameter. This can also be deduced from equation (8), which shows that the mass transfer coefficient does not depend on the electrode diameter, but on the number of revolutions, viscosity and diffusion coefficient.

Figures 13a, 13b and 13c show a comparison of the theoretically calculated and experimentally determined values of the mass transfer coefficient as a function of rotation speed for electrodes with different diameters. It can be observed that the mass transfer coefficient increases with increasing rotation speed of the electrode. The experimentally determined values of the mass transfer coefficient show good agreement with the theoretical values. The average relative error between the experimental and theoretical values of the mass transfer coefficient is -13.05%.



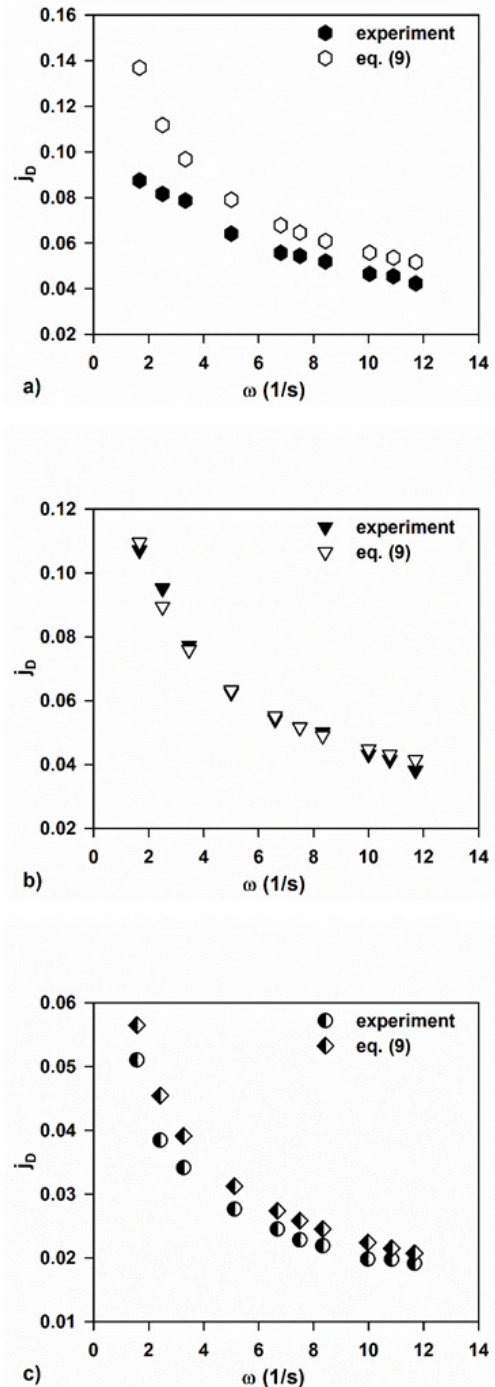


**Figure 13.** Comparison of experimental values of the mass transfer coefficient with values calculated by correlation (8) for disk electrodes with a diameter of a) 0.8 cm, b) 1 cm, c) 2 cm

Based on the obtained values of the mass transfer coefficient, the dimensionless mass transfer factor  $j_D$  was determined:

$$j_D = \frac{Sh}{Sc^{1/3} \cdot Re} \dots\dots\dots(9)$$

Figure 14 shows a comparison of experimental and theoretical values of the dimensionless mass transfer factor as a function of the rotation speed for electrodes with different diameters. From Figure 14, it can be seen that the dimensionless mass transfer factor decreases with increasing RDE rotation speed, and the experimental results agree well with the theoretical values.

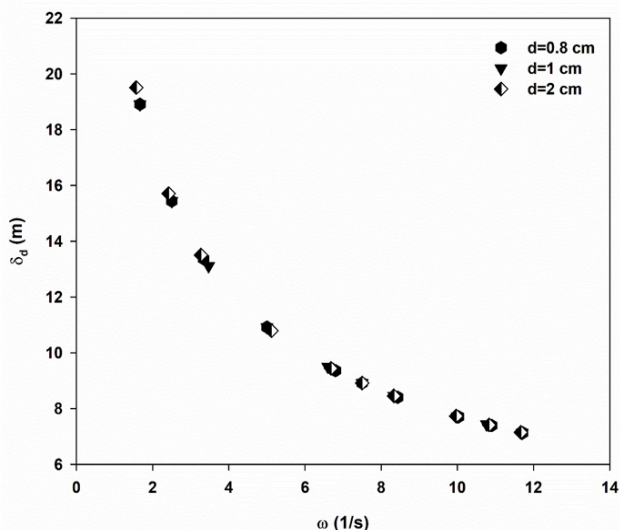


**Figure 14.** Comparison of experimental values of the dimensionless mass transfer factor with values calculated by correlation (9) for electrodes with a diameter of a) 0.8 cm, b) 1 cm, c) 2 cm

The Nernst diffusion layer model assumes that the concentration profile of the reactants is linear, which means that within this layer mass transfer occurs exclusively by diffusion and outside exclusively by convection. Using the Levich's equation [6], the thickness of the Nernst diffusion layer can be determined using the following correlation:

$$\delta_d = 1.61 \cdot D_0^{2/3} \nu^{1/6} \cdot \omega^{-1/2} \dots \dots \dots (10)$$

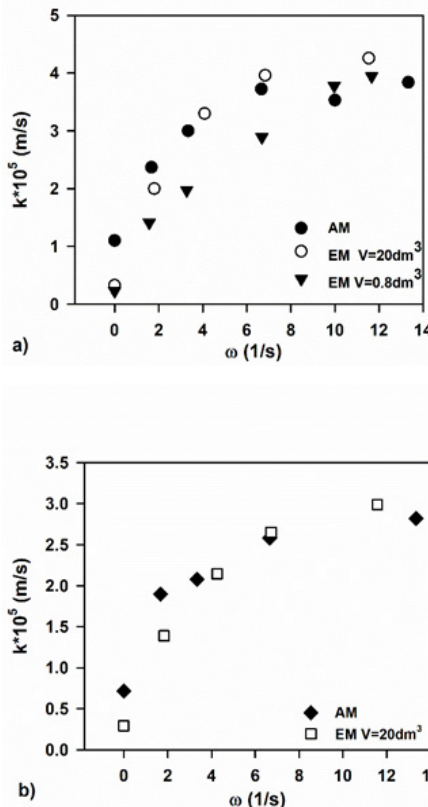
Figure 15 shows the dependence of the thickness of the diffusion layer on the rotation speed of electrodes with different diameters. It can be observed that the thickness of the diffusion layer decreases as the rotation speed of the RDE increases and does not depend on the diameter of the electrode, which can also be concluded from equation (10).



**Figure 15.** Dependence of the thickness of the diffusion layer on the rotation speed of electrode with different diameters

The mass transfer coefficient values obtained by the adsorption method were compared with the mass transfer coefficient values obtained by the electrochemical method for disks/electrodes with diameters of 2 cm and 5.6 cm. Figure 16 shows the dependence of the mass transfer coefficient on the electrode rotation speed obtained by the electrochemical method (EM) and the same dependence obtained by the adsorption method (AM) for a disk with a diameter of 2 cm (Figure 16a) and a disk with a diameter of 5.6 cm (Figure 16b). For electrodes/disks with diameters of 2 cm and 5.6 cm, the mass transfer coefficient values obtained by the electrochemical method are lower than those obtained by the adsorption method at a lower number of rotations, and at a higher number of rotations, the mass transfer coefficient values obtained by the adsorption and electrochemical methods are approximately the same. It can be noted that the values of mass transfer coefficients increase slightly with the rotation speed of the disk when the number of revolutions exceeds 6s<sup>-1</sup> and do not depend on the rotation speed of the disk/electrode, regardless of the method used to determine the mass transfer coefficient.

lutions exceeds 6s<sup>-1</sup> and do not depend on the rotation speed of the disk/electrode, regardless of the method used to determine the mass transfer coefficient.



**Figure 16.** Comparison of experimental values of the mass transfer coefficient obtained by adsorption (AM) and electrochemical methods (EM) for a disk/electrode with a diameter of a) 2 cm and b) 5.6 cm

**Conclusion**

In this paper, the mass transfer coefficient from the rotating disk to the fluid was determined experimentally by adsorption and electrochemical methods.

When the mass transfer was tested by the adsorption method, it was found that as the rotation speed of the disk increases, the intensity of the surface coloration increases and so does the mass transfer coefficient. At a higher rotation speed (> 6s<sup>-1</sup>), the values of the mass transfer coefficients change only slightly, so that they practically do not depend on the rotation speed of the disk. It was found that the highest value of the mass transfer coefficient is obtained when using a disk with a diameter of 2 cm, i.e. the mass transfer coefficient decreases with increasing disk diameter.

When the mass transfer was studied by electrochemical method in an aqueous solution of copper sulfate and sulfuric acid, a linear dependence of the experimental current density values on the electrode rotation speed was found, indicating a diffusion-controlled reaction. However, the experimentally determined mass transfer

coefficient values did not show good agreement with the theoretically calculated values, which was due to the low sulfuric acid concentrations causing ion migration and electrode vibration. The mean relative error between the experimental and theoretical mass transfer coefficient values was 34.3%.

The experimental determination of the mass transfer coefficient was carried out by the electrochemical method in an aqueous solution of potassium ferricyanide, potassium ferrocyanide, and potassium chloride. The results of these measurements showed good agreement between the experimental values of the mass transfer coefficients and the theoretically calculated values with a mean relative error of -13.05%. The results in this system showed that the dimensionless mass transfer factor and the thickness of the diffusion layer decrease with increasing RDE rotation speed, and that the mass transfer coefficient and the thickness of the diffusion layer do not depend on the electrode diameter.

By comparing the mass transfer coefficient values obtained by the electrochemical and adsorption methods, it was found that the mass transfer coefficient values obtained by the electrochemical method are lower than those obtained by the adsorption method at a lower number of revolutions. At a higher number of revolutions, the values of mass transfer coefficients obtained by the adsorption and electrochemical methods are approximately equal. At a number of revolutions greater than  $6s^{-1}$ , the values of mass transfer coefficients increase slightly with the rotation speed of the disk, regardless of the method used to determine the mass transfer coefficient.

### Nomenclature

$A$	electrode geometric area, $m^2$
$c_o$	bulk concentration of methylene blue, $kg/m^3$
$c_p$	surface concentration of methylene blue on adsorbent layer, $kg/m^2$
$c_o^o$	bulk concentration of reactant, $mol/m^3$
$d$	disk / electrode diameter, $cm$
$D_o$	the diffusion coefficient of the reactant, $m^2/s$
$E$	electrode potential, $V$
$F$	Faraday constant (96 485 C/mol)
$I_d$	diffusion limited current, $A$
$j_d$	limit diffusion current density, $A/m^2$
$j_D$	dimensionless mass transfer factor
$k$	mass transfer coefficient, $m/s$
$n$	number of electrons transferred in the reaction
$t$	time, $s$
$Re$	Reynolds number, $(\omega \cdot d/\nu)$
$Sh$	Sherwoods number $(k \cdot d/D_o)$
$Sc$	Schmidts number $(\nu/D_o)$

### Greek letters

$\nu$	kinematic viscosity, $m^2/s$
$\omega$	disk / electrode rotation speed, $rpm$ or $1/s$

$\delta_d$	thickness of the diffusion layer, $m$
$\delta_h$	thickness of the hydrodynamic layer, $m$

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## Izvod

# PRENOS MASE NA ROTIRAJUĆI DISK ADSORPCIONOM I ELEKTROHEMIJSKOM METODOM

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Jedan od načina za intenzifikaciju procesa je upotreba rotirajućih elemenata, koji višestruko povećavaju koeficijente prenosa mase. U ovom radu, koeficijent prenosa mase je određen adsorpcionom i elektrohemijom, korišćenjem rotirajućeg diska (RD) u cilju proučavanja uticaja rotacije na intenzitet prenosa mase. Pri ispitivanju prenosa mase adsorpcionom metodom, korišćen je razblažen rastvor metilenskog plavog, a kao adsorbenti su korišćene folije silika gela na rotirajućem disku. Merenja su obavljena u difuziono kontrolisanim uslovima, a intenzitet obojenja površine je određen korišćenjem softvera Sigma Scan Pro. Ispitivanje prenosa mase elektrohemijom izvedeno je u šaržnim sistemima zapremine 20 dm<sup>3</sup> i 0,8 dm<sup>3</sup>, korišćenjem rastvora sumporne kiseline i bakar sulfata, i kalijum fericijanida(III), kalijum fericijanida(II) i kalijum hlorida. Korišćeni su diskovi prečnika 0,8 cm, 1 cm, 2 cm, 5,6 cm i 20 cm u opsegu rotacije do 800 o/min. Nakon određivanja radnog napona, meren je intenzitet struje pri različitim obrtajima i izračunati su koeficijenti prenosa mase. Utvrđeno je da se koeficijent prenosa mase povećava sa povećanjem brzine rotacije RD, i da ne zavisi od prečnika RD. Pokazano je da gustina struje raste sa povećanjem brzine rotacije RD, dok se debljina difuzionog sloja smanjuje. Urađena je komparativna analiza rezultata dobijenih adsorpcionom i elektrohemijom, kao i poređenje dobijenih rezultata sa literaturnim korelacijama.

**Ključne reči:** prenos mase, rotirajuća disk elektroda, granična difuziona struja