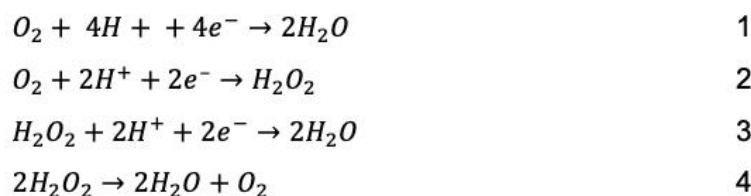


# Oxygen Reduction Reaction with the Rotating Ring Disk Electrode

The oxygen reduction reaction (ORR) is one of the most studied reactions in the field of electrocatalysis. The ORR in aqueous acidic electrolyte can proceed through different pathways depending on the reaction conditions. In most cases, the desired

reaction is the 4-electron process shown in **Equation 1**. Other possible reaction pathways include the combinations of **Equations 2** and **3**, where  $H_2O_2$  is formed as an intermediate, and **Equations 2** and **4**, where the reduction is incomplete.



## RÉSUMÉ

If hydrogen peroxide ( $H_2O_2$ ) is formed as a product or intermediate during the ORR, it can be detected

electrochemically through its oxidation reaction, **Equation 5**.



The ORR is generally studied in hydrodynamic conditions using a rotating working electrode (WE) to induce forced convection within the electrochemical cell. This strategy is applied to achieve a stable mass

transfer limited current density that may otherwise be difficult to maintain because of the slow kinetics of the reaction. In this application note, a rotating ring disk electrode (RRDE) set up is used to study the ORR.

## EXPERIMENTAL CONDITIONS

An Autolab PGSTAT302N potentiostat/galvanostat fitted with the BA module, a dual-mode bipotentiostat, was used in combination with the Autolab RRDE hardware. The measurements were carried out in a four electrode configuration using the Autolab RRDE electrochemical cell.

Since the electrochemical signals from Pt electrodes are sensitive to system impurities, all cell components in contact with the electrolyte were thoroughly cleaned. The cleaning procedure consists of soaking the components a diluted solution of  $\text{H}_2\text{SO}_4$  with  $\text{H}_2\text{O}_2$ , followed by rinsing several times with boiling water. The working electrodes were the Pt disk (WE1) and Pt ring (WE2), which are both built into a single RRDE tip. The RRDE tips have a theoretical collection efficiency of 24.9% based on the geometry of the disk and the ring. Determination of the experimental collection efficiency and the meaning of the theoretical collection efficiency value are outside the scope of this application note. The counter electrode (CE) was a platinum sheet and the reference electrode

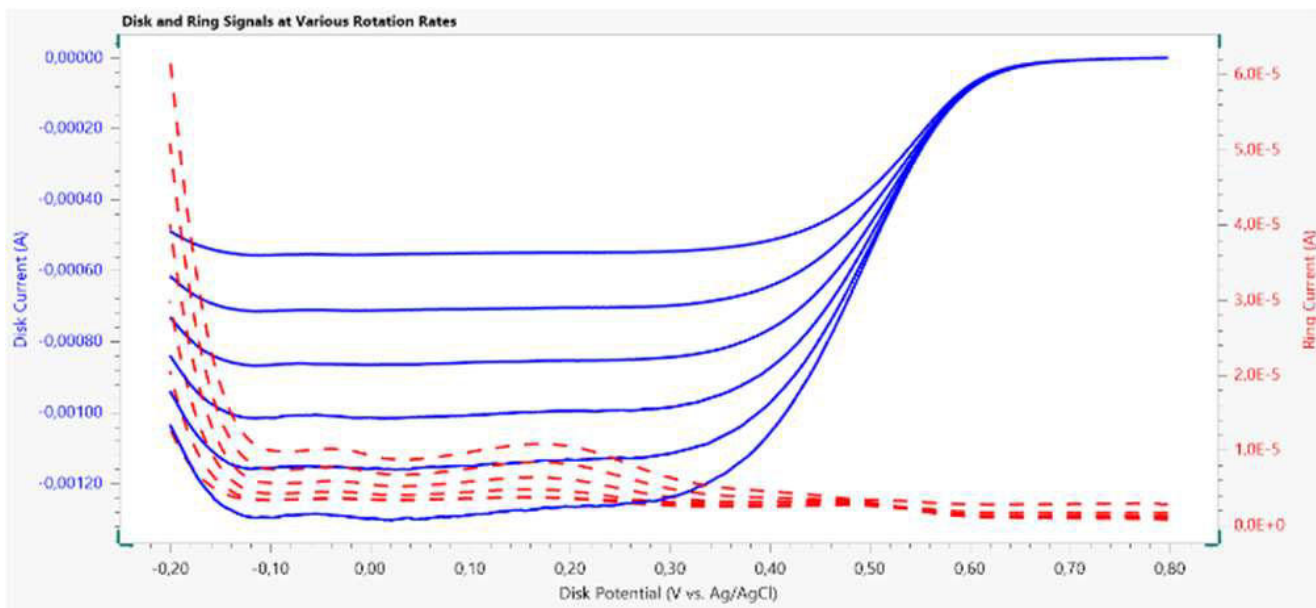
(RE) was a double junction Ag/AgCl electrode with 3 M aqueous KCl solution in the inner compartment and the working electrolyte (0.5 M  $\text{H}_2\text{SO}_4$ ) in the outer compartment. Both the CE and the RE were inserted into the cell at a height slightly above that of the bottom of the RRDE electrode tip in order to avoid disturbing the hydrodynamic flow profile. The 0.5 M  $\text{H}_2\text{SO}_4$  electrolyte was purged with high purity  $\text{O}_2$  gas for fifteen minutes prior to beginning the experiments in order to reach a saturated concentration of dissolved  $\text{O}_2$ . During the measurement, a blanket of  $\text{O}_2$  gas was maintained over the surface of the electrolyte to ensure that the concentration of dissolved  $\text{O}_2$  remained stable.

The experimental procedure *hydrodynamic linear sweep with RRDE* was applied using the NOVA software. At the disk, linear voltammetry staircase sweeps from 0.70 to  $-0.20$  V vs. Ag/AgCl were applied with various electrode rotation rates ( $\omega$ ). At the ring, the potential was fixed at 1.00 V and the current response was recorded.

## EXPERIMENTAL RESULTS

Figure 1 shows the results of a typical ORR RRDE experiment. The blue curves correspond to the current at the Pt disk (WE1) as the  $E$  is swept from 0.70 to  $-0.20$  V at a scan rate of  $50 \text{ mV s}^{-1}$  with

various electrode rotation rates ( $\omega$ ). The red curves correspond to the current signal at the Pt ring (WE2), whose potential is fixed at a value of 1.00 V, at the same  $\omega$  values as the disk.



**Figure 1.** Plot of the disk (blue solid lines) and ring (red dashed lines) current data vs. the disk potential, collected during the hydrodynamic RRDE study of the ORR using a Pt disk and Pt ring.

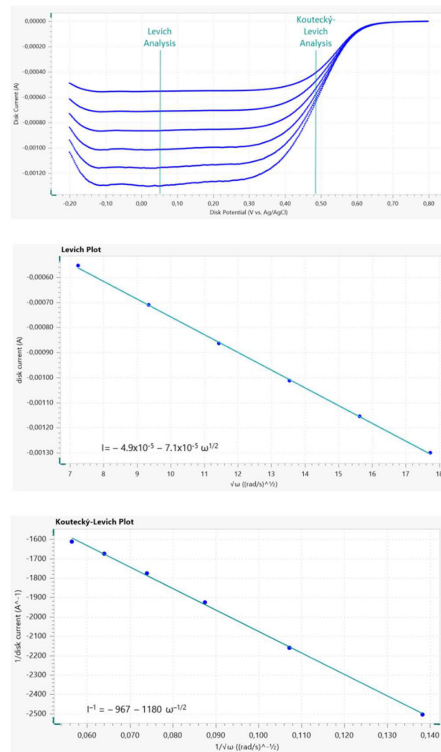
The  $\omega$  values varied between 500 and 3000 RPM; they were chosen with a square root relationship for intuitive representation on the Levich plot. As the potential at the disk is swept from high to low values, the onset of ORR gives rise to a negative (cathodic) signals that is observable at approximately 0.65 V.

The current increases with decreasing potential then reaches a plateau region at approximately  $E = 0.20$  V to  $-0.10$  V. This plateau is also known as the mass transfer limited region of the voltammetry profile where the rate of the ORR reaction is limited by the availability of oxygen at the electrode surface. The cathodic current increases in magnitude with increasing  $\omega$  according to the Levich relationship. At the lowest potential values (i.e., lower than  $-0.10$  V), cathodic current decreases in magnitude as the adsorption of hydrogen on the Pt electrode surface interferes with the ORR. The potential at the ring is fixed at 1.00 V, thus the X-axis of the graph in **Figure 1** does not apply to the ring data. Although the potential of the ring is fixed, the current signal at the ring changes as the potential of the disk is swept. This

is because the disk and the ring are in close proximity of each other (there is a separation of  $375 \mu\text{m}$  between the disk and ring). Thus, the chemical environment at the disk influences the ring. As oxygen is reduced at the disk, reaction products, such as  $\text{H}_2\text{O}_2$ , diffuse from the disk to the ring and may undergo further reaction. The oxidation of  $\text{H}_2\text{O}_2$  gives rise to a positive (anodic) current signal and therefore the current at the ring is indicative of  $\text{H}_2\text{O}_2$  production at the disk. The anodic current at the ring increases as the potential of the disk is swept to low values that give rise to ORR at a significant rate. When the disk current is limited by mass transfer (plateau region of the blue curves), the current corresponding to  $\text{H}_2\text{O}_2$  oxidation at the ring continues at a relatively stable value. When the cathodic disk current decreases due to the presence of adsorbed hydrogen on its surface, the ring current increases sharply; this indicates a change in the ORR mechanism where a greater proportion of the reaction is now following a pathway that favors  $\text{H}_2\text{O}_2$  production.

**Figure 2** shows the Levich and Koutecky-Levich plots

for the ORR which demonstrate the relationship between the current and the rotation rate at a fixed potential.



**Figure 2.** Linear sweep voltammetry profiles (top) from the disk electrode at various rotation rates; the potential value for the Levich and Koutecký-Levich analyses are indicated. Levich (middle) and Koutecký-Levich (bottom) plots.

When the potential value is selected within the mass-transfer limiting plateau of  $i$  vs.  $E$  curves, the Levich

plot follows a linear relationship according to Equation 6.

$$i_l = 0.62 \times AnFD^{2/3}v^{-1/6}C\sqrt{\omega} \quad 6$$

When the potential is selected from the region where the current is under a mixture of kinetic and mass

transfer control, the Koutecký-Levich plot is linear according to Equation 7.

$$\frac{1}{i} = \frac{1}{i_k} + \frac{1}{0.62 \times AnFD^{2/3}v^{-1/6}C\sqrt{\omega}} \quad 7$$

For both **Equations 6** and **7**, the variables are defined as:

$A$  ( $cm^2$ ) is the geometric area of the disk  $F$  ( $= 96485 C mol^{-1}$ ) is the Faraday's constant  $D$  ( $cm^2 s^{-1}$ ) is the diffusion coefficient of  $O_2$  in the electrolyte  $v$  ( $cm^2 s^{-1}$ )

The Levich and the Koutecky-Levich plots can be fitted using linear regression to calculate the slopes and intercepts. For the Koutecky-Levich plot, the kinetic current  $i_k$  is calculated from the y-intercept which is

$$i_k = nFAkC$$

**8**

is the kinematic viscosity of the electrolyte  $C$  ( $mol cm^{-3}$ ) is the concentration of  $O_2$  in the electrolyte  $\omega$  ( $rad s^{-1}$ ) is the angular frequency of rotation  $n$  is the number of electrons involved in the reaction

equal to  $1/i_k$ . According to **Equation 8**, the  $i_k$  value can be related to the rate constant for electron transfer  $k$ . In order for **Equation 8** to be applied, the number of electrons involved in the reaction  $n$  must be known.

Information about the dominant mechanistic pathway at a given potential value can be elucidated based on the presence of  $H_2O_2$  detected at the ring (WE2). The data presented in **Figure 1** indicates that ORR proceeds via a mixture of the four-electron and two-electron pathways at potential values within the mass transfer limited plateau. At potential values less than  $-0.10 V$  the two-electron mechanism becomes dominant, as evidenced by the increase in  $H_2O_2$  detected at the ring.

It is possible to calculate the diffusion coefficient of oxygen in the system using the slope value from the linear regression applied to the Levich plot in **Figure 2**. The variables relating to the system that are required for this calculation are listed in **Table 1**. The

concentration of  $O_2$  in the electrolyte is assumed to be equal to its solubility; in other words the solution is saturated. This experiment yields a diffusion coefficient value for oxygen in the electrolyte of  $7.6E-5 cm^2 s^{-1}$  when assuming a four-electron process and  $2.2E-5 cm^2 s^{-1}$  when assuming two electrons are transferred. In reality, both processes contribute to the measured electrochemical signal. The diffusion coefficient value is high when compared with a literature value of  $1.4E-5 cm^2 s^{-1}$  (see references). This property is sensitive to experimental parameters such as the concentration of  $O_2$  in the electrolyte, which is likely to be the most significant source of uncertainty in this measurement.

**Table 1.** System variables for the oxygen reduction reaction in 0.5 M H2SO4 electrolyte at room temperature.

Parameter	Value	Unit
Kinematic viscosity	0.010	$cm^2 s^{-1}$
Solubility of $O_2$	1.1E-6	$mol cm^{-3}$
Electrode geometric area	0.20	$cm^2$

## CONCLUSIONS

In this application note, the Autolab RRDE system was used to study the oxygen reduction reaction with a Pt disk/Pt ring electrode. The  $\text{H}_2\text{O}_2$  formed at the disk electrode during ORR was detected at the ring electrode; its presence was used as an indicator of the reaction pathway. The Levich and Koutecky-Levich

plots were fitted using linear regression. The resulting equations can be used to calculate the diffusion coefficient  $\text{O}_2$  in the electrolyte, the number of electrons transferred during the reaction, and the rate constant for electron transfer.

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## CONTACT

Metrohm Suisse SA  
Industriestrasse 13  
4800 Zofingen

[info@metrohm.ch](mailto:info@metrohm.ch)

## CONFIGURATION



### Autolab PGSTAT204

Le PGSTAT204 associe faible encombrement et conception modulaire. Cet appareil comprend un potentiostat/galvanostat de base avec une tension disponible de 20 V et une intensité maximum de 400 mA ou 10 A en association avec le BOOSTER10A. Le potentiostat peut évoluer à tout moment au moyen d'un module complémentaire, comme le module de spectroscopie d'impédance électrochimique (SIE) FRA32M.

Le PGSTAT204 est un appareil d'un prix abordable qui trouve toujours une place dans le laboratoire. Il dispose d'entrées et de sorties analogiques et numériques pour contrôler les accessoires Autolab et les appareils externes. Le PGSTAT204 comprend un intégrateur analogique intégré. Associé au logiciel performant NOVA, il peut être utilisé pour la plupart des techniques d'électrochimie standard.



### Autolab PGSTAT302N

Ce potentiostat/galvanostat haut de gamme pour courant élevé, avec une tension disponible de 30 V et une bande passante de 1 MHz, associé à notre module FRA32M, est spécialement conçu pour la spectroscopie d'impédance électrochimique.

Le PGSTAT302N est le successeur du très populaire PGSTAT30. L'intensité maximale est de 2 A, la gamme d'intensité peut être étendue à 20 A avec le BOOSTER20A, la résolution de l'intensité est de 30 fA pour une gamme d'intensité de 10 nA.



### Cellule Autolab RRDE pour électrocatalyse

La cellule Autolab RRDE est une cellule électrochimique complète conçue pour la réalisation d'expériences sous convection forcée avec l'Autolab RRDE (ou l'Autolab RDE2). L'ensemble comprend un récipient en verre d'un volume de 300 mL pourvu d'une gaine thermostatique permettant la régulation de la température.

Tous les composants susceptibles d'entrer en contact avec la solution peuvent être nettoyés dans des conditions agressives, ce qui autorise l'utilisation de la cellule pour des expériences par électrocatalyse typiques ou des mesures sensibles par électrochimie interfaciale.



### Électrode à disque et à anneau tournante

L'Autolab RRDE est une électrode tournante à disque et à anneau à faible bruit, qui peut être utilisée pour réaliser des mesures électrochimiques dans des conditions hydrodynamiques contrôlées. La combinaison de l'électrode à disque et de l'électrode annulaire permet de détecter les intermédiaires réactionnels in situ par une suite d'expériences.

L'électrode Autolab RRDE utilise 2 contacts sans friction identiques en mercure pour des mesures à faible bruit et peut être utilisée avec tout potentiostat/galvanostat Autolab équipé du module BA, bipotentiostat bimode.

La vitesse de rotation de la RRDE est contrôlée manuellement par le bouton sur la face avant de l'unité de commande du moteur. La RRDE peut aussi être commandée à distance par le logiciel Autolab. La vitesse de rotation peut être modifiée en continu de 100 à 10 000 trs/min selon une résolution de 1 tr/min.





### Logiciel avancé pour la recherche électrochimique

NOVA est le progiciel conçu pour le contrôle de tous les instruments Autolab avec interface USB.

Conçu par des électrochimistes pour des électrochimistes, NOVA apporte plus de puissance et plus de flexibilité à votre potentiostat/galvanostat Autolab en intégrant plus de deux décennies d'expérience utilisateur et la toute dernière technologie logicielle .NET.

NOVA propose les fonctionnalités inédites suivantes :

- Un éditeur de procédures performant et flexible
- Une vue d'ensemble claire des données pertinentes en temps réel
- Des outils d'analyse de données et de tracés puissants
- Contrôle intégré des périphériques externes comme les instruments LQH Metrohm