REDUCTION OF DISOLVED OXYGEN
AT A COPPER ROTATING-DISC ELECTRODE

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Industrial electrochemistry, which concerns the controlled
interconversion of electrical and chemical energy, has a
wide scope. The applications of electrochemistry include
batteries and fuel cells, materials extraction and synthesis,
chemical sensors, pollution control, corrosion monitoring and
the surface finishing of metals.11 The discipline of electro-
chemical engineering has been defined as "the understanding
and development of practical materials and processes
which involve charge transfer at electrode surfaces."12 Electro-
chemical engineering is the branch of engineering that
embraces electrochemical processes, the means of processing,
the resulting products, and the industrial/commercial/
social use of the products.12,13

In contrast to the well-established field of chemical engi-
neering, the specialist discipline of electrochemical engineer-
ing is much younger, having evolved over the last forty years
or so, as evidenced by the progressive appearance of texts
and monographs.14-20 It is important that undergraduate engi-
neers have a working knowledge of electrochemical engi-
neering principles in order to appreciate the scale and scope
of electrochemistry and its industrial and technological rele-
van ce. Electrochemical engineering has all the challenges
of chemical engineering with the added challenge of elec-
 trode potential as a controlling influence and current distri-
 bution as an essential reaction parameter. A number of edu-
cators have realized the importance of the discipline of elec-
trochemical engineering and have described its introduction
into chemical engineering process laboratory courses.111

The literature in the field of chemical sciences education
contains many papers on electrochemistry experiments; for
example, some 159 articles have been published in the Journal
of Chemical Education since 1995, with the emphasis
often being on the demonstration of physical aspects of chem-
istry to the early stages of undergraduate courses and to sci-
cence courses in schools. Examples include a slide projector
corrosion cell12 and the determination of Avogadro’s num-
ber by electropotentiometry.13 There are still, however, relatively
few articles that have been devised for undergraduate engi-
neers in order to demonstrate the principles and practice of
electrochemical engineering in a clear, quantitative fashion.
Examples of education papers in electrochemical technology
include the topics of aluminium-air cells,14 proton exchange
membrane fuel cells,15 reduction of ferrocyanide ion at a ro-

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and industrial engineers in the areas of energy conversion and surface
engineering.
We believe that this paper will prove useful to electrochemical engineering and electrochemistry courses involving the study of corrosion processes, materials science, and environmental electrochemistry. The level of teaching is relevant to second- or final-year undergraduates, master degree students, and to the first year of postgraduate MPhil/PhD research programs.

tating disc electrode,\textsuperscript{[17]} and environmental recycling of materials.\textsuperscript{[18]}

In the case of metal corrosion, one of the authors has over 25 years experience in dealing with industrial corrosion problems, many of them being attributable to a poor appreciation of the principles of metallic corrosion by practicing engineers. The field of corrosion and protection of metals is well established, as evidenced by many texts.\textsuperscript{[19-21]} The subject areas of fluid flow and mass transport, however, are often covered superficially. The reduction of dissolved oxygen is a key cathodic reaction and hence a major contributor to many cases of industrial corrosion, and it is essential to consider the effects of fluid flow and mass transport of dissolved oxygen to the electrode surface in a systematic and quantitative manner. The chemical education literature contains relatively few articles on the electrochemistry of oxygen although topics covered include correlations to describe oxygen transfer from air to water\textsuperscript{[22]} and an oxygen sensor for automotive gas streams.\textsuperscript{[23]}

This paper describes a training tool in electrochemical engineering, electrochemical technology, and corrosion. The approach is in line with the desire for students to “learn by doing”\textsuperscript{[24]} and has been used as part of a “consultant-in-the-classroom” approach.\textsuperscript{[25]} We believe that the paper will prove useful to electrochemical engineering and electrochemistry courses involving the study of corrosion processes, materials science, and environmental electrochemistry. The level of teaching is relevant to second- or final-year undergraduates, master degree students, and to the first year of postgraduate MPhil/PhD research programs. Delegates on short courses in electrochemical engineering and corrosion have found the experiment to be informative and successful in explaining the role of cathodic kinetics in (and mass transport contributions to) corrosion reactions. Students have appreciated that a (typically) 90-minute set of experiments can provide quantitative data on mass transport rates under controlled fluid-flow conditions.

The experiment has been used as part of a training program for first-year PhD students in electrochemical engineering and applied electrochemistry at the Universities of Bath, Portsmouth, Queensland, and Southampton. The material has been used as a laboratory exercise leading to BSc degrees in applied chemistry and BSc in environmental sciences (University of Portsmouth) together with BEng and MEng in chemical engineering and short courses on electrochemical techniques, pure and applied, for industry (University of Bath). The technique has also contributed to the study of flow-enhanced materials degradation via MEng and PhD mechanical engineering research projects at the University of Queensland. The early training of PhD students in electrochemical engineering at the University of Southamp ton has also benefited from studies described in this paper.

The reduction of oxygen at a cathode surface\textsuperscript{[26]} is important in several areas of technology, including the positive electrode of metal-air batteries,\textsuperscript{[27]} fuel cells,\textsuperscript{[28]} batteries,\textsuperscript{[29]} and gas sensors,\textsuperscript{[30]} a competitive reaction during metal ion removal\textsuperscript{[31]} and a common cathodic process enabling the corrosion of metals.\textsuperscript{[19-21]}

In neutral or alkaline electrolytes (as in the present studies in seawater, at approximately pH 8), oxygen reduction can be stated as

\[
O_2 + 2 H_2O + 4 e^- \rightarrow 4 OH^- \quad (1)
\]

The electrochemistry of oxygen reduction can be studied using linear sweep voltammetry at a disc electrode. In this technique, the electrode potential, \(E\), is controlled (volts, V vs. a reference electrode) by a potentiostat and swept at a constant rate between fixed potentials. The current is continuously monitored during this process and steady-state current vs. potential curves can be recorded on a microcomputer (or an x-y chart recorder).

**DETAILS OF THE EXPERIMENT**

The instrumentation and experimental arrangement are shown in Figure 1 and Figure 2 (next page). All measurements were made at 25 ± 0.2°C in air-saturated, filtered seawater. (The electrolyte used in this study can readily be replaced by the simpler 3.5% NaCl.) An Eco Chemie, Autolab was used with a PGSTAT20 computer-controlled potentiostat system with GPES (General Purpose Electrochemical Software) version 4.5 coupled to the Pine Instruments Company (model AFMSR9) analytical rotor. The rotator mechanism provided better than 1% accuracy over a 50- to 10,000-rpm speed range. A standard, RDE, three-compartment, electrochemical cell was used with a platinum gauze counter electrode, and a Radiometer Analytical A/S, REF 401, saturated
calomel electrode (SCE) was used in conjunction with a Luggin-Haber capillary. The cell was fitted with a thermostatically controlled water jacket.

The counter-electrode and working-electrode sections of the electrochemical cell were separated from each other with a Nafion® 423 ion-exchange membrane. The internal, wetted dimensions of the RDE cell were 5.5-cm diameter and 6.0-cm height. From these values, a mean electrolyte volume of approximately 140 cm³ was used. Electrolytes were aerated for at least five minutes prior to the commencement of measurement with a gas diffuser connected to an air pump. In order to establish the background current, de-aeration was achieved by sparging with standard oxygen-free nitrogen (supplied by British Oxygen Company) for at least 10 minutes prior to measurement. Salinity was measured directly with a ProLine LF 197, WTW Measurement Systems, Inc., salinometer and indirectly via conductivity measurements with the Metler-Toledo MPC 227 conductivity/pH meter. Kinematic viscosity was measured directly with a B-type Ostwald U-tube viscometer, and oxygen concentrations were estimated with a Jenway 3420 dissolved oxygen meter. All potentials are quoted relative to the saturated calomel electrode (SCE).

The electrode surfaces were first degreased in ethanol then wet polished, with a 0.3 µm alumina slurry, on micro-polishing cloth, followed by three series of 1-minute polishings on double-distilled water soaked polishing cloth.

From a health and safety perspective, the electrolyte has been chosen to provide an inherently safe, low-cost, aqueous, and room-temperature solution. The use of rotating parts requires appropriate care, and demonstrators point this out to the student. A low-power rotator is used and the rotating parts are shielded from the students when in use.

THE OXYGEN REDUCTION REACTION

A simplified relationship for the complete reduction of oxygen involves an overall exchange of four electrons, resulting in the production of hydroxyl ions (or water molecules at low pH). The complete, four-electron reduction of oxygen may occur directly, as in Eq. (1) above, or indirectly, via two steps each involving two electrons

\[ \text{O}_2 + 2 \text{H}_2\text{O} + 2e^- \rightarrow \text{HO}_2^- + \text{OH}^- \quad (2) \]

\[ \text{HO}_2^- + \text{H}_2\text{O} + 2e^- \rightarrow 3 \text{OH}^- \quad (3) \]

Hydroxyl ions or water molecules can be products of a single four-electron step or the result of cumulative two-electron reduction steps where oxygen is reduced to peroxide, which in turn is reduced to hydroxyl ions. The general scheme describing the reduction mechanism of the reduction of oxygen is shown in Figure 3.\[26,20\]

Figure 3 shows the steps involved during the reduction of oxygen. First, oxygen has to be transported to the electrode surface—this process depends on the convection or mass transport, i.e., fluid velocity or electrode rotation. Once on the electrode surface, the oxygen molecule reacts to produce hydrogen peroxide and hydroxyl ions, a step that is controlled by the electron transfer rate. The kinetics of oxygen reduction are expected to be very specific to the

![Figure 1. Arrangement of instrumentation to obtain current vs. potential (voltammetry) curves at controlled rotation speed of a disc electrode. WE—working electrode (copper rotating disc electrode); CE—counter electrode (platinum mesh); RE—reference electrode (saturated calomel electrode).](image)

![Figure 2. Three-electrode electrochemical cell: (a) saturated calomel electrode (SCE) reference electrode; (b) air gas blanket outlet; (c) Pine Instruments MSRX arbor; ACMDS 808C rotator arm; (d) thermostatic water jacket; (e) copper rotating disc working electrode; (f) Luggin-Haber capillary; (g) air diffuser; (h) platinum gauze counter electrode; (i) perplex cell lid; (j) glass flange containing cation exchange membrane (Nafion 423).](image)
system under study, where the character of the substrate, surface condition, temperature, and electrolyte conditions all have an influence over each step in the reduction mechanism.\textsuperscript{24,31-33} Once the product is formed, its removal from the electrode surface depends again on mass transport. Delahay performed an early study dealing with the reduction of dissolved oxygen at copper in chloride media in 1950.\textsuperscript{34} Over the whole range of negative overpotentials studied in this case, it was determined from polarization curves and oxygen-consumption data that the number of electrons consumed was predominantly four. Although hydrogen peroxide was always formed, catalytic decomposition of hydrogen peroxide was found to prevent the build up of the intermediate reduction product.

**RESULTS AND DISCUSSION**

The experiments described in this paper have a number of learning outcomes, which are summarized in Table 1. The impact of the experiment on parts of a BEEng/MEng chemical engineering curriculum can be illustrated by the following examples: (a) mass transport rates and dimensionless group correlations (year 1 or 2), (b) process intensification due to agitation (year 3), (c) fluid flow around rotating systems (year 1), (d) corrosion and materials degradation (years 1 to 3), (e) electrochemical engineering techniques (a year 2 option), and (h) physical transport phenomena (year 1).

Application of the rotating disc electrode, RDE, to electrochemical systems is a well-established method of quantitatively controlling the fluid flow and mass transport conditions. The use of ferri-cyanide ion reduction or copper deposition have been well rehearsed in the literature but we have preferred in teaching experiments to use the reduction of dissolved oxygen, which (a) is relevant to corrosion and a wide range of other electrochemical technologies, (b) involves no significant phase changes on the electrode surface, (c) provides a simple reactant at a controlled level, (d) facilitates the use of an inexpensive RDE material, and (e) shows regions of potential where the reaction is under charge-, mixed- or mass-transport control.

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**TABLE 1**

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>LEARNING OUTCOME</th>
<th>EVIDENCED BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumentation for electrochemistry</td>
<td>Appreciate the typical equipments used to obtain current vs. potential curves at a controlled rotation speed of the disc electrode.</td>
<td>Student’s ability to describe the properties of the instruments and electrochemical cell (in Figure 1).</td>
</tr>
<tr>
<td>Three-electrode electrochemical cells</td>
<td>Understand the need for three electrodes.</td>
<td>Student’s ability to define the three electrodes used in the study (i.e., working reference and counter electrodes in Figure 2).</td>
</tr>
<tr>
<td>Fluid flow and its control</td>
<td>Appreciate that the rotating disc electrode provides effective control of fluid flow.</td>
<td>Student’s knowledge that the fluid flow is laminar as long as the disc surface is hydrodynamically smooth and the rotation speed is within appropriate limits.</td>
</tr>
<tr>
<td>Mechanism of oxygen reduction</td>
<td>Know the steps involved in transport of oxygen to the electrode surface followed by its reduction.</td>
<td>Appreciation of the charge transfer and mass transport steps involved (Figure 3).</td>
</tr>
<tr>
<td>Electrochemical voltammetry</td>
<td>Understand the equipment needs for electrochemical voltammetry.</td>
<td>Obtaining correct current vs. potential curves (Fig. 4).</td>
</tr>
<tr>
<td>Types of rate control</td>
<td>Appreciate the different types of rate control, namely, charge transfer, mass transport, and mixed control.</td>
<td>The shape of the current vs. potential curves at a fixed rotation speed indicates the potential regions for various types of rate control (Figure 4).</td>
</tr>
<tr>
<td>The rotating disc electrode</td>
<td>Understand the relationship between fluid flow and mass transport rates.</td>
<td>Measurement of limiting current vs. potential for a series of rotation speeds and the application of the Levich equation (Figure 5).</td>
</tr>
</tbody>
</table>
Figure 4 shows a family of current vs. potential curves for oxygen reduction at the copper RDE. The potential has been linearly increased, with time, from the open-circuit potential to a value of approximately -1.4 V vs. SCE, at a rate of 0.5 mV s⁻¹, while the current is continuously monitored. The linear sweep voltammetry in Figure 4 shows a single wave for oxygen reduction, which indicates an overall 4-electron exchange for this system. The curves can be divided into the following regions:

(a) At low overpotentials, the current rises exponentially with potential and the reaction is under “complete charge transfer control,” i.e., the reaction rate is governed by the speed of electron transfer from the cathode to the oxygen adsorbed at the electrode surface.

(b) At more negative potentials, the current increases with potential; the current is affected both by potential and by the speed of the rotating disc electrode. This is the “mixed control” region.

(c) Further increase of potential reaches a region where the current is approximately constant. This is the limiting current (I_L) plateau where the oxygen reduction is under “complete mass-transport control.” The rate-determining factor is the speed at which the reactant (dissolved oxygen) can reach the cathode surface. Under complete mass-transport control, the reaction is very flow-dependent. Increasing the relative velocity between the cathode and the electrolyte (i.e., agitation of the solution) will increase the rate of mass transport and, hence, I_L will increase. (Students are encouraged to consider alternative methods of agitation, such as impeller stirring, pumped flow and the use of jets or turbulence promoters together with their practicality).

(d) When the potential is made more negative, a secondary cathode reaction, hydrogen evolution takes place in addition to the oxygen reduction

$$2 \text{H}_2\text{O} + 2 \text{e}^- \rightarrow \text{H}_2 + 2 \text{OH}^-$$ (4)

The entire oxygen-reduction curve can be analyzed (considering charge-, mixed- and mass-transport control) using a Rounteck-Levich approach. Here, we focus complete mass-transport control on the limiting-current region. The limiting current depends on several factors, including the bulk concentration of dissolved oxygen, c_b, the active area of the electrode A, and the averaged mass transport coefficient k_m

$$I_L = k_m A z F c_b$$ (5)

where z is the number of electrons transferred per oxygen molecule (z = 4) and F is the Faraday constant (96,485 C mol⁻¹). The mass transport coefficient can be consid-
Electrochemical engineering has all the challenges of chemical engineering with the added challenge of electrode potential as a controlling influence and current distribution as an essential reaction parameter.

From the slope $K$, the diffusion coefficient $D$, can be calculated via a rearrangement of Eq. (11) to give

$$D^{0.666} = \frac{|K|}{0.62 z F Av^{-0.166} c_b}$$  \hspace{1cm} (12)

From Eq. (12), the diffusion coefficient of dissolved oxygen is given by

$$D = \frac{|K|}{0.62 z F Av^{-0.166} C_o^0}$$  \hspace{1cm} (13)

The experimental program had three objectives

- To characterize the oxygen reduction reaction and to define the electrode potential ranges for kinetic (charge transfer) control, mixed control, mass transport control and the side reaction.
- To show the relationship between flow conditions and mass transport and, hence, the dependence of reaction rate on rotation speed of the disc electrode.
- To determine the diffusion coefficient for dissolved $O_2$ under controlled conditions of temperature and saturated concentration of dissolved $O_2$.

As predicted by the Levich equation (Eq. 9), the limiting current of each member of the family of current vs. potential curves showed in Figure 4 depends on the mass transport conditions, i.e., the rate of rotation of the electrode. The limiting current at each rotation rate can be obtained by subtraction of the background current (dotted line), i.e., the current of the electrolyte with no oxygen dissolved. Figure 5 shows the plot of the limiting current vs. the square root of angular velocity of the rotation disc electrode, according to Eqs. (9) and (10). The linear plot passed through the origin according to the theory and demonstrated that the reduction of oxygen at the limiting current is proportional to the square root of the angular velocity. Limiting current densities of approximately $-0.32$ to $-2.38$ mA cm$^{-2}$ were measured for square root angular velocities of 4.6 to 31.6 rad$^{-0.5}$ s$^{-1}$. The mean diffusion coefficient was calculated as $(1.5 \pm 0.2) \times 10^{-4}$ cm$^2$ s$^{-1}$. The data indicates that, under full mass transport control, the exchange of four electrons controls the rate of oxygen reduction (the reduction of a hydrogen peroxide intermediate was not observed during oxygen reduction in these experiments).
SPECIMEN CALCULATION OF $D_{O_2}$ USING EQ. (13)

\[
D_{O_2} = \left( \frac{9.399 \times 10^{-6} \text{ A rad}^{0.5} s^{0.5}}{0.62 (4) \left[ 0.6485 \text{ C mol}^{-1} \right] \left[ 0.113 \text{ cm}^3 \right] \left[ 9.33 \times 10^{-3} \text{ cm}^2 \text{s}^{-1} \right] \left[ 2.625 \times 10^{-7} \text{ mol cm}^{-3} \right]^{0.166}} \right)^3
\]

\[
D_{O_2} = \left( 6.08 \times 10^{-4} \right)^3 = (1.5 \pm 0.2) \times 10^{-5} \text{ cm}^2 \text{s}^{-1} \quad \text{at} \quad 25 \pm 1^\circ \text{C}
\]

Using an experimentally derived value of $K$, the experimentally determined diffusion coefficient for oxygen in filtered seawater compares favorably with literature values obtained at copper of $1.4 \times 10^{-3}$ cm$^2$ s$^{-1}$ at 20°C in 0.5 mol dm$^{-3}$ NaCl,$^{13}$ 1.7 $\times 10^{-3}$ cm$^2$ s$^{-1}$ at 23°C in 1 mol dm$^{-3}$ NaCl,$^{13,37}$ and 1.8 $\times 10^{-3}$ cm$^2$ s$^{-1}$ at 23°C in 1 mol dm$^{-3}$ NaCl.$^{38,39}$ The experiments can be extended to rationalize the rate of corrosion of copper in chloride electrolytes under mass-transport controlled conditions, the analysis of the mixed control region of current vs. potential curves using a Koutecky-Levich approach, and the use of a rotating cylinder electrode to study oxygen reduction under turbulent flow conditions.$^{40,41}$

CONCLUSIONS

Technical achievements

1. The experimental current potential curves in Figure 4 showed various zones: (a) the charge transfer zone between $0.3$ and $0.5$ V vs. SCE where the current is independent of the rotation rate, (b) the mixed zone where the rotation rate partially influences the current values, (c) the mass transport zone where the current depends completely on the rotation rate and the charge transfer was fast, and (d) the secondary reaction zone where hydrogen evolution occurs together with the desired reaction.

2. Linear sweep voltammetry was used to obtain qualitative data, such as the limiting current for the reduction of oxygen on a copper electrode surface as a function of rotation speed and the diffusion coefficient of oxygen. A single, 4-electron wave for the reduction of oxygen on a rotating disc copper electrode was observed and under full mass transport control.

3. The rotating disc electrode (RDE) technique allowed the reduction of oxygen to be studied under controlled conditions of laminar fluid flow.

4. The mass transport coefficient, $k_m$, was proportional to the square root of the rotation rate of the disc electrode, $\omega^{0.5}$, under the experimental conditions.

5. A linear, Levich plot of $I_L$ vs. $\omega^{0.5}$ allowed the diffusion coefficient, $D$, of oxygen, in air saturated seawater, to be calculated as $1.5 \times 10^{-3}$ cm$^2$ s$^{-1}$ at 25°C in good agreement with literature values.

Educational experience

The specific learning outcomes of the experiments together with their relevant subject areas are summarized in Table I. The subject areas concerned include instrumentation and cells for voltammetric techniques in electrochemistry, fluid flow and its control, the mechanism of oxygen reduction, types of rate control, and appreciation of mass transport control using a rotating electrode.

ACKNOWLEDGMENTS

Early tutorial studies on oxygen reduction at rotating disc electrodes were carried out in the Applied Electrochemistry Group at the University of Portsmouth, U.K. G. Kear and H.C. Walsh are grateful to Dr. B. Des Barker (University of Portsmouth) for early tutoring in electrochemical corrosion.

NOMENCLATURE

| Meaning [Units] | A | c_b | d | D | F | I_L | j | $k_m$ | K | r | U | z | v | \(\nu\) | \(\omega\) |
|----------------|---|-----|---|---|---|-----|---|------|---|---|---|---|---|---|
| active RDE area (A = 0.113 cm$^2$) [cm$^2$] | | | | | | | | | | | | | | | |
| bulk oxygen concentration ($c_b = 2.63 \times 10^4$ mol cm$^{-3}$) [mol cm$^{-3}$] | | | | | | | | | | | | | | | |
| electrode diameter [cm] | | | | | | | | | | | | | | | |
| diffusion coefficient of dissolved oxygen [cm$^2$s$^{-1}$] | | | | | | | | | | | | | | | |
| Faraday constant ($F = 96485$) [A s mol$^{-1}$] | | | | | | | | | | | | | | | |
| limiting current [A] | | | | | | | | | | | | | | | |
| current density [A cm$^{-2}$] | | | | | | | | | | | | | | | |
| mass transport coefficient [cm s$^{-1}$] | | | | | | | | | | | | | | | |
| proportionality constant in Levich equation ($K = 9.40 \times 10^4$) [A rad$^{0.5}$ s$^{0.5}$] | | | | | | | | | | | | | | | |
| radius of rotating disc electrode [cm] | | | | | | | | | | | | | | | |
| velocity of rotating disc electrode [cm s$^{-1}$] | | | | | | | | | | | | | | | |
| number of electrons transferred ($z = 4$) [dimensionless] | | | | | | | | | | | | | | | |
| kinematic viscosity of electrolyte ($\nu = 9.33 \times 10^{-6}$ cm$^2$s$^{-1}$) | | | | | | | | | | | | | | | |
| angular velocity of the rotating disc electrode [rad s$^{-1}$] | | | | | | | | | | | | | | | |
REFERENCES

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34. Delahay, P., J. Electrochem. Soc., 97, 205 (1950)