ChE *classroom*

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.[1] The discipline of electrochemical engineering has been defined as "the understanding and development of practical materials and processes which involve charge transfer at electrode surfaces."[2] Electrochemical 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.[2,3]

In contrast to the well-established field of chemical engineering, the specialist discipline of electrochemical engineering is much younger, having evolved over the last forty years or so, as evidenced by the progressive appearance of texts and monographs.[4-10] It is important that undergraduate engineers have a working knowledge of electrochemical engineering principles in order to appreciate the scale and scope of electrochemistry and its industrial and technological relevance. 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. A number of educators have realized the importance of the discipline of electrochemical engineering and have described its introduction into chemical engineering process laboratory courses.[11]

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 chemistry to the early stages of undergraduate courses and to science courses in schools. Examples include a slide projector corrosion cell[12] and the determination of Avogadro's number by electroplating.[13] There are still, however, relatively few articles that have been devised for undergraduate engineers 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 ferricyanide ion at a rotating disc electrode,[16] electrodeposition of copper at a ro-

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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,[17] and environmental recycling of materials.[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.[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[22] and an oxygen sensor for automotive gas streams.[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"[24] and has been used as part of a "consultant-in-the-classroom" approach.[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 Southampton has also benefited from studies described in this paper.

The reduction of oxygen at a cathode surface[26] is important in several areas of technology, including the positive electrode of metal-air batteries,[14] fuel cells,[27] batteries,[28] and gas sensors,[29] a competitive reaction during metal ion removal[30] and a common cathodic process enabling the corrosion of metals.[19-21]

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

$$O_2 + 2\,H_2O + 4\,e^- \rightarrow 4\,OH^- \tag{1}$$

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 AFMSRX) analytical rotator. 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 cm^3 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 Profi-Line 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

$$O_2 + 2\,H_2O + 2\,e^- \rightarrow HO_2^- + OH^- \tag{2}$$

$$HO_2^- + H_2O + 2\,e^- \rightarrow 3\,OH^- \tag{3}$$

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.[26,29]

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

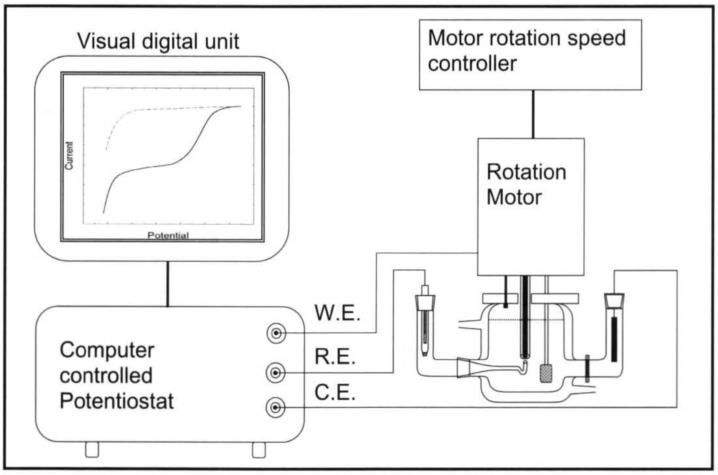

Figure 1. *Arrangement of instrumentation to obtain current vs. potential (voltammetry) curves at controlled rotation speed of a disc electrode. WE—working electrode (copper rotating disc electrode: CE—counter electrode (platinum mesh); RE—reference electrode (saturated calomel electrode).*

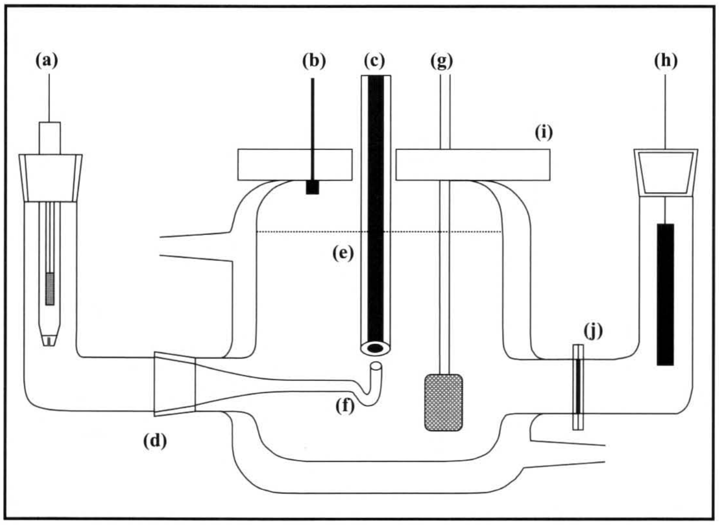

Figure 2. *Three-electrode electrochemical cell:* ***(a)*** *saturated calomel electrode (SCE) reference electrode;* ***(b)*** *air gas blanket outlet;* ***(c)*** *Pine Instruments MSRX arbor, ACMDII 906C rotator arm;* ***(d)*** *thermostatic water jacket;* ***(e)*** *copper rotating disc working electrode;* ***(f)*** *Luggin-Haber capillary;* ***(g)*** *air diffuser;* ***(h)*** *platinum gauze counter electode;* ***(i)*** *perpex cell lid;* ***(j)*** *glass flange containing cation exchange membrane (Nafion 423).*

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.[26,31-33] 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.[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.

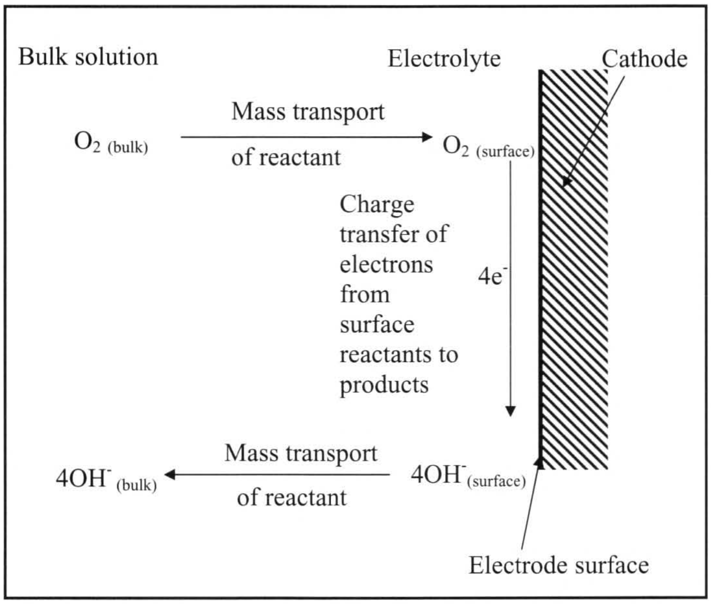

Figure 3. *The stages of oxygen reduction consisting of mass transport to and from the electrode surface and electron transfer reaction.*

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 BEng/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[31-33,36] method of quantitatively controlling the fluid flow and mass transport conditions. The use of ferricyanide 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.

TABLE 1
Learning Outcomes of the Experiments

TOPIC	*LEARNING OUTCOME*	*EVIDENCED BY...*
Instrumentation for electrochemistry	Appreciate the typical equipments used to obtain current vs. potential curves at a controlled rotation speed of the disc electrode.	Student's ability to describe the properties of the instruments and electrochemical cell (in Figure1).
Three-electrode electrochemical cells	Understand the need for three electrodes.	Student's ability to define the three electrodes used in the study (*i.e.,* working reference and counter electrodes in Figure 2).
Fluid flow and its control	Appreciate that the rotating disc electrode provides effective control of fluid flow.	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.
Mechanism of oxygen reduction	Know the steps involved in transport of oxygen to the electrode surface followed by its reduction.	Appreciation of the charge transfer and mass transport steps involved (Figure 3).
Electrochemical voltammetry	Understand the equipment needs for electrochemical voltammetry.	Obtaining correct current vs. potential curves (Fig. 4).
Types of rate control	Appreciate the different types of rate control, namely, charge transfer, mass transport, and mixed control.	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).
The rotating disc electrode	Understand the relationship between fluid flow and mass transport rates.	Measurement of limiting current vs. potential for a series of rotation speeds and the application of the Levich equation (Figure 5).

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

$$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^- \qquad (4)$$

The entire oxygen-reduction curve can be analyzed (considering charge-, mixed- and mass-transport control) using a Koutecky-Levich approach.[31-33] 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

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

where z is the number of electrons transferred per oxygen molecule (= 4) and F is the Faraday constant (96 485 C mol^{-1}). The mass transport coefficient can be consid-

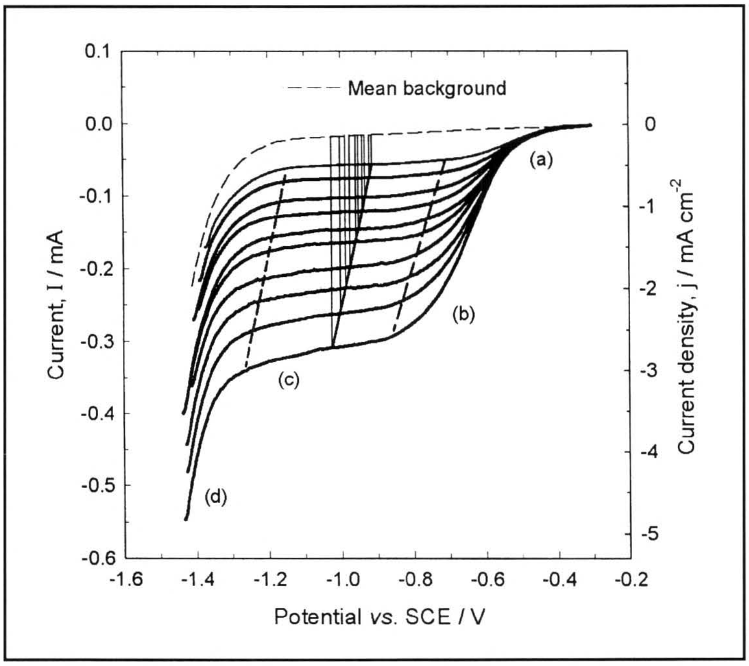

Figure 4. *Cathodic polarization curves for oxygen reduction at a copper RDE in aerated seawater at 25 °C. Potential sweep rate—0.5 mV s^{-1}; increasing order of rotation rates—21,42, 84, 126, 188, 251, 366, 503, 681, and 995 rad s^{-1}.* ***(a)*** *electron transfer control,* ***(b)*** *mixed control,* ***(c)*** *mass transport control, and* ***(d)*** *secondary reaction (hydrogen evolution). The broken lines show the region of mass transport and the vertical lines show the points at which the limiting current was measured in each current-potential curve. The mean background current was measured in de-aerated electrolytes.*

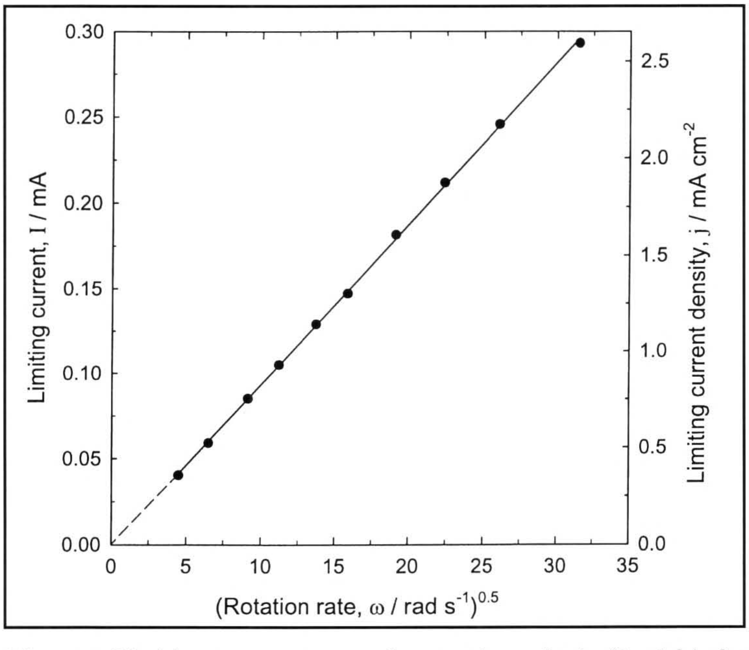

Figure 5. *Limiting current vs. angular rotation velocity (Levich) plot for oxygen reduction at a copper RDE in seawater at 25 °C. Limiting current values were taken from the cross of the vertical lines and the current potential curves in the plateaux of Figure 4.*

ered as a rate constant that is normalized with respect to dissolved oxygen concentration and cathode area. (Students are encouraged to consider appropriate ways of measuring the disc area and the accuracies involved; *e.g.*, the assumption of a circular area versus direct measurement using an optical microscope.)

In this experiment, the electrode area is kept constant by using the polished, flat surface of a fixed radius, r (0.19 cm) rotating disc ($A = \pi r^2 = 0.113\ \text{cm}^2$) of pure copper. The bulk concentration of oxygen is held constant by continuous surface aeration of the seawater electrolyte to achieve a saturated concentration ($c_b = 2.63 \times 10^{-7}\ \text{mol cm}^{-3}$) at 25°C.[35] In other cases of electrode reactions, the bulk concentration of reactant may be varied by volumetric preparation.

For a fixed electrode geometry and constant electrolyte conditions, the mass transport coefficient is dependent on the relative velocity, U, between the electrode and the electrolyte[1-10]

$$k_m \,\alpha\, U^x \tag{6}$$

The rotating disc electrode (RDE) enables the electrolyte velocity towards the electrode to be carefully controlled under conditions of highly reproducible laminar fluid flow. For a polished RDE, the velocity exponent is very consistent between experimental systems, where $x = 0.5$. In this case, Eqs. (5) and (6) can be combined to give

$$I_L \propto \omega^{0.5} \tag{7}$$

Here, the rotation speed, ω is in units of radians per second. Conversion of rotation rate of the RDE in rpm to angular velocity in rad s^{-1} can be achieved by

$$\text{rad s}^{-1} = \frac{\left(\text{rev min}^{-1}\right)\left(2\,\pi\ \text{rad rev}^{-1}\right)}{60\ \text{s min}^{-1}} \tag{8}$$

The influence of the physical properties of the fluid on mass transport were established by Levich,[36] who confirmed that, for the smooth RDE, the limiting current, I_L will vary to the square root of the rotation rate

$$I_L = 0.62\ zFAD^{0.666}\nu^{-0.166}c_b\ \ \omega^{0.5} \tag{9}$$

where ν is the kinematic viscosity of the electrolyte and D is the diffusion coefficient of oxygen (sometimes called the diffusivity, in the older literature). Under conditions of complete mass transport control and for constant z, A, ν and c_b, the Levich equation simplifies to

$$I_L = K\omega^{0.5} \tag{10}$$

and a Levich plot of the limiting current *vs.* the square root of rotation rate of the RDE should be linear and through the origin with a gradient, K, where

$$K = 0.62\ zFAD^{0.666}\nu^{-0.166}\ c_b \tag{11}$$

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

$$D^{0.666} = \frac{|K|}{0.62\ z\ F\ A\nu^{-0.166}\ c_b} \tag{12}$$

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

$$D = \sqrt{\left(\frac{|K|}{0.62\ z\ F\ A\nu^{-0.166}\ C_b}\right)^3} \tag{13}$$

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 $\text{rad}^{0.5}\ \text{s}^{-0.5}$. The mean diffusion coefficient was calculated as $(1.5 \pm 0.2) \times 10^{-5}\ \text{cm}^2\ \text{s}^{-1}$. 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)

$$D_{O_2} = \sqrt{\left(\frac{\left|9.399\times10^{-6}\ \mathrm{A\ rad^{0.5}\ s^{0.5}}\right|}{(0.62)(4)\left(96485\ \mathrm{C\ mol^{-1}}\right)\left(0.113\ \mathrm{cm^3}\right)\left(9.33\times10^{-3}\ \mathrm{cm^2 s^{-1}}\right)^{-0.166}\left(2.625\times10^{-7}\ \mathrm{mol\ cm^{-3}}\right)}\right)^3} \tag{14}$$

$$D_{O_2} = \sqrt{\left(6.08\times10^{-4}\right)^3} = (1.5\pm0.2)\times10^{-5}\ \mathrm{cm^2\ s^{-1}} \quad \text{at} \quad 25\pm0.1^{\circ}\mathrm{C} \tag{15}$$

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 x 10^{-5} cm^2 s^{-1} at 20°C in 0.5 mol dm^{-3} NaCl,[34] 1.7 x 10^{-5} cm^2 s^{-1} at 23°C in 1 mol dm^{-3} NaCl,[37] and 1.8 x 10^{-5} 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]

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, $\omega^{1/2}$, under the experimental conditions*
5. *A linear, Levich plot of I_L vs. $\omega^{1/2}$ allowed the diffusion coefficient, D, of oxygen, in air saturated seawater, to be calculated as 1.5 x 10^{-5} 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, UK. G. Kear and F.C. Walsh are grateful to Dr B. Des Barker (University of Portsmouth) for early tutoring in electrochemical corrosion.

NOMENCLATURE

	Meaning [Units]
A	active RDE area (A = 0.113 cm^2) [cm^2]
c_b	bulk oxygen concentration (c_b = 2.63 x 10^{-7} mol cm^{-3}) [mol cm^{-3}]
d	electrode diameter [cm]
D	diffusion coefficient of dissolved oxygen [cm^2 s^{-1}]
F	Faraday constant (F = 96 485)[A s mol^{-1}]
I_L	limiting current [A]
j	current density [A cm^{-2}]
k_m	mass transport coefficient [cm s^{-1}]
K	proportionality constant in Levich equation (K = 9.40 x 10^{-6}) [A $rad^{-0.5}s^{0.5}$]
r	radius of rotating disc electrode [cm]
U	velocity of rotating disc electrode [cm s^{-1}]
z	number of electrons transferred (z = 4) [dimensionless]
ν	kinematic viscosity of electrolyte ($\nu_{seawater}$ = 9.33 x $10^{-3}cm^2s^{-1}$ at 25°C and a salinity of 3.5% wt[37]) [cm^2 s^{-1}]
ω	angular velocity of the rotating disc electrode [rad s^{-1}]

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