Direct Methanol Fuel Cells

TECHNOLOGICAL ADVANCES AND FURTHER REQUIREMENTS

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The direct methanol fuel cell (DMFC) has been considered as the ideal fuel cell system since it produces electric power by the direct conversion of the methanol fuel at the fuel cell anode. This is more attractive than the conventional hydrogen fuelled cells, particularly for transportation applications, which rely on bulky and often unresponsive reformer systems to convert methanol, or other hydrocarbon fuels, to hydrogen. However, commercialisation of the DMFC has been impeded by its poor performance compared with hydrogen/air systems, the major limitation being the anode performance which requires highly efficient methanol oxidation catalysts. Such catalyst materials have been sought, and it appears that only platinum-based materials show reasonable activity and the required stability. The recent application of proton exchange membrane electrolyte materials has extended the operational temperature of DMFCs beyond those attainable with traditional liquid electrolytes, and this has led to major improvements in performance over the last five years. This article describes some key work tackling the above limitations and suggests that the DMFC is approaching the stage where it may become a commercially viable alternative to hydrogen/air systems.

Fuel cells have attracted attention as an alternative to internal combustion engine (ICE) technology, since they offer numerous benefits, including low or even zero emissions, higher efficiency and reliability. Batteries, which are another alternative technology, offer the prospect of a true local zero-emission vehicle, however, there are environmental and engineering drawbacks to all the current types of battery, and limitations to the distances offered by battery systems, before recharging is required. Battery systems are thus only viewed as a short term solution, and fuel cell systems represent the best possible option in the longer term.

A fuel cell is an electrochemical engine which can convert the free energy change of a chemical reaction directly into electrical energy. This may, for example, be the catalysed electrochemical reaction between hydrogen and oxygen to produce water. This is analogous to the combustion process which occurs in a heat engine, however, in a fuel cell this can take place at much lower temperatures leading to higher efficiencies and reduced polluting emissions. A variety of types of fuel cells are under development, each with advantages and limitations.

Current Fuel Cell Technologies

Although fuel cells are attractive in principle, there are several barriers which must be overcome before they can become a cheap and economical alternative to the ICE. A key requirement is system size and the need to generate sufficient power within the available space to meet the demands of the particular vehicle. The system must also be able to start rapidly and respond quickly to changes in power demand. These requirements are not met by fuel cell systems based on molten carbonate and solid oxide electrolytes, since these operate at temperatures in the range 700 to 1000°C, and therefore require extended, high power consuming, periods to reach operating temperature (1). Proton exchange membrane fuel cell
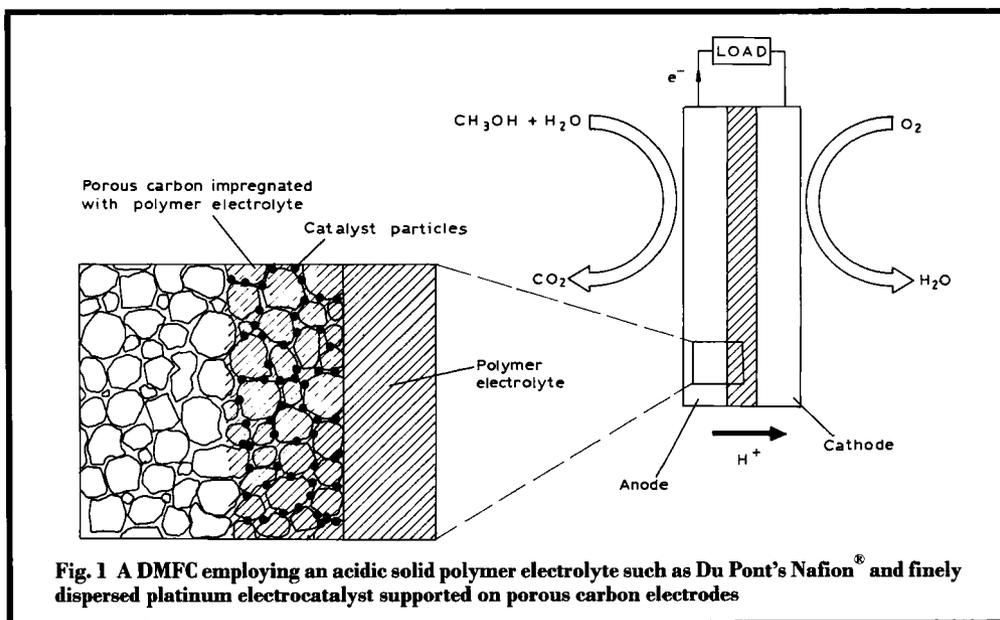
LOAD

e⁻

$CH_3OH + H_2O$

O_2

Porous carbon impregnated
with polymer electrolyte

Catalyst particles

CO_2

H_2O

Polymer
electrolyte

Cathode

H^+

Anode

Fig. 1 A DMFC employing an acidic solid polymer electrolyte such as Du Pont's Nafion® and finely dispersed platinum electrocatalyst supported on porous carbon electrodes

(PEMFC) technology has advanced in the last few years to the point where demonstration devices have been successfully implemented within vehicles. These cells use platinum-based catalysts to promote the electrode reactions, and a solid acidic proton conducting polymer electrolyte, often Du Pont's Nafion® perfluorinated sulphonic acid-type materials. However, the present PEMFC powered vehicles are almost exclusively based on the use of pure hydrogen as the fuel. While this may be a more than acceptable fuel option for transportation applications involving larger, depot based, fleet vehicles, such as transit buses, it is unlikely that this will be suitable for small, privately owned cars, due to fuel distribution, handling and storage difficulties and on-vehicle space and weight constraints. Thus, methanol has attracted interest as the fuel of choice, because of its compatibility with the existing distribution networks and its high energy density.
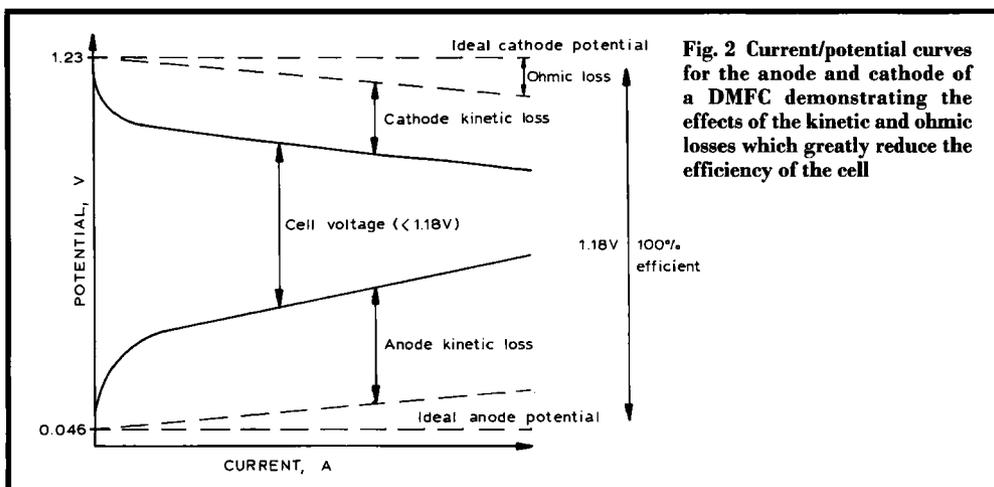
The use of methanol offers two distinct approaches. The currently favoured option involves an on-board reformer system which converts methanol into a hydrogen-rich gas which can then be consumed by the fuel cell. However, this fuel feed is diluted with carbon dioxide and possibly nitrogen, and may contain traces of carbon monoxide which acts as a catalyst poison. Carbon monoxide can be removed from the fuel feed with water gas shift and preferential oxidation reactors, but the removal can reduce the overall system efficiency and increase the weight, volume, start-up time and response to changes in power demand of the system.
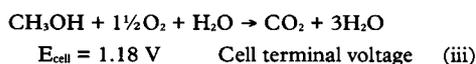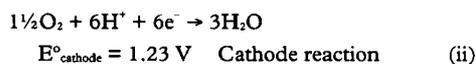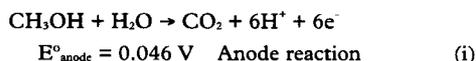
In terms of system simplicity, the alternative and more desirable option is to use the direct methanol fuel cell – DMFC – where methanol fuel is supplied directly to the cell. However, there are drawbacks to this system which reduce its power output and efficiency. Therefore a number of research programmes have been undertaken to find both more active anode catalysts for promoting methanol oxidation and more advanced electrolyte materials to combat fuel cross-over. The latter is essentially a chemical 'short circuit' which results in a mixed potential at the cathode, greatly reducing its efficiency.

Principles of the DMFC

A schematic of a DMFC is shown in Figure 1. Methanol and water react electrochemically (methanol being oxidised) at the anode to produce carbon dioxide, protons and electrons as

Fig. 2 Current/potential curves for the anode and cathode of a DMFC demonstrating the effects of the kinetic and ohmic losses which greatly reduce the efficiency of the cell

shown in Equation (i). The DMFC must contain an acidic electrolyte to aid carbon dioxide rejection, since insoluble carbonates form in alkaline electrolytes. The protons produced at the anode migrate through the polymer electrolyte to the cathode where they react with oxygen (usually from the air) to produce water, as shown in Equation (ii). The electrons produced at the anode carry the free energy change of the chemical reaction and travel through the external circuit where they can be made to do useful work, such as power an electric motor. The overall cell reaction, as shown in Equation (iii), is therefore the reaction of methanol and oxygen to produce water and carbon dioxide. In a practical system, these reactions are promoted by the incorporation of platinum-based electrocatalyst materials in the electrodes.

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$$
$$E^\circ_{anode} = 0.046 \text{ V} \quad \text{Anode reaction} \quad \text{(i)}$$

$$1\frac{1}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$
$$E^\circ_{cathode} = 1.23 \text{ V} \quad \text{Cathode reaction} \quad \text{(ii)}$$

$$CH_3OH + 1\frac{1}{2}O_2 + H_2O \rightarrow CO_2 + 3H_2O$$
$$E_{cell} = 1.18 \text{ V} \quad \text{Cell terminal voltage} \quad \text{(iii)}$$

In principle, methanol should be oxidised spontaneously when the anode potential is above 0.046 V, with respect to the reversible hydrogen electrode (RHE). Similarly, oxygen should be reduced spontaneously when the cathode

assumes a potential below 1.23 V. In reality, and in common with all fuel cell types, poor electrode kinetics (kinetic losses) cause the electrode reactions to deviate from their ideal thermodynamic values so as to incur a practical reduction of the extremely high theoretical efficiency possible from the cell. The real behaviour of the individual electrodes in the DMFC system is shown in Figure 2. In practice, a far more positive potential is required at the anode and a more negative potential at the cathode to accelerate the reactions to a reasonable rate. Besides kinetic losses, there are ohmic losses deriving from the internal resistance of the fuel cell. Hence, the output of a real DMFC is substantially lower than that of the ideal cell, which would give 1.18 V at any current rating.

In the present generation of hydrogen fuelled systems the kinetics of the hydrogen oxidation reaction at the anode are relatively facile, and most losses occur only at the cathode. This enables the practical H₂/air PEMFC to attain very high cell power densities of 500 to 600 mW/cm² at power efficient cell voltages of 0.6 to 0.7 V. Due to the additional poorer kinetics of the DMFC anode, it is unlikely that such high power densities will be achievable at practical cell voltages. However, because the need for a fuel reformer (with associated volume and efficiency losses) is removed, it is believed that to enable the methanol/air DMFC to become

Fig. 3 Surface electro-sorption of methanol in a sulphuric acid electrolyte showing sequential proton and electron stripping to give the predominant catalyst poison, CO_{ads}
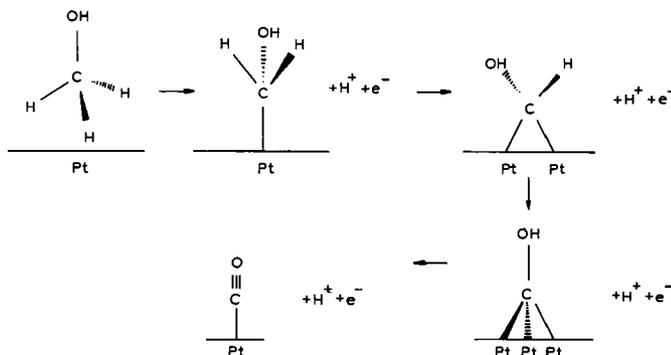
competitive with its hydrogen fuelled counter-parts, lower power densities of 200 to 300 mW/cm² need to be attained at cell voltages of 0.5 V.

Kinetic Limitations

The poor electrode kinetics at the anode and cathode result from the electrochemical processes being much more complex than Equations (i) and (ii) suggest. Each oxygen molecule requires the transfer of four electrons for complete reduction. The simultaneous transfer of these electrons is difficult to achieve, and in fact only partial electron transfer takes place, leading to the formation of surface intermediates, such as superoxide. Using a platinum electrocatalyst allows the stabilisation of these intermediates and permits the reaction to proceed at a reasonable and useful rate. The catalyst may also accelerate the reaction by opening up new reaction pathways. The picture is even less clear for the methanol reaction and the electro-oxidation of methanol again only occurs at a useful rate in the presence of platinum or a platinum-based electrocatalyst. Therefore this reaction has remained an active focus of research, and substantial studies into this process are present in the literature. The discrepancies between sets of experimental data may be due to the wide range of experimental conditions.

The electro-oxidation of methanol to carbon dioxide requires the transfer of six electrons, but it is highly unlikely that these electrons will transfer simultaneously. It is also unlikely that partial electron transfer will lead to the formation
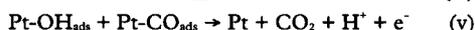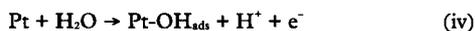
of a range of stable solution intermediates. Clearly, there must be surface adsorbed species present on the surface of the platinum electrocatalyst across its useful potential range, and it is these species which are responsible for the poor catalytic activity of platinum towards methanol electro-oxidation.

The postulated mechanisms for methanol electro-oxidation were reviewed by Parsons and Vandernoot (2), and can be summarised as:
Step 1: Electrosorption of methanol onto the substrate to form carbon-containing intermediates.
Step 2: Addition of oxygen (from water) to the adsorbed carbon-containing intermediates to generate carbon dioxide.

In the first process, very few materials are able to electrosorb methanol, and in acidic electrolytes only platinum-based electrocatalysts have the required activity and chemical stability. The adsorption mechanism is believed to take place through the sequence of steps shown in Figure 3 (3–5). The electrosorption of methanol on the surface of platinum occurs with sequential proton and electron stripping, giving the main catalyst poison, linearly bonded carbon monoxide (Pt-C≡O). Subsequent reactions are believed to involve oxygen transfer to the Pt-CO species to produce carbon dioxide.

$$Pt + H_2O \rightarrow Pt\text{-}OH_{ads} + H^+ + e^- \qquad (iv)$$
$$Pt\text{-}OH_{ads} + Pt\text{-}CO_{ads} \rightarrow Pt + CO_2 + H^+ + e^- \qquad (v)$$

At potentials below about 450 mV the surface of platinum is poisoned by a layer of strongly
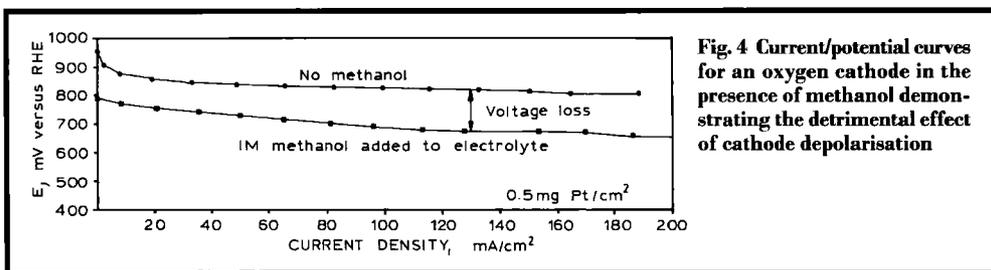
Fig. 4 Current/potential curves for an oxygen cathode in the presence of methanol demonstrating the detrimental effect of cathode depolarisation

bonded -CO_{ads} species and further chemisorption of methanol cannot proceed until the surface bound CO_{ads} is oxidised from the platinum surface. But at these potentials this process occurs at an insignificant rate, and hence the platinum surface remains poisoned throughout its useful potential range. This had led to an intensive search for alternative materials which can oxidise methanol at lower overpotentials, and in particular for additional secondary materials that might combine with platinum to promote the above processes.

Advanced Materials

Some of the advanced materials that have been developed display enhanced activities, and there are a number of possible explanations to account for this. The most likely are:

(a) The secondary metal (for example, ruthenium) modifies the electronic properties of the catalyst, weakening the chemical bond between platinum and the surface intermediate.

(b) The secondary metal (for example, ruthenium, tin, lead and rhodium) is unstable and leaches out of the alloy leaving a highly reticulated and active surface. This results in a higher number of extended step sites associated with the methanol electrosorption process. In addition, these low co-ordinate sites may be much more easily oxidised, giving rise to Pt-OH_{ads} species at potentials far below that at which planar platinum is oxidised.

(c) The secondary metal (such as ruthenium, tin and tungsten) is able to provide a site with -OH_{ads}, adjacent to the platinum, through a spill-over process. Hence, the catalyst activity is governed by the potential at which the secondary metal oxidises and donates -OH_{ads} to adjacent platinum sites. For materials such as ruthenium, this can occur at significantly lower potentials, below 250 mV, than is possible on a platinum surface (6–9), and indeed, at present the most active catalysts are based on platinum-ruthenium alloy materials.

Half Cell Data

The development of the DMFC was pioneered in the 1960s and 1970s by Shell and Exxon-Alsthom using liquid sulphuric acid and alkaline electrolytes, respectively. However, these programmes failed to produce stacks with sufficiently higher power densities, due to poor electrode kinetics and severe fuel cross-over between the electrodes. In sulphuric acid electrolyte, methanol cross-over was a particular problem, since both the anode and cathode catalysts were based on platinum. The performance of the cathode is reduced due to the ability of the platinum to electrochemically oxidise any methanol reaching it by diffusion from the anode. This can be seen in Figure 4 from half cell data, which are routinely used to measure the current versus voltage relationships of the individual electrodes. Clearly, the electrode efficiency is considerably reduced even when only low methanol concentrations are added to the electrolyte in the cell. The anode performance in sulphuric acid electrolytes was much lower than the target levels, with half cell data in the 1980s typically having current densities of 20 to 25 mA/cm^2 at 0.4 V (vs. RHE) for anodes with platinum loadings of 0.5 mg/cm^2 (10).

In recent years, however, significant progress has been made in the development of the DMFC using solid polymer electrolyte materials. These polymer materials have extended

the operating temperature of the cell from 60°C to close to 100°C, and this coupled with the possibility of enhanced intrinsic kinetics by use of the perfluorosulphonic acid electrolyte has led to the improved performances. Electrocatalyst developments have also continued and have centred around the need for stable materials with higher intrinsic activity for methanol electrooxidation. The group at the University of Newcastle upon Tyne (11) have reported Nafion® containing platinum-ruthenium electrodes, with platinum loadings of 3.0 mg/cm^2, achieving over 200 mA/cm^2 at 0.3 V at 80°C. The Jet Propulsion Laboratory in the U.S. has been working with lower platinum loading anodes (0.5 mg/cm^2) which will be required for low cost target applications, such as transportation, and has reported over 100 mA/cm^2 at 0.4 V, at 60°C (12).
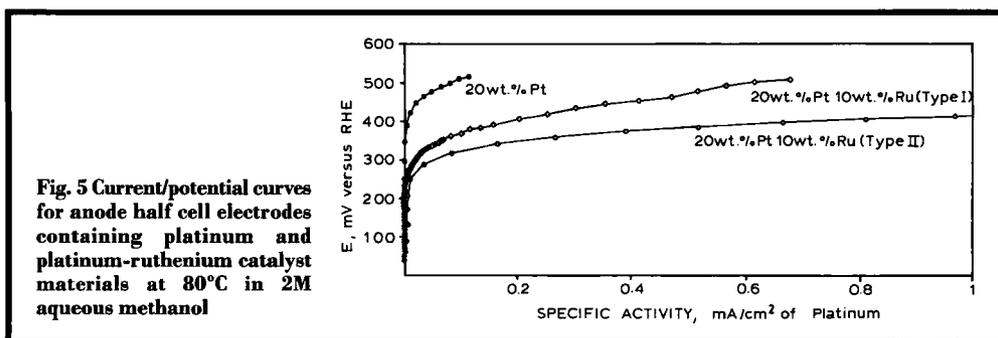
Recent work in the DMFC programme at Johnson Matthey indicates that it is also possible to improve further the intrinsic catalyst activity of the platinum-ruthenium materials for DMFC applications. Figure 5 shows the methanol oxidation activities of electrodes fabricated from 20 wt. % platinum and 20 wt. % platinum-10 wt. % ruthenium catalysts supported on carbon black and comprising a soluble form of the polymer electrolyte, bound as a thin layer between a Nafion®-117 membrane and current collecting substrate. One important consideration, rarely mentioned in the literature, in determining catalyst activity, is measuring activity in terms of real metal surface area (mA/cm^2 platinum). This is determined by the in-situ measurement of chemisorption of a monolayer of

carbon monoxide on the metal surface. The monolayer is then electrochemically oxidised from the surface to produce a charge which can be equated to the total electrochemical metal area available for reaction. This technique allows catalysts to be characterised independent of surface area, and readily identifies materials which have higher intrinsic activities. Platinum-ruthenium materials clearly possess substantially higher intrinsic activities than platinum, with the Type II platinum-ruthenium catalyst being significantly more active than the standard Type I platinum-ruthenium.

Single Cell Data

There are a number of engineering criteria associated with the design and construction of a DMFC. The wide range of operating temperatures possible with a solid polymer electrolyte system means that methanol can be supplied either as a liquid or a vapour. Vapour systems, while offering higher performance and improved mass transport, are more complex as they require additional hardware to provide cooling. Fuel preheating is also necessary before injection; this carries a large energy penalty. The simplest systems from the engineering standpoint appear to be liquid-feed systems. Circulating the liquid fuel mixture prevents excessive heating of the cell, thus reducing the number of components and the size of the system. It is therefore not surprising that the majority of fuel cell research groups have chosen to construct liquid-feed systems.

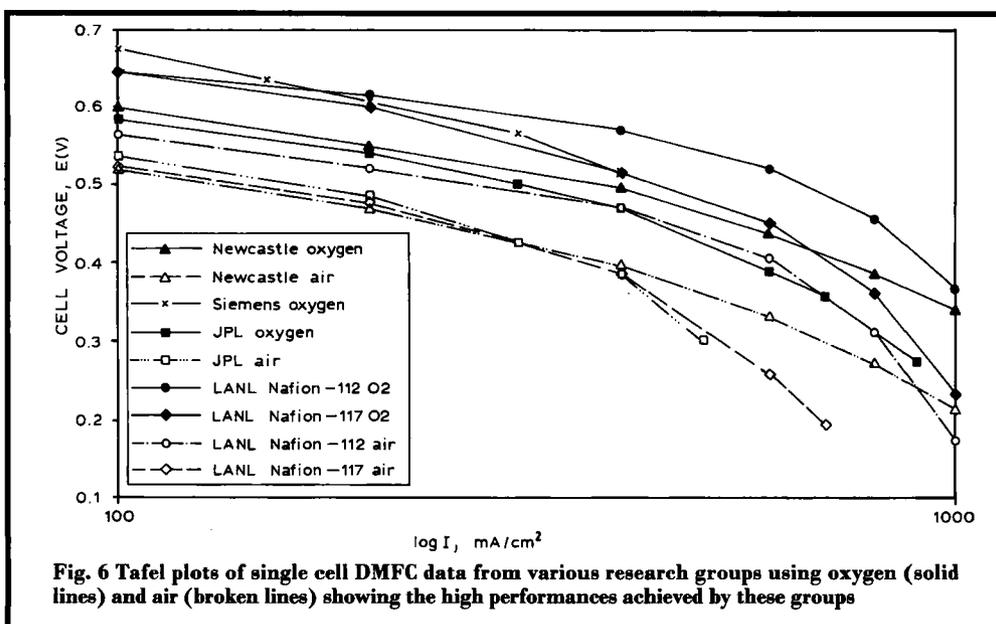In the U.S.A., the Advanced Research Projects Agency (ARPA) regards the DMFC as a

Fig. 5 Current/potential curves for anode half cell electrodes containing platinum and platinum-ruthenium catalyst materials at 80°C in 2M aqueous methanol

Summary of Recent Single Cell Results

Group	Type/Electrolyte	Catalyst		Loading, mg/cm²	Temperature, °C	Anode feed	Cathode feed	Pressure		Cell performance, at 400mA/cm²	Ref.
		Anode	Cathode					Anode	Cathode		
Siemens	Vapour-feed Nafion-117	Pt/Ru	Pt	8.0 Pt	130	2M	O_2	4.4 bar	5.0 bar	0.52 V	13
Newcastle	Vapour-feed Nafion-117	Pt/Ru/C	Pt/C	2.5 Pt	98	2M	O_2 air	ambient ambient	5.0 bar 5.0 bar	0.5 V 0.4 V	15–17
LANL	Liquid-feed Nafion-112	Pt-RuO$_x$	Pt black	2.2, 2.3 Pt	130 110	1M	O_2 air	3 atm 1.8 atm	5.0 atm 3.0 atm	0.57 V 0.52 V	18,19
LANL	Liquid-feed Nafion-117	Pt-RuO$_x$	Pt black	2.2, 2.3 Pt	130 110	1M	O_2 air	3 atm 1.8 atm	5.0 atm 3.0 atm	0.47 V 0.39 V	18,19
JPL Giner	Liquid-feed Nafion-117	Pt/Ru/C	Pt/Ru/C	4	90 90	1M 1M	O_2 air	ambient ambient	2.36 atm 2.36 atm	0.47 V 0.38 V	12

potential mobile power source and also as a possible replacement for some of the primary batteries which are widely used by U.S. military forces. Several groups, funded by ARPA and the U.S. Department of Energy, have been collaborating to develop DMFC technologies. These groups include the Jet Propulsion Laboratory (JPL) and Giner Inc., Los Alamos National Laboratory (LANL) and International Fuel Cells (IFC). In Europe, the European Commission has actively funded DMFC projects for the past ten years under the framework of the Joule Programmes, and several groups have been active during this period; the most successful being Siemens (Germany) and Newcastle University. Johnson Matthey has recently been collaborating with Siemens and Innovision (Denmark) under the framework of 'Joule 3' to develop a fuel cell stack. This programme aims to develop highly efficient DMFC stacks operating with liquid fuel at ambient pressures.

The above groups have achieved a wide range of cell performances using a variety of electrode compositions and operating conditions; this makes direct comparison of the data difficult, see the Table. The minimum goal required for commercialisation of fuel cells operating on methanol and air is judged to be about 200 mW/cm² at a cell voltage of 0.5 to 0.6 V. Some recent results achieved for single cell work by the above mentioned groups are compared in Figure 6. Data plotted with a broken line correspond to the cell operation with air as oxidant, the solid lines representing data obtained on pure oxygen operation.

Siemens have developed their single cell technology around highly loaded unsupported platinum-ruthenium black anodes (4 mg/cm²) and platinum black cathodes (4 mg/cm²), operating at high

Fig. 6 Tafel plots of single cell DMFC data from various research groups using oxygen (solid lines) and air (broken lines) showing the high performances achieved by these groups

temperatures and pressures (13). Their best data show a high performance of 0.52 V at 400 mA/cm^2 and 130°C with pressurised methanol/water vapour and oxygen at 4.4 bar and 5 bar, respectively. This produces a respectable power density of about 200 mW/cm^2 which meets the target for a practical device, although this was achieved with pure oxygen. Durability testing of the single cell shows that stability is not yet sufficient for practical applications (14). However, following the successful demonstration of such high performances, Siemens are currently working with Johnson Matthey and Innovision to develop cost effective cells that operate under more realistic conditions.

The Newcastle group has considered both liquid-feed and vapour-feed systems, with electrodes loaded at 2.5 mg platinum/cm^2 (15–17). A maximum performance of 0.5 V at 400 mA/cm^2 was achieved at 98°C with oxygen at 5 bar pressure and 2 M methanol/water vapour at 200°C. The maximum power output with oxygen was over 350 mW/cm^2 at 1.2 A/cm^2. With pressurised air, the cell voltage fell to 0.4 V at 400 mA/cm^2, with a maximum power output of 220 mW/cm^2. However, at a practical cell voltage of 0.5 V the cell was able to generate only

50 mW/cm^2, which is still somewhat short of the target 200 mW/cm^2. Good short term stability of the electrode assemblies was, however, reported.

JPL/Giner Inc. present cell data of 0.47 and 0.38 V at a current density of 400 mA/cm^2 for their liquid-feed DMFC system operating at 90°C with 2.26 atm oxygen and air pressure, respectively (12). They also present impressive results for electrodes with low platinum loadings of 0.5 mg/cm^2, which are capable of cell voltages near 0.5 V at a current density of 300 mA/cm^2 at 95°C.

Data from LANL (18, 19) are also very impressive with a best performance of 0.57 V at 400 mA/cm^2 for oxygen operation. This was achieved using Nafion®-112 membrane, which is thinner than the currently used Nafion®-117. The enhanced performance is a result of the reduced internal resistance of the cell. The catalysts consisted of unsupported platinum/RuO$_x$ at the anode and platinum black at the cathode. LANL also use high temperatures and pressures to enhance the electrode kinetics and to counter fuel cross-over. Current membrane materials are severely limited by fuel cross-over, and most research groups are relieving this problem by

using high gas pressures and flow rates. The performance of the LANL cell in air was 0.52 V at 400 mA/cm² at 110°C with anode and cathode pressures of 1.8 and 3 atm, respectively. It is unclear whether LANL are encountering enhanced fuel cross-over with the thinner Nafion®-112 membranes, as would be expected. They do, however, suggest that the cell performance is limited by the anode catalyst activity, and that their cathode exhibits a degree of methanol tolerance. The performance of their electrode with Nafion®-117 is very similar to the data presented by the Newcastle and JPL groups.

Summary and Future Opportunities

In the last few years there has been a considerable improvement in the activity of methanol electro-oxidation catalysts, through improved operating conditions and better dispersion and control of the composition of existing platinum-ruthenium materials. Electrode technology has also advanced with the introduction of solid polymer electrolytes, such as Nafion®, which has extended the operational temperature and reduced the complexity of modern cells.

The single cell data presented by various groups demonstrate the influence of parameters such as temperature, pressure, concentration of reactants and electrode structure. The present level of technology requires high temperatures (130°C) and pressures before practical cell power densities can be obtained.

Most groups appear to use high noble metal loading of up to 4 mg/cm² on the anode to increase the methanol turnover to a useful rate. This level of catalyst loading is too high for transportation applications and clearly indicates that the anode catalyst activity has still to increase, perhaps by a factor of at least ten, to reduce the noble metal loadings to more acceptable levels of below 0.5 mg/cm². Optimisation of the electrode structure, leading to higher catalyst utilisation, will also contribute to increased cell performance.

Methanol cross-over from the anode to the cathode appears to be a major limitation at present. This is reflected in the high platinum catalyst loadings and the high gas pressure and flow rates which are necessary for reasonable cathode performance. The performance of the DMFC would be improved considerably if a methanol-impermeable electrolyte or a methanol-tolerant cathode existed. In order to minimise the effects of methanol cross-over, alternative membrane materials have been sought. Present electrolyte materials are restricted by poor water management and therefore can only operate at temperatures below 100°C at ambient pressures. If the operational temperature could be increased to 150°C at ambient pressures, this would considerably enhance the kinetics of the anode reaction. However, this requires new materials which do not require humidification to maintain high conductivity.

An alternative to new membrane technology is to employ methanol tolerant cathode catalysts. A possible class of materials are high surface chevrel phase composites which consist of molybdenum, ruthenium and sulphur. Although these may not offer the same oxygen reduction performance as platinum-based materials, this may outweigh the performance loss attributable to methanol cross-over seen with platinum-based materials.

The DMFC has always been considered as the ideal fuel cell. Its simplified system design and direct use of liquid fuel have in the past been outweighed by the very low power densities achievable. The poor performance of the cell was due to the poor kinetics of the anode reaction and fuel cross-over. Although performance levels are not yet sufficient for commercial application, if the progress made over the past two to three years is continued, then this fuel cell could emerge from the shadows of its hydrogen-fuelled counterparts.

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A Dream, a Challenge, Perhaps a Necessity

Fuel Cells and Their Applications

The development of each major type of fuel cell is comprehensively reviewed in this book, which begins with an overview of the current position. This is followed by chapters on general aspects of fuel cell systems and their basic thermodynamic principles. In Chapter 4, the main chapter, the electrochemistry of each fuel cell type is discussed, together with materials, cell designs and the performances for each type of cell. Readers requiring more detailed information on the science of fuel cells are directed to other publications by an extensive list of references at the end of this chapter.

Technological developments in alkaline fuel cells (AFC), of which Kordesch has long practical experience, are explained by reference to the activities of the industrial companies involved. Milestones in the development of other types of fuel cells are discussed in later chapters.

Chapter 5 describes stationary applications and concentrates on fuel cell applications in dispersed energy systems, while Chapter 6 covers on-site integrated energy systems and industrial co-generation. The transport applications of fuel cells in electric vehicles are covered in Chapter 7. This chapter concentrates mainly on historical activities, particularly those related to AFC; regrettably, more recent developments in the field of polymer electrolyte fuel cells (PEFC) are listed rather than analysed. No reference is made to small portable fuel cells as an alternative to batteries or generator sets.

One strength of the chapters on applications is the use of high quality photographs, tables and diagrams, which complement the text. In general, sections covering PEFC applications are more up-to-date than those covering phosphoric acid fuel cells (PAFC).

In Chapter 8, the various fuels used for fuel cells are discussed together with methods of producing hydrogen from them. This chapter clarifies the value of considering fuel cells in terms of systems rather than as stacks alone. Chapter 9, the last chapter, summarises the worldwide state-of-the-art and looks to beyond 2000.

Although reference is made throughout the book to the role of platinum group metals as catalysts in low temperature AFC, PEFC, PAFC and direct methanol fuel cells (DMFC), it does not dwell on the catalyst science. The book concentrates mainly on materials, engineering, systems and applications. The sections covering solid oxide fuel cells do not include any references to recent developments which utilise platinum or ruthenium.

The authors suggest reconsidering the use of AFC for transportation applications, pointing out recent work which questions the established views regarding carbon dioxide sensitivity. However, industry is presently clearly focused on PEFC, while academic interest in PEFC alternatives is directed toward solid oxide and DMFC.

To conclude, this book reviews the last 25 years of fuel cell history. It is a valuable reference tool for those new to the field and an extensive review for the more experienced.   R.J.D.E.