



RHODIUM ELECTROCATALYST AND METHOD OF PREPARATION

STATE OF THE ART

The electrolysis of aqueous HCl solutions is a well known method for the recovery of high-value chlorine gas. Aqueous hydrochloric acid is an abundant chemical by-product, especially in chemical plants making use of chlorine as a reactant: in this case, the chlorine evolved at the anodic compartment of the electrolyser can be recycled as a feedstock to the chemical plant. Electrolysis becomes extremely attractive when the standard hydrogen-evolving cathode is substituted with an oxygen-consuming gas diffusion electrode due to the significant drop in energy consumption. The ability of the gas diffusion electrode to operate successfully in this context is crucially dependent on the nature and performance of the catalyst, but also on the structure of the gas diffusion electrode.

Platinum is generally acknowledged as the most effective catalyst for the electroreduction of oxygen in a wide range of conditions; the activation of gas diffusion electrodes with platinum based catalysts is well known in the art, and finds widespread application in fuel cells and electrolyzers of many kinds. However, the case of aqueous HCl electrolysis poses some serious drawbacks to the use of platinum as cathodic catalyst, as it is inevitable for the gas diffusion cathode to come at least partially in contact with the liquid electrolyte, which contains chloride ion and dissolved chlorine. First of all, platinum is susceptible to chloride ion poisoning which negatively affects its activity toward oxygen reduction. Even more importantly, the combined complexing action of hydrochloric acid and dissolved chlorine gas changes the platinum metal into a soluble salt which is dissolved away, making this material inappropriate for use in gas diffusion electrodes.

Other platinum group metals appear to follow a similar fate. For example, according to Pourbaix' Atlas of Electrochemical Equilibria in Aqueous Solutions, finely divided rhodium metal dissolves in hot concentrated sulphuric acid, aqua regia, and oxygenated hydrochloric acid. Similarly, (hydrated) $\text{Rh}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ dissolves readily in HCl and other acids. These problems have been partially



mitigated with the disclosure of the rhodium / rhodium oxide based catalyst described in concurrent U.S. Pat. Application 09/013,080. In particular, the rhodium/rhodium oxide system, although slightly less active than platinum towards oxygen reduction, is not poisoned by chloride ions. Also the chemical resistance to aqueous hydrochloric acid with small amounts of dissolved chlorine is sensibly enhanced with respect to platinum. However, an activation step is needed to obtain a sufficiently active and stable form of this catalyst, and some limitations arise when such catalyst has to be included in a gas diffusion electrode; for instance, the chemical and electronic state of the catalyst is changed upon sintering in air, a very common step in gas diffusion electrode preparations known in the art. Cumbersome and/or costly operations have to be carried out to replace this step, or to restore the active and stable form of the catalyst afterwards, as disclosed in U.S. Patent Application Serial No. 09/013,080. Furthermore, the required chemical stability is displayed only in the potential range typical of the electrolysis operation; extremely careful precautions have to be taken during the periodical shut-downs of the electrolyzers, otherwise the sudden shift in the cathodic potential, combined to the highly aggressive chemical environment, causes the dissolution of a significant amount of catalyst, and the partial deactivation of the remaining portion. While tailored procedures for planned shut-downs of the electrolyzers can be set up, although resulting in additional costs, little or nothing can be done in case a sudden, uncontrolled shut-down due to unpredictable causes (for instance, power shortages in the electric network) should occur.

OBJECTS OF THE INVENTION

It is an object of the invention to provide a novel catalyst for oxygen reduction having desirable and unexpected chemical stability towards highly corrosive media.

It is another object of the invention to provide novel gas diffusion electrodes with a novel catalyst therein having desirable and unexpected electrocatalytic properties.

It is another object of the invention to provide a novel electrolytic cell containing a gas diffusion electrode of the invention and to provide an improved method of electrolysing hydrochloric acid to chlorine.

These and other objects and advantages of the invention will become obvious from the following detailed description.

THE INVENTION

The novel electrochemical catalyst of the invention is comprised of rhodium sulphide, which may be either supported on a conductive inert carrier or unsupported. This catalyst does not require any activation step prior to its use, and surprisingly retains all of its electrocatalytic activity towards oxygen reduction in presence of chloride ions and organic molecules. Moreover, the catalyst is surprisingly not dissolved by the complexing action of aqueous hydrochloric acid / chlorine mixtures, thereby requiring no particular precautions during shut-downs when used in hydrochloric acid electrolyzers. The catalyst is preferably coated on at least one side of a web, and may be used alone, with a binder, blended with a conductive support and a binder, or supported on a conductive support and combined with a binder. The binder may be hydrophobic or hydrophilic, and the mixture can be coated on one or both sides of the web. The web can be woven or non-woven or made of carbon cloth, carbon paper, or any conductive metal mesh.

Examples of high surface area supports include graphite, various forms of carbon and other finely divided supports but carbon black is preferred.

Such catalyst coated webs can be employed as gas diffusion cathodes exhibiting cell voltages, current densities and a lifetime that could not be previously obtained under normal operating conditions, especially when used in highly

aggressive environments, such as the case of electrolysis of by-product hydrochloric acid.

The catalyst may be easily prepared upon sparging hydrogen sulphide gas in an aqueous solution of a water soluble rhodium salt. Nitrogen gas may be used as a carrier for hydrogen sulphide, and a pure nitrogen flow may advantageously be used to purge excess hydrogen sulphide upon completion of the reaction. The resulting solids are recovered by filtration, washing and drying to constant weight at 125°C, for example. The rhodium sulphide obtained in this way is unsupported (unsupported catalyst). However, when the aqueous solution of the water soluble rhodium salt further contains a suspension of a suitable conductive support, then the rhodium sulphide is preferentially deposited as tiny particles on the surface of the conductive particles (supported catalyst). The resulting hydrated form of rhodium sulphide must be heated in an inert atmosphere at 550 to 650°C, and preferably above 600°C to form an anhydrous form of rhodium sulphide catalyst. The heating may be for several hours depending on the size of the batch, and the choice of the temperature is crucial for the formation of a sufficiently stable catalyst.

If the temperature is too low such as 300°C, the resulting crystallites are not well-defined and the catalyst stability is not sufficient. If the temperature is too high, i.e., 725°C, the unsupported catalyst has excellent acid stability but is not electrically conductive enough.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic of reaction set-up for the generation of supported or unsupported rhodium sulphide.

Figures 2 shows X-ray diffraction patterns for rhodium sulphide precursors as a function of oven temperature. Trace 1: 30% RhSx on carbon, dried at 125°C. Trace 2: 30% RhSx on carbon, 300°C in argon. Trace 3: 30% RhSx on carbon, 650°C in argon.

Figure 3 is a schematic of flow system for the generation of Cl_2 from HCl using an oxygen depolarised gas diffusion electrode.

Figure 4 shows typical platinum catalyst data, incorporated in a standard ELAT™ structure with 30% Pt/C, 1.1 mg/cm^2 , coated with 0.70 mg/cm^2 Nafion, operating in HCl/Cl_2 solution at 3 kA/m^2 . ELAT is a trademark of E-Tek, Natick (MA), U.S.A., which identifies gas diffusion electrodes comprising a carbon web and a mixture of catalyst and fluorinated binder incorporated therein.

Figure 5 shows data obtained with rhodium-rhodium oxide, incorporated in a single-sided ELAT™ structure with 30% Rh/C, 1.01 mg/cm^2 , coated with 0.70 mg/cm^2 Nafion, operating in HCl/Cl_2 solution at 3 kA/m^2 .

Figure 6 shows data obtained with 30% RhS_x/C , incorporated in a single-sided ELAT™ structure with 30% Rh/C, 1 mg/cm^2 , coated with 0.70 mg/cm^2 Nafion, operating in HCl/Cl_2 solution at 3 kA/m^2 .

In the following examples, there are described several preferred embodiments to illustrate the invention. However, it is to be understood that the invention is not intended to be limited to the specific embodiments.

EXAMPLE 1

100 grams of supported rhodium sulphide were prepared by the following procedure: 57.3 grams of $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ (39.88% given as rhodium metal) were dissolved in 2 litres of de-ionised (D.I.) water, without any pH adjustment. 53.4 grams of Vulcan XC-72 active carbon were added, and the mixture was slurried with a magnetic stirrer.

Hydrogen sulphide gas was then sparged through the slurry at ambient temperature using nitrogen as a carrier gas, according to the scheme of Figure 1. The mixture has been allowed to react as described for 7 hours. Upon completion of the reaction, nitrogen was purged through the system to remove residual H_2S . The remaining solution was vacuum filtered to isolate the solids, which were then washed with de-ionised water and dried at 125°C to a constant weight.

The resulting catalyst cake was finally ground to a fine powder and subjected to 650°C under flowing argon for two hours. A load of catalyst on carbon of 30%, given as rhodium metal, was obtained.

As already stated before, this final thermal treatment is a crucial step in the preparation of the desired stable and active metal sulphide. Figure 2 shows the development of a preparation of rhodium sulphide as outlined above as a function of treatment temperature. In particular, figure 2 shows the results of a powder sample XRD scan on a.) the supported catalyst after filtration and drying, b.) the supported catalyst of a.) after heating to 300°C in argon, and c.) the supported catalyst of b.) after heating to 650°C. The increase in number and clarity of peaks in these scans indicates the formation of well-defined crystallites containing rhodium and sulphur. These changes induced in the XRD spectrograph by the temperature treatment also reflect corresponding substantial gains in catalyst stability.

EXAMPLE 2

8 grams of unsupported rhodium sulphide were prepared by the following procedure: 12.1 grams of $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ (39.88% given as rhodium metal) were dissolved in 700 ml of de-ionised water, without any pH adjustment. Hydrogen sulphide gas was then sparged through the slurry at ambient temperature using nitrogen as a carrier gas, according to the scheme of Figure 1. The mixture has been allowed to react as described for 4 hours. Upon completion of the reaction, nitrogen was purged through the system to remove residual H_2S . The remaining solution was vacuum filtered to isolate the solids, which were then washed with de-ionised water and dried at 125°C to a constant weight. The resulting catalyst cake was finally ground to a fine powder and subjected to 650°C under flowing argon for two hours.

COMPARATIVE EXAMPLE 1

A rhodium oxide/rhodium catalyst on Vulcan XC-72 was prepared following the method disclosed in co-pending U.S. Patent Serial No. 09/013,080 (26 Feb.

98) and herebelow repeated. 9.43 g of $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ (39.88% given as rhodium metal) were dissolved in 2 litres of de-ionised water at room temperature, and the resulting solution was added to a dispersion of 8.75 g of Vulcan XC-72 in 500 ml of D.I. water. The mixture was stirred to maintain a uniform carbon slurry while slowly adding (2-3 ml/min) a 0.5 molar solution of ammonium hydroxide. Besides the 220 ml of ammonium hydroxide theoretically required to form $\text{Rh}(\text{OH})_3$, a 20% excess of ammonium hydroxide was added to set a basic environment. The basic slurry was then stirred at 60-70°C for 30-60 minutes and filtered hot. The filter cake was washed with about 200 ml D.I. water at 60-70°C and dried in air at 125°C for 15 hours.

The resulting cake was then ground to a fine powder and heated at 650°C under flowing argon gas to dehydrate and stabilise the catalyst. The load of catalyst on carbon was 30%, given as rhodium metal. The catalyst powder was further subjected to an activation step by heating at 500°C for 30 minutes under flowing hydrogen gas to further reduce some of the rhodium oxide to rhodium metal. As emphasised in co-pending U.S. Patent Serial No. 09/013,080 (26 Feb. 98), activation of rhodium-rhodium oxide catalyst is essential to obtain the most active form of this catalyst.

COMPARATIVE EXAMPLE 2

100 grams of supported platinum sulphide were prepared according to the procedure of the above Example 1, whereby a solution of chloroplatinic acid was employed instead of the rhodium chloride salt.

EXAMPLE 3

The catalysts of all the above reported examples, along with commercially available platinum on Vulcan XC-72 (for example from E-TEK, Inc.), can be utilised in several different configurations. The catalyst of this invention is not limited by the structure of the gas diffusion electrode: for instance, in the present case, each catalyst of the above examples and comparative examples was incorporated in

four different types of electrode structure, thereby obtaining sixteen different samples, according to the following procedures:

a) ELAT: A web of carbon cloth with a warp-to-fill ratio of unity and about 25 to 50 yarns per inch, and a 97-99% of carbon content was selected from a commercially available product with a thickness of 10 to 15 mils. Carbon cloth with a thickness of 5 to 50 mils could have advantageously been used for this purpose. A mixture of fluorinated polymer (polytetrafluoroethylene, P.T.F.E., commercialised by DuPont under the trademark Teflon®) and Shawinigan Acetylene Black (SAB) carbon, commercialised by Cabot Corp., was coated on each side of the carbon cloth, air drying at room temperature after each coat, until reaching at a total loading of 8 to 10 mg/cm². A mixture of the powdered catalyst and Teflon® was then applied on one side of the carbon web in multiple coats until obtaining a layer of 0.5 to 2 mg of catalyst per square cm. After the final coat, the carbon cloth was heated to 340°C for 20 minutes.

b). Single-sided ELAT: The above procedure for preparation of the ELAT was repeated except the SAB/Teflon® mixture was applied to only one side of the carbon cloth, with a loading of 4 to 5 mg/cm². The catalyst coat was applied on the same side, on top of the SAB/Teflon® layer.

c). Flow-through Electrode: A carbon cloth with the same specifications for the ELAT electrode was selected and 2 to 5 coats of a mixture of catalyst powder and Teflon® were applied to one side thereof. The coated fabric was then heated at 340°C for about 20 minutes to obtain 1.03 mg/cm² of rhodium metal. The final heating step or sintering step is believed to melt the Teflon® and distribute it across the carbon catalyst. However, the sintering step may be successfully omitted for this electrode.

d). Membrane Electrode Assembly: An ink was formulated consisting of approximately 3 parts catalyst and 1 part (as dry weight) Nafion® ionomer, such as that sold by Solutions Technology, (Mendenhall, Penn.) as a suspension in a mixture of water and lower aliphatic alcohols such as methanol, propanol, and/or

butanol. The ink was applied to a Nafion[®] 324 ion exchange membrane, commercialised by DuPont, held in place with a heated vacuum table, via spraying or painting. Other ion exchange membranes known in the art may have alternatively been utilised. Subsequent layers of the ink were applied until depositing 0.05 to 1 mg metal/cm² of catalyst. The assembly was further heated to remove solvents, and assembled with an appropriate electrode backing such as those disclosed in co-pending Patent Serial Number 09/184,089 (30 October 98). The catalyst ink as described could alternatively have been applied to an electrode backing, subsequently heated to remove solvents and assembled with an ion exchange membrane to form an equivalent membrane electrode assembly.

EXAMPLE 4

Prior to incorporation in gas diffusion electrodes, the resistance of this invention's catalyst to corrosive media such as boiling solutions of HCl/Cl₂ can be simply determined and compared to prior art catalysts as well as rhodium sulphide prepared at various temperatures. One to five grams of the catalysts of Table 1 were placed in a 250 ml beaker containing 130g/l chlorine-saturated HCl and heated to boiling. The formation of a deep colour indicates the dissolution of the metal from the catalyst, thus providing evidence for whether the catalyst would be appropriate for use in systems for the recovery of chlorine from aqueous HCl solutions.

Table 1 Summary of stability experiments for supported platinum and rhodium compounds, in boiling chlorine-saturated HCl

Sample	Colour
Pt on Vulcan XC-72 (Commercial)	Gold
Pt _x S _x /C Comparative Example 2	Yellow
Rh ^o -Rh ₂ O ₃ /C Comparative Example 1	Rose
Rh _x S _x /C Example 1, (no heat treatment)	Brown
Rh _x S _x /C Example 1	Trace pink, essentially stable

From this Table it is evident that in order to produce a stable form of rhodium sulphide, some heat treatment step is mandatory. It is also possible to conclude that not all sulphides of precious metals are stable in these conditions, and furthermore, in view of the instability of supported platinum sulphide, it is surprising to find supported rhodium sulphide relatively inert in these conditions.

EXAMPLE 5

The electrodes of Example 3 were subjected to an electrolysis laboratory test according to the scheme of Fig. 3. This configuration had a 3 mm gap between the cathode and the anode. However, equivalent results were obtained with a "zero-gap" adjustment, where the cathode and the anode were both pressed against the membrane. The exposed electrode surface area was 6.45 cm² and the membrane was Nafion 324. The anode was titanium mesh activated with ruthenium oxide catalyst. Oxygen was fed to the cathode at a rate of up to five-fold stoichiometric excess at 45-50 mbar pressure and 17% aqueous hydrochloric acid (184± 10 g/l) was fed to the anode. A by-product acid coming from a chemical plant was used as the master 33% solution. The said electrolyte was recirculated until 50% of the hydrogen chloride was depleted and then fresh electrolyte was added. The 50% depletion leads to a temporary increase in cell voltage, and is exhibited as "spikes" on a graph of voltage versus time. The electrolyte flow rate was 4 ml per minute or 0.372 m³/hour/m² at a back-pressure of 120 mbar. Unless stated otherwise, the cells were run at 3 kA/m² and all voltages were uncorrected for current collector resistance. The temperature of the cell and electrolyte was held at 55°C ± 5°C with heating tape applied to the cell metal end plates and an air conditioning unit.

In commercial electrochemical plants, two common temporary operation modes are encountered which reflect the situations of either scheduled repair or replacement of worn-out components, or the unscheduled failure of these components. For the scheduled shut-downs, one can induce a "controlled" procedure, whereby elements of the plant are systematically turned off or

attenuated to a lower operational level. In particular, chlorine can be degassed on the anode side and oxygen can be substituted with nitrogen on the cathode side. Conversely, during the unscheduled failures ("uncontrolled" shut-downs), components of the plant are typically subjected to the most rigorous of operating conditions. In particular, chlorine and oxygen are left in the cell and as a consequence severe corrosion conditions arise. Since it is an object of this invention to provide a catalyst and gas diffusion electrode capable of operation in an electrochemical plant, the catalyst-electrode assemblies were tested in simulated controlled and uncontrolled shutdowns.

These two interventions differ in the manner of turning off various components. For the controlled shutdown, an inert gas was fed to the cathode, and the rectifier current was slowly decreased, followed by turning the rectifier off. Once the rectifier was off, the pumps were halted. For the uncontrolled shut-down, oxygen flow was halted to the cathode while the rectifier and pump circuits were suddenly shut off, without the gradual decrease in current or flow rate.

The catalyst of this invention was subjected to testing under the uncontrolled shut-down, and compared to current state-of-the art catalysts. Figure 4 shows the typical platinum catalyst in an ELAT™ electrode. While the operating voltage is 1.15 volts, the uncontrolled shut-down causes the catalyst to experience the full corrosive force of the electrolyte, and the cell potential increases by over 500 mV. Figure 5 shows the case of the rhodium/rhodium oxide of Comparative Example 1, incorporated in a single-sided ELAT, as described in Example 3, paragraph b). Here the initial steady-state voltage is just over 1.2 V, and only after activation does the voltage decrease below 1.2 V to approximately 1.18 V. Figure 6 is the case of a single-sided ELAT made with the rhodium sulphide catalyst of Example 1, as described in Example 3, paragraph b). The steady-state voltage of 1.15 V was obtained without any form of activation of the catalyst, either prior to assembly in the electrode or during operation in the laboratory test system. Figure 6 demonstrates that this new catalyst obtains desirable performance without an

additional activation step, and that the catalyst activity is preserved after being exposed to the full corrosive force of solutions of HCl/Cl_2 .

1. A catalyst for the electroreduction of oxygen comprising rhodium sulfide.
2. The catalyst of claim 1, further comprising a conductive inert carrier.
3. A Membrane Electrode Assembly comprising the catalyst of claim 1.
4. A gas diffusion electrode, comprising an electrically conductive web provided on at least one side thereof with a mixture comprising the catalyst of claim 1 and optionally at least one fluorinated binder .
5. The gas diffusion electrode of claim 4 wherein said conductive web is provided on both sides with a coating comprising at least one fluorinated binder and at least one electrically conductive carbon powder, and is further coated on one side only with said mixture of said catalyst and said at least one fluorinated binder.
6. The gas diffusion electrode of claim 4 wherein said electrically conductive web is provided on one side only with a coating comprising at least one fluorinated polymer and at least one conductive carbon powder, and is further coated on the same side with said mixture of said catalyst and said at least one fluorinated polymer.
7. An electrochemical cell comprising an anode compartment containing an anode and a cathode compartment containing a cathode separated by a separator, the improvement comprising the cathode is a gas diffusion electrode of claim 4.
8. A method for the production of the catalyst of claim 1, comprising sparging a solution of a rhodium compound with hydrogen sulphide, recovering and drying the resulting product, grinding the product, and subjecting the ground product to a thermal treatment between 550 and 700°C.
9. The method of claim 8 wherein the aqueous solution also contains at least one powder of a conductive inert carrier.
10. The method of claim 9 wherein the at least one powder of a conductive inert carrier is a carbon powder.

11. A process for electrolyzing an aqueous solution of hydrochloric acid to chlorine in an electrochemical cell of claim 7 comprising introducing aqueous hydrochloric acid into the anode compartment and oxygen into the cathode compartment while impressing a direct electric current on the cell.
12. The process of claim 7 wherein said hydrochloric acid is a by-product acid.
13. The electrochemical cell of claim 7 wherein the separator is an ion exchange membrane.