Oxygen Sensor using Zinc-Air Electrochemical Cells; A Simple Device to Demonstrate Applied Technology in Electrochemistry Teaching

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The oxygen sensor is a simple device which is able to demonstrate a practical use of electrochemical cells. The device is inexpensive and safe to use in a science classroom.

Abstract

An electrochemical cell that consists of a small sheet of zinc as the anode, a carbon bar or rod (as available) as the cathode, KOH-bentonite paste electrolyte (a mixture of potassium hydroxide solution and bentonite clay), and an amount of oxygen scavenger was developed to demonstrate a simple oxygen sensor. The device can demonstrate the principles of electrochemical cells' use as a gas sensor and hence, can be utilized as a medium for teaching applied technology of electrochemistry. In this simple sensor device, the decrease in oxygen concentration caused by the gas reaction with the oxygen scavenger can be observed as a decrease in cell potential difference.

Keywords: simple oxygen sensor, electrochemistry teaching, KOH-bentonite paste

Introduction

In schools, electrochemical cells that produce electricity from a redox reaction are commonly used as examples in the teaching of electrochemistry. The most common types are dry cells or accumulators. Some of these electricity generating cells do not use two electrolytes connected by a salt bridge, hence they may create confusion among students trying to connect the concept to its application. Thus, galvanic cells that can clarify the connection between electrochemistry as a concept and its application could solve the problem. As an alternative, aluminium-air cells that are able to reflect the development and roles of electrochemical cells in current technology were developed (Morris, Ottewill, and Barker, 2002). One of the advantages of this experimental device is that it can give a clear illustration of the ongoing process as the cells use a series of external electrodes. These cells can be considered as an improvement to the commonly used lemon battery (Worley and Fournier, 1998). Although the lemon battery can be regarded as a useful "fun item" to introduce the topic, we consider the battery to be insufficient to show the concept of a battery in science (Morris, Ottewill, and Barker, 2002).

Another approach to teach the electrochemistry concept and its application is by introducing the application of electrochemical cells as oxygen sensors. *Custom Sensor Solution Inc*. has developed a simple oxygen sensor that is made from a used hearing aid battery designed in such a way as to produce a circuit potential difference of 1.4 volts (*Custom Sensor Solution Inc.*, 2013). A similar idea of using a zinc-air to detect oxygen and to estimate its concentration was reported by Hooi and co-workers (2014). This oxygen sensor serves as an electrochemistry teaching/learning approach which is not only simple, but also easy, inexpensive, and safe to make and use in class and at home. However, the use of commercially available batteries causes students to act more as end users and not to have the opportunity to directly get involved in the making process. Components of electrochemical cells such as cathodes, anodes, and electrolytes cannot be directly identified as the batteries are already compactly packaged.

Using a similar electrochemical reaction, the present study has developed an electrochemical cell that consists of a small sheet of zinc as the anode, a carbon bar or rod (as available) as the cathode, and potassium hydroxide (KOH)-bentonite paste as the electrolyte, packed in a transparent container to allow for identification of those components easily. The paste is a mixture of 12 grams of potassium hydroxide and 3 grams of bentonite clay powder prepared by gently grinding the powders in a mortar with a pestle, to get a smooth mixture. Ten drops of aquadest from a pipet were added into the mixture during the grinding. The paste is formed as a result of the absorption and swelling properties of bentonite upon interaction with potassium hydroxide and water. KOH-bentonite paste is used because it has a good conductivity and it is easy to handle.

This device is ideal to demonstrate electrochemical cell construction, a zinc-air cell, and its electrochemical cell application as an oxygen sensor.

Technical Background and Experimental Procedure

An electrochemical sensor is a detection device that operates via a reaction between a sensor component and a substance in the form of gas or solution whose concentration is to be measured, by producing an electric current. The strength of this current depends on the concentration of the gas or solution. Electrochemical sensors usually consists of three main components: a working electrode, a reference electrode, and an electrolyte.

The simple oxygen sensor developed uses two different electrodes; hence it works based on a potential difference. The design is shown in Figure 1. This equipment consists of a transparent container and its cover made from acrylic polymer resin tightly sealed with silicon rubber to keep out the air. The sensor’s main parts are the anode in the form of a small sheet of zinc measuring 1.0 cm x 0.05 cm x 5.0 cm and the cathode a bar of carbon (1.0 cm x 0.3 cm x 5.0 cm). The dimensions are not critical and a carbon rod might be more readily available. These two electrodes are submerged into the KOH-bentonite paste electrolyte and are connected to a voltmeter which can show the potential difference produced by the cell. A resistor of value 47 Ω is connected across the cell to limit the current to a small value and knowing the resistance enables the current being delivered to be calculated. Inside the container, KOH-bentonite paste, electrolyte, and oxygen scavenger are placed in the device, see Figure 1.

Approximate position for Figure 1

Figure 2 shows the schematic electrochemical cell reaction in a simple oxygen sensor. A reduction reaction between oxygen and water takes place at the cathode resulting in reduction of hydroxyde ion; meanwhile zinc is oxidized to zinc (II) in the anode. The electrochemical reaction between the oxygen and the cell composing substances becomes the basis to detect the existence of the oxygen. The overall redox reaction described in Figure 2 is shown in equation (1).

$$2Zn(s) + O_2(g) + 2H_2O(l) \rightarrow 2Zn^{2+}(aq) + 4OH^-(aq) \qquad (1)$$

Theoretically, the cell potential can be calculated by using the Nernst equation that indicates relationship between the potential and the concentration of the cell components, the hydroxide ion concentration, $[OH^-]$, and the oxygen pressure, P_{O_2}, as shown in equation (2). Note that P_{O_2} here as in the formula below

$$E_{Cell} = E^0_{Cell} - \frac{RT}{nF} \ln \frac{[Zn^{2+}][OH^-]}{P_{O_2}} \qquad (2)$$

Approximate position for Figure 2

The reduction of oxygen concentration around the cell environment, represented by the P_{O_2} in the equation (2), will lead to the decrease of cell potential. In its application, the oxygen for the electrochemical reaction as shown in equation (1) may come from the open air.

When any oxygen scavenger is placed inside the sensor container, it will consume oxygen, and thus reduce its concentration. This will decrease the amount of oxygen reacting in the cathode. As a result the cell potential will also decrease. Some examples of oxygen scavengers are sodium sulphite (Na_2SO_3), iron (Fe), and ascorbic acid. In our experiments, 10 grams of solid sodium sulfite was used as the oxygen scavenger. Since sodium sulphite, and iron are harmful, its is strongly sugested that ascorbic acid should be used as the oxygen scavenger. An example of chemical reaction involving oxygen and sodium sulphite as an oxygen scavenger is shown in equation (3):

$$2Na_2SO_3(s) + O_2(g) \rightarrow Na_2SO_4(s) \qquad (3)$$

Prior to the study reported here, the cell circuit was pre-tested by passing gas mixture of oxygen and nitrogen (Setiabudi, Hardian, and Aihaningsih, 2012). The oxygen concentrations were of 0, 5%(v/v), 10%(v/v), 15%(v/v), 20%(v/v) and 50%(v/v), respectively. These increasing oxygen concentrations resulted in increasing cell potential i.e. 0 , 2.4 mV, 14.1 mV, 28.4 mV, 48.2 mV, 89.3 mV, respectively. A linear plot of cell potential versus oxygen concentration logarithm was obtained . The test was aimed at producing a sensor cell circuit that works using electrochemistry.

A series of trials have been carried out to evaluate the operability and data reliability of the device. The electrochemical cell was built using the procedure exemplified previously and illustrated in Figure 1. A voltmeter was connected to the carbon electrode, and to the zinc electrode. The two electrodes were fixed beneath the cover so that when the cover was placed on the container, they were partly submerged in the electrolyte. The cell potential was noted every minute for 22 minutes.

To observe the effect of oxygen concentration, 10 grams of solid sodium sulfite was put into the prepared container and acted as an oxygen scavenger. When the sensor container was closed, the stopwatch was started. The cell potential as indicated by the voltmeter was recorded every minute until it was stable, identified by the constant values of cell potential.

Results and Discussion

Device Operability

The results of the cell potential measurement at different times in the sensor cell condition without and with the involvement of the oxygen scavenger are presented in Table 1 and shown graphically in Figure 3. Experiments with the oxygen scavenger were carried out three times.

<u>Approximate position of Table 1</u>

<u>Approximate position of Figure 3</u>

When the cell was in contact with the air, the cell potential was relatively constant, around 56 mV to 58 mV, and remained stable at least for 30 minutes. In this condition, the oxygen concentration inside the container was the same as the oxygen level in the air, which is usually quoted as 21%. When the oxygen scavenger (sodium sulfite) was placed into the container, the cell potential decreased gradually to around 20 mV within 22 minutes. The amount of the oxygen inside the sensor chamber, which was initially about 21%, had decreased. This led to a gradual decrease of the cell potential. In a real sensor device, it is necessary to have an interface that changes the cell potential value into oxygen concentration display. A calibration process is needed for this purpose.

The experimental data are in agreement with those of oxygen detection experiment using commercial a zinc-air battery (Hooi, Nakano, and Koga, 2014). Although actual oxygen concentration was not measured in this reported experiment, the decrease of cell potential by the addition of an oxygen scavenger demonstrates the oxygen sensor principle.

Potential Application in Teaching

Pedagogically, there are two benefits from the use of the device in a classroom demonstration. Firstly, students are introduced to the construction of an electrochemical cell that can produce electrical energy. This potential application is similar to that of the aluminium-air experiment, as reported by (Morris, Ottewill, and Barker, 2002) who constructed an experimental approach to learning the rudiments of battery technology. The approach handled the traditional `black box' approach, where students experience battery science in a `packaged' cell. In the aluminium-air experiment and in our study, open cells involving separate and distinctive electrodes in a liquid or in a paste were used, enabling much better insight to their operation.

The constructed equipment utilized the KOH-bentonite paste, as a new alternative for ammonium chloride (NH_4Cl) aqueous paste as the electrolyte used in commercial dry cells. In some places where bentonite is locally available, this may give students a valuable perspective and exploration concerning materials that can be used to create electrochemical cells. In case that bentonite is hardly available, ammonium chloride paste might again be used.

Secondly students are not only able to measure the cell potential as a source of energy but they also have a first-hand experience to observe the decrease of a potential difference as a result of decrease in oxygen concentration. Students should understand that the decrease in the oxygen concentration is a result of a reaction between oxygen and the oxygen scavenger (in this case, the sodium sulfite). This serves as a simple illustration of the electrochemical cell application in sensor technology.

Teachers who use this application can have a useful discussion with their students about the use of oxygen sensors and oxygen scavengers in industries. A commercial oxygen sensor, for example, could be positioned in the exhaust of an internal combustion engine. By calculating and identifying the amount of the remaining oxygen, an electronic control unit can use look-up tables to determine the amount of fuel required to burn at the stoichiometric ratio (14.7:1 air : fuel by mass for petrol) to ensure complete combustion (Garrett, Steeds, and Newton; 2001)

The concept can be considered as a real life illustration and this can be seen from the fact that such principles are used for applications such as confined space monitoring for worker safety, medical applications related to anaesthesiology, respiratory therapy etc., and the monitoring of industrial processes where the oxygen concentration level is critical (Wang and Warburton, 1999).

The use of oxygen scavengers in the experiment can initiate student-teacher discussion on the topic. For example, in industry, oxygen scavengers can be used to avoid corrosion caused by oxygen in a boiler. This is carried out by the addition of oxygen scavenger to the pre-boiler section of the steam generating system. It is generally fed, along with other treatment chemicals, as an aqueous solution to the feed water either just upstream or, preferably, just downstream of the deaerator, although it is sometimes added into the return lines to scavenge oxygen in the condensate (Arkema, 2000).

Conclusion

The device along with the experimental procedure reported in this article shows that a zinc-air electrochemical cell circuit, using zinc and carbon electrodes and KOH-bentonite paste as the electrolyte, is capable of demonstrating the construction of the electrochemical cell and its components. In the device, the decrease in the oxygen concentration caused by the gas reaction with the oxygen scavenger is observed as a decrease in cell potential. The device is simple, inexpensive and safe to operate and able to demonstrate the principles behind the use of electrochemical cells as gas sensors.

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Number of words in this article are 2531

Table 1. Cell potential of the oxygen sensor exposed air without and with oxygen scavenger

Time	Without oxygen scavenger	With oxygen scavenger		
		1st expt	2nd expt	3rd expt
0	55.6	56.8	57.6	56.5
1	56.7	48.3	46.9	47.8
2	54.8	46.8	45.7	44.4
3	55.2	45.1	45.2	42.6
4	55.8	43.2	41.6	38.7
5	56.3	39.7	39.4	34.4
6	56.3	36.4	38.2	33.9
7	55.8	35.8	36.7	32.8
8	55.9	35.4	35.8	33.2
9	55.7	35.1	35.1	32.1
10	55.6	34.7	34.7	31.9
11	55.3	33	34.3	31.2
12	56.1	31.4	33.3	30.8
13	56.6	29.9	32.9	29.7
14	56.2	28.4	32.4	29.2
15	56.3	28.9	31.4	28.5
16	56.3	28.4	30.9	27.8
17	56.2	27.4	30.7	26.9
18	54.8	26.3	28.9	25.9
19	56.2	25.3	27.4	25.2
20	56,0	23.5	25.8	23.7
21	55.9	22.3	23.4	22.6
22	55.4	20.4	19.9	18.5

Lists of Figures

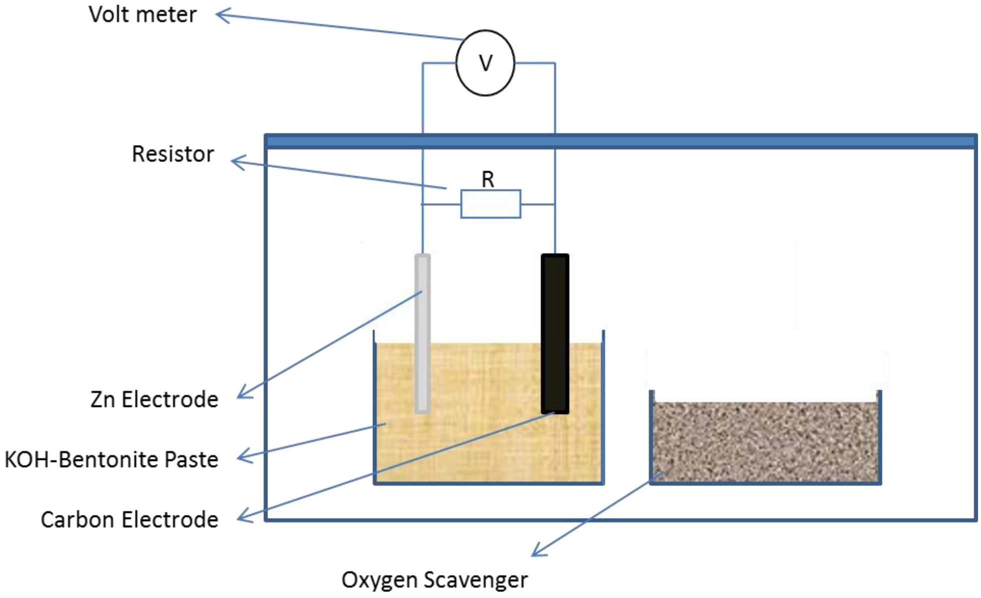

Figure 1. The construction of a simple oxygen sensor demonstration device

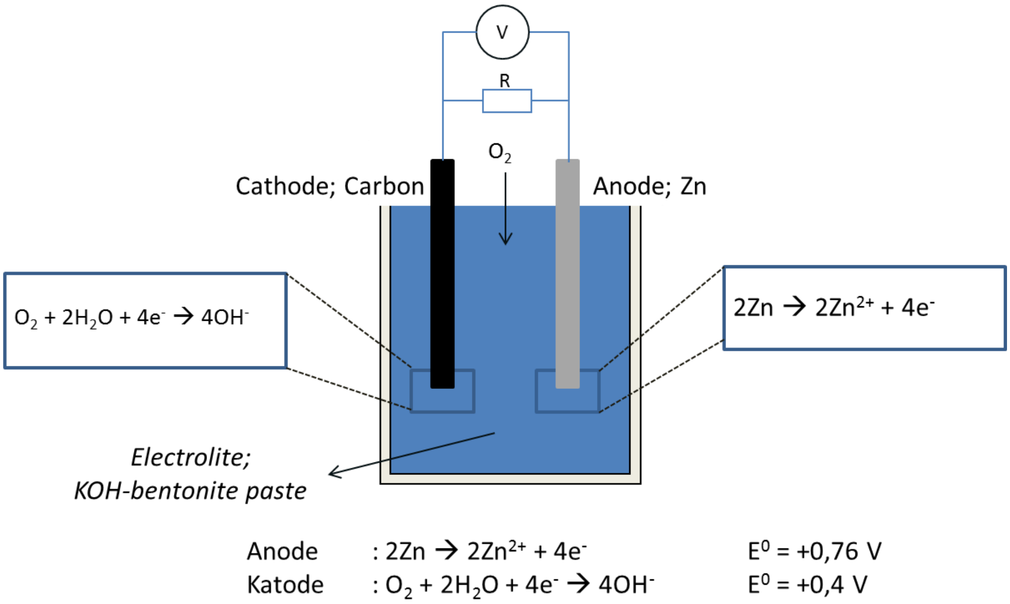

Figure 2. The schematic diagram of electrochemical cell reactions in the developed oxygen sensor

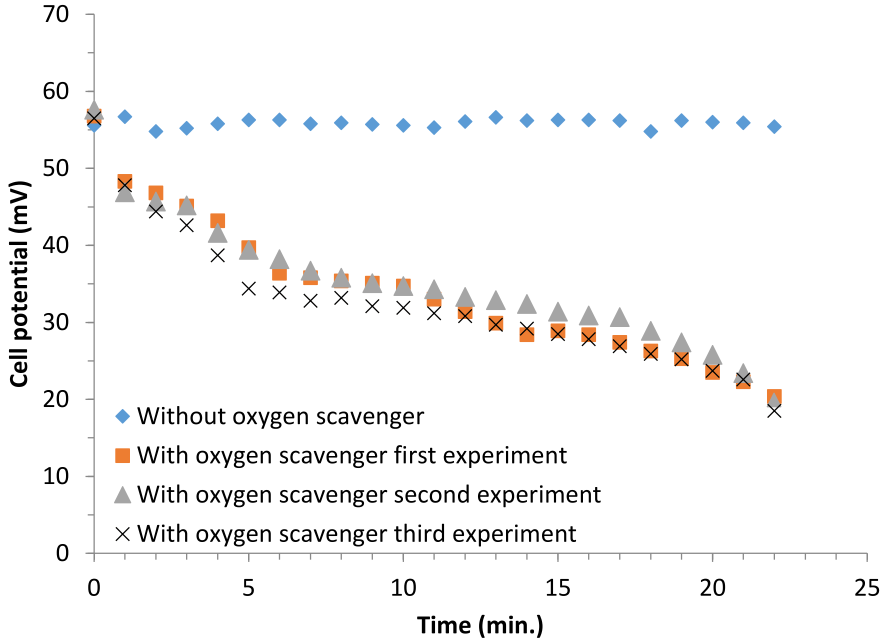

Figure 3. Cell potential of the sensor as a function of time in the presence and in the absence of oxygen scavenger