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A Convenient Measurement of Oxygen Concentration using Zinc-air Battery

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Abstract

For utilizing as an experimental tool at schools, the present work was intended to develop a convenient measuring method of oxygen concentration using commercially available zinc-air battery as a sensor. An apparent linear correlation between the oxygen concentration and the current value of a series circuit of zinc-air battery with adopted external resistance was observed in a wide range of atmospheric oxygen concentration. After investigating the appropriate measuring conditions, a simple device for measurement was constructed using a plastic syringe. Through testing the practical usefulness of the present convenient method by comparing with the detector tube method utilized widely at schools, it was concluded that the present convenient method can be applied as the low-cost experimental tool to various student experiments at schools.

Introduction

Zinc-air batteries, utilized for small electric devices such as a hearing aid, work by consuming oxygen molecules in air as the cathode active material. By utilizing successfully the cathode reaction in zinc-air batteries, Kamata et.al. have developed an electrochemical experiment for exploring Faraday’s law of electrolysis by evaluating the quantitative relation between the quantity of electricity and the molar amount of oxygen molecules consumed [1-3]. It is also known as one of the characteristics of the zinc-air batteries that the current value changes largely depending on the partial pressure of oxygen in the ambient atmosphere. If the change in the current value could be correlated with the partial pressure of oxygen by a certain manner, the zinc-air battery can be utilized as an oxygen sensor for the convenient measurement. Because the quasi-quantitative measurements of the oxygen concentration in ambient atmosphere have been adopted in various teaching materials for the basic science courses at elementary and secondary schools, it is highly expected that the convenient measurement of oxygen concentration using the zinc-air battery can be utilized in schools as a low cost experimental tool.

By focusing on the change in current value with partial pressure of oxygen, it was examined in the present study to develop a convenient measurement of oxygen concentration using the zinc-air batteries as the sensor. The performances of the commercially available zinc-air batteries as the oxygen sensor were tested by measuring the current of a series circuit constructed by a battery and an external resistance in various controlled concentrations of oxygen. After reviewing the measuring conditions such as the external resistance, measuring temperature, and waiting time for reading the current value, a simple measuring device of oxygen concentration was developed using a plastic syringe. The practical usefulness of the present method as applying to the measurement of oxygen concentrations at schools was evaluated by comparing with the detector tube method [4] utilized widely at schools .

Experimental

Performance of zinc-air battery as an oxygen sensor. Two kinds of commercially available zinc-air batteries of PR2330 (Panasonic 1.4 V) and PR44 (Panasonic 1.4 V) were selected for testing the performance as the possible oxygen sensor. A series circuit was constructed using a zinc-air battery and an external resistance of 10 Ω. The zinc-air battery connected to the circuit was placed in a plastic bag filled with mixed gases of nitrogen and oxygen with a known oxygen concentration. The potential of the zinc-air battery and the current of the circuit were measured at different oxygen concentrations using a digital multi-meter (Type 2407A; BK Precision).

Examination of the appropriate measuring conditions. Constructing series circuits using different external resistances of 0 and 1 Ω, the circuit current was measured under the conditions otherwise identical with the above measurement. Influence of the ambient temperature on the current value was examined by the measurements with keeping the mixed gas in the plastic bag at different temperatures. To determining the appropriate waiting time for measurement, time-dependent change in the current value was also recorded.

Construction of a simple device for measurement. A simple device for measuring the oxygen concentration developed in the present study was shown in Fig. 1. The zinc-air battery was placed in the rubber cap at the top of the piston rod in a plastic syringe (50 cm^3), where the top of the rubber cap was cut to expose the zinc-air battery to the gas in the syringe. At the outside of the syringe, an external resistance (10 Ω) and a digital multi-meter were connected in a series circuit by wires loaded from the cathode and anode of the zinc-air battery.

Test for the practical usefulness. The change in the oxygen concentration before and after burning of candle in a gas-collecting bottle was measured using the present device. The oxygen concentration in expiration collected in a plastic bag was also subjected to the measurement. The results of these measurements were compared with those determined by the detector tube method using a pump (Gastec GV-100) and a detector tube (Gastec No.31B O_2 6~24 %).

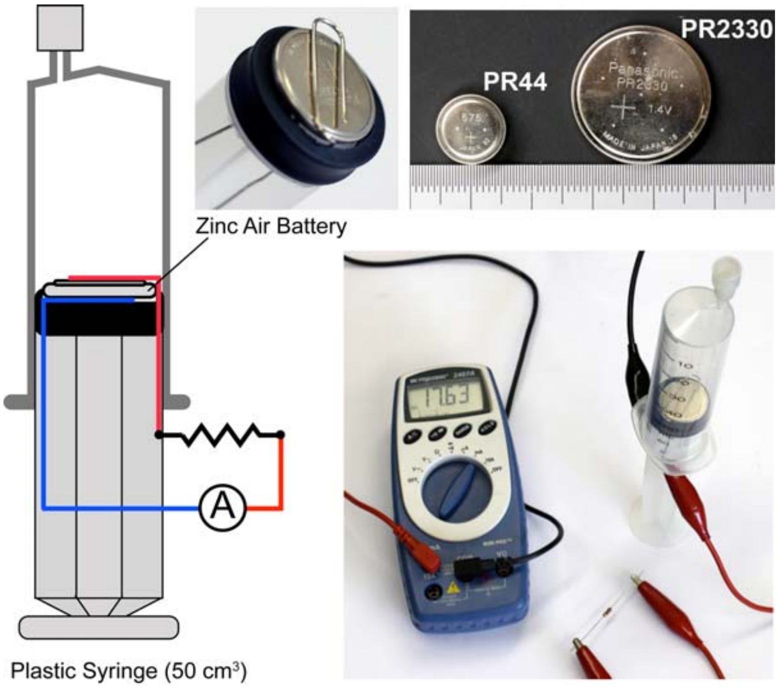

Figure 1　　A simple device for measuring oxygen concentration.

Results and discussion

Influences of oxygen concentration on the potential and current of the series circuit. Figure 2 shows the changes in the potential and current of the series circuit, when using a PR2330 and an external resistance of 10 Ω and reading after discharging for 10 min by exposing the zinc-air battery in atmospheres of various oxygen concentrations. The potential increases slightly from 1.34 to 1.37 V with increasing the oxygen concentration in the ambient atmosphere from 0 to 100 %. The respective electrode reactions of zinc-air battery are expressed by [5];

(−)　　$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$　　(E^o=1.25 V)　　(1)

(+)　　$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$　　(E^o=−0.4 V)　　(2).

Thus the overall reaction of the battery is

$2Zn + O_2 \rightarrow 2ZnO$　　(E^o=1.65 V)　　(3).

According to the Nernst's equation, the electromotive force, E, of the zinc-air battery is correlated to the partial pressure of O_2, $p(O_2)$, as follows.

$$E = E^\circ - \frac{RT}{4F}\ln\frac{1}{p(O_2)} \qquad (4)$$

where E^o, R, T, and F are the standard electromotive force, gas constant, absolute temperature and Faraday's constant, respectively. The slight change in the measured potential with the concentration of O_2 is understood as the result of the change in $p(O_2)$.

For the circuit current, the value increases linearly from 16.2 to 57.7 mA with increasing the atmospheric oxygen concentration from 5 to 40 %. Above 50 % of oxygen concentration, the current value is nearly saturated with the averaged value of 63.6±2.1 mA. Because the reactant oxygen molecules are preserved temporary in the air-diffuser layer inside the cell, the residual current at the zero oxygen concentration and the saturated current above 50 % of oxygen concentration can probably be explained by the residual oxygen molecules and saturation of oxygen concentration in the air-diffuser layer, respectively. The linear dependence between the measured potential and the concentration of atmospheric oxygen observed in the concentration range ≤40 % is likely to indicate that the overall rate of the cathode reaction v is expressed apparently by the first order reaction with respect to the oxygen concentration $[O_2]$ in the air-diffuser layer.

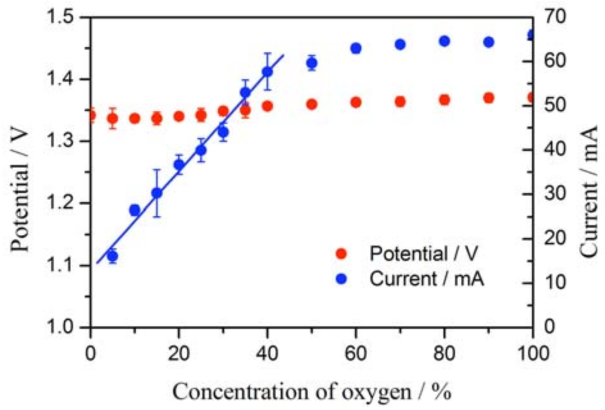

Figure 2 Changes in the potential and current of the circuit depending on oxygen concentration. (cell: PR2330, R =10Ω, t =23 °C, Waiting time=10 min)

$$v = k[O_2] \qquad (5)$$

It is very probable that the relation between the circuit current and the concentration of atmospheric oxygen can be utilized as the calibration curve for determining semi-quantitatively the oxygen concentration.

Appropriate measuring conditions. Figure 3 shows typical results of circuit current measurements using different external resistances. Although the current value at the same oxygen concentration increases with decreasing the external resistance, the similar changing behavior depending on the oxygen concentration is observed. Taking account of the empirically observed fluctuation of the current value when measured the circuit without the external resistance, an appropriate external resistance can

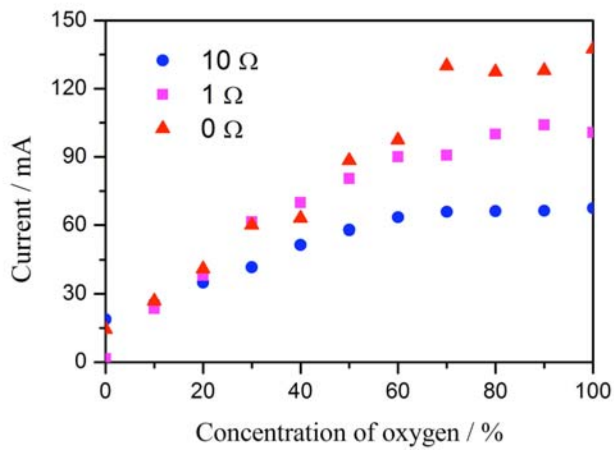

Figure 3 Change in the relationship between oxygen concentration and circuit current depending on the external resistance.
(cell: PR2330, t=23 °C, Waiting time=10 min)

be selected depending on the ammeter utilized.

As shown in Fig.4, influence of the sample gas temperature on the relationship between the oxygen concentration and the circuit current was examined by selecting three different temperatures of 10, 23, and 40 ºC. Although slight deviations are observed for the current values at 10 ºC, the values at 23 and 40 ºC are comparable. The results indicate that the relationship between the oxygen concentration and the circuit current is hardly influenced by the temperature of sample gas around the temperature range between the room temperature and body temperature, being in good agreement with the known performance of the zinc-air batteries for the practical use. For the measurement of the sample gas at the temperature lower than room temperature, it is recommended to establish another calibration line at that temperature.

For evaluating the appropriate waiting time for reading the circuit current, change in the circuit current with the discharging time was measured using two types of zinc-air batteries, PR2330 and PR44, under three different oxygen concentrations of 10, 20, and 30 %. Figure 5 shows typical time dependent change of the current. At the start of the discharging, the current value is nearly saturated value due to the stored oxygen in the air-diffuser layer. The value decreases gradually with discharging time. The discharging times required for getting within 5 % of the respective final values were 10 and 3 min for PR2330 and PR44, respectively. Because these behaviors were identical in the examinations under different oxygen concentrations, these times can be taken as the appropriate waiting time for the measurements. It is worth noting that the waiting time can be shortened drastically by using the

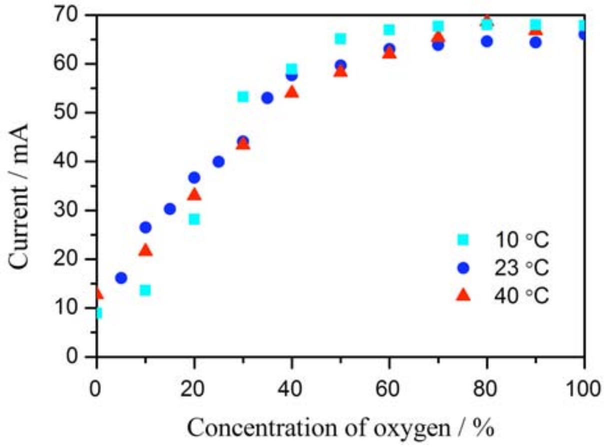

Figure 4　Relationship between oxygen concentration and circuit current at different measuring temperatures. (cell: PR2330, R=10Ω, Waiting time=10 min)

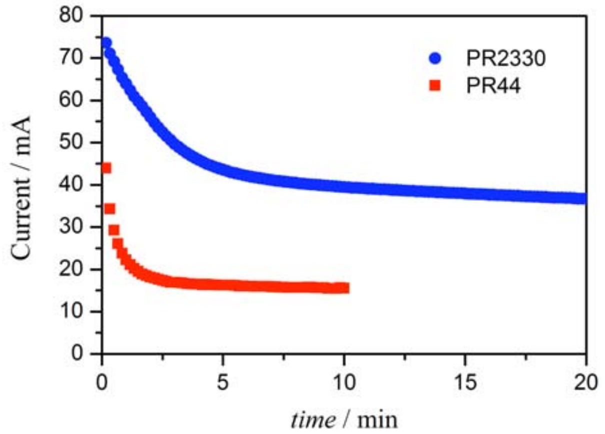

Figure 5　Changes in the circuit current with time. (Oxygen concentration: 20 %, t=23 °C)

zinc-air battery with smaller specification, i.e., PR44.

A simple device for the measurement. For establishing the calibration line for the measurement of oxygen concentration, the discharge currents at various oxygen concentrations were measured using the simple device shown in Fig.1. Figure 6 shows the relationship between the oxygen concentration and the discharge current recorded using two kinds of zinc-air batteries. It is apparent from Fig.6 that the simple measuring device contributes not only to simplify the measurement procedures, but also to reduce the distributions of the measured data. In addition, the range of oxygen concentration, where the current changes linearly with oxygen concentration, was enlarged remarkably. Within the range of oxygen concentration from 0 to 70 %, the respective calibration lines for the two kinds of zinc-air batteries can be drawn with the correlation coefficients better than 0.998, see Fig. 6. These improvements are likely due to the standardization of the measuring conditions by the use of the measuring device.

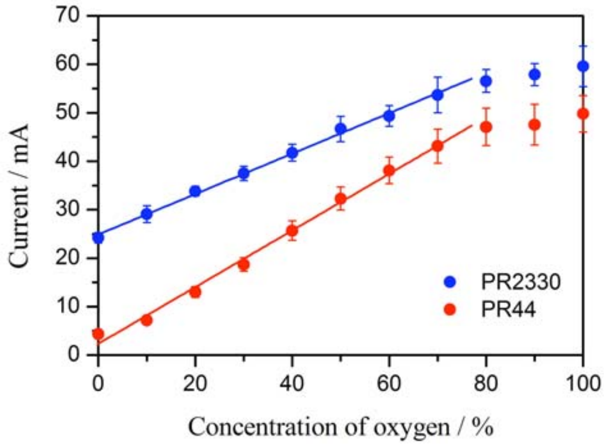

Figure 6 Calibration lines between oxygen concentration and the circuit current for the simple measuring devices using PR2330 and PR44. (t=23 °C, Waiting time=10 min (PR2330) and 3 min (PR44))

Test for the practical usefulness. The measured values of oxygen concentration by the present method and the detector tube method were compared in order to evaluate the practical usefulness of the present method. The simple experiments of measuring the changes in the oxygen concentrations by the combustion of candle and by man respiration were selected as the test reactions. Table 1 compares the oxygen concentrations measured by the two different methods. Because both of these methods are in semi-quantitative measurements, correspondences of the measured values by the respective methods are acceptable as applying to these student experiments. One conclusive benefit to use the present method is that the measurements can be repeated until the zinc-air battery goes down, in contrast to the disposable nature of the detector tube. On the other hand, the present method needs to convert the measured current value to oxygen concentration via the calibration line. An appropriate conversion method, such as graphical method, conversion table method, numerical calculation method, computer-aided method and so on, have to be selected by considering the ability of students.

Table 1　Comparison of the measurement results of oxygen concentration by the present method and the detector tube method

(cell: PR2330, *R*=10 W, *t*=23 °C, Waiting time=10 min)

Experiment	Sample gas	Concentration of oxygen / %	
		Present method[1)]	Detector tube method[2)]
Combustion of candle	before	19.2±1.7	18.8
	after	13.6±0.9	15.1
Respiration	inspiration	22.1±0.4	19.5
	expiration	16.9±1.1	16.2

[1)] Averaged value of five times measurements.

[2)] Value of single measurement.

Conclusions

The discharge current of commercially available zinc-air batteries changes linearly with the concentration of atmospheric oxygen. The linear relationship between the oxygen concentration and discharge current, observed in a wide range of oxygen concentration, can be utilized for determining oxygen concentration by measuring the discharge current of a series circuit composed of a zinc-air battery and an external resistance. A simple measuring device constructed using a plastic syringe makes it possible to measure the oxygen concentration semi-quantitatively and repeatedly.

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