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Removal of Carbon Dioxide from Breathing Gas Mixtures Using an Electrochemical Membrane Cell

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NOTE

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Abstract

The capability of an electrochemical membrane cell has been assessed for carbon dioxide removal from a breathing gas mixture. The experimental results were obtained under various operating conditions. The effects of such operating variables as CO_2 input rates and current densities on the extent of CO_2 separation are presented, and the usefulness of the electrochemical membrane cell in the removal of CO_2 from a breathing gas mixture is discussed.

INTRODUCTION

It is absolutely essential that the concentration of carbon dioxide in a sealed environment has to be controlled to a well-defined level. Without means of carbon dioxide removal, the accumulation of carbon dioxide in a breathing gas mixture will result in toxic effects to humans. In breathing systems of closed-circuit or semiclosed-circuit apparatus, normally used in diving applications, the removal of carbon dioxide is achieved by using a canister which contains caustic materials as a chemical absorbent. Because the chemical activity in the absorbent makes the gas uncomfortably hot for breathing and increases the probability in inhaling dust, the use of a chemical absorbent as a carbon dioxide scrubber often has some physiological effects on human lungs. Although there are a number of satisfactory canister designs which overcome such a deficiency, it would be preferable if the chemical absorption method could be replaced by a more conventional physical method such as a membrane process or an electrical gas separation technique.

Use of a membrane process for removal of carbon dioxide from breathing gas mixtures has received considerable attention in recent years. Sarich (*1*) investigated the feasibility of this process for a self-contained breathing system, using a silicone rubber membrane as the permeation barrier. This membrane material gives preferential permeation to carbon dioxide, and it may be used to remove an excess of carbon dioxide in the breathing system. Li et al. (*2*, *3*) also studied the problem of carbon dioxide removal from life support systems by using a membrane permeator. A purge technique on the permeate side was introduced in their study. It has been shown that a small stream of purge on the permeate side can improve the effectiveness of carbon dioxide removal and reduce the need to maintain a high pressure ratio across the membrane.

A practical difficulty of using membranes for a self-contained breathing system for removing CO_2 is to maintain the pressure difference across the membrane. Even a small pressure difference would be difficult to apply under water. In this study, the removal of CO_2 from life support systems is further investigated by using a membrane cell in which an electrochemical membrane was mounted. Therefore, instead of employing the pressure difference across the membrane, an electrical field was applied on both sides of the membrane. The usefulness of using an electrochemical membrane for the separation of gas mixtures has been described by Winnick (*4*).

EXPERIMENTAL

The electrochemical membrane cell used in this study, shown schematically in Fig. 1A, is a thin channel type with a channel height of 1–1.5 mm and an effective membrane area of 81 cm^2. A porous polyamide in the form of a thin sheet (1 mm in thickness) was used as a support on which a saturated aqueous solution of potassium carbonate was immobilized. The polyamide support was then pressed between two nickel screens which served as electrodes for the purpose of electrical field loading. In order to prevent the loss of the electrolyte, the polyamide support together with the nickel screens were covered by a hydrophobic membrane (polypropylene, microporous type) which has no resistance to the gas mixture used in this study. Thus, the electrochemical membrane employed in this study comprises a porous polyamide support immobilized with saturated potassium carbonate solution, two nickel screens, and the polypropylene hydrophobic membranes. Figure 1B shows a schematic diagram of the electrochemical membrane.

A feed gas containing 4% CO_2 and 56% O_2, with the balance being N_2, was introduced into the cathode compartment at the desired flow rate. With a proper loading of the electrical field, almost pure carbon dioxide

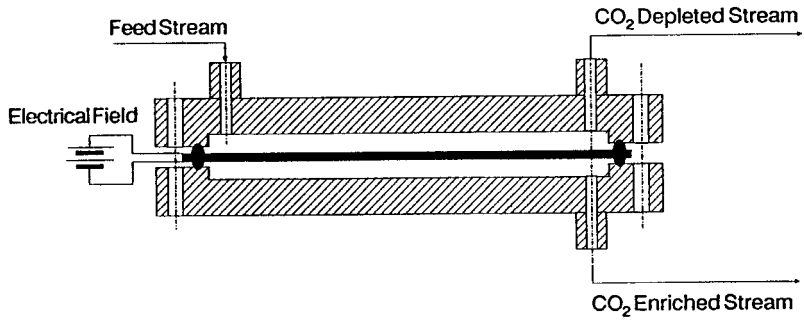

FIG. 1A. Electrochemical membrane cell.

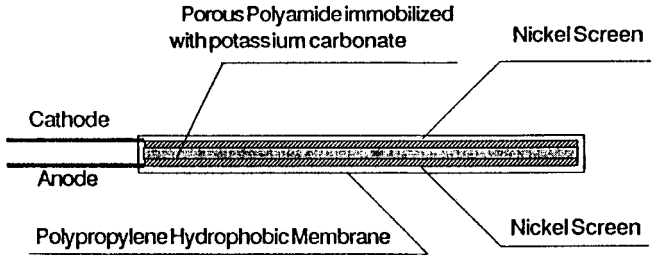

FIG. 1B. Electrochemical membrane.

together with a small amount of oxygen can be collected in the anode compartment. Carbon dioxide, oxygen, and nitrogen concentrations in the various flow streams were measured by using a gas chromatograph. A dc generator was employed for the purpose of electrical field loading. The voltage, between 1 and 3 V, was applied to the membrane cell, resulting in an electrical current in a range between 0.5 and 2 A.

RESULTS

The experimental results obtained in this study are presented and discussed using the example of CO_2 removal from a closed or semiclosed breathing environment. The feed composition consists of a mixture of 4% CO_2, 56% O_2, and the balance of N_2. The amount of CO_2 present represents the maximum local concentration in exhaled gas that might exist in, for example, the mouthpiece of a breathing apparatus. The oxygen level selected spans the range of concentrations used in shallow diving applications. The primary interest of this study, however, was to establish whether or not the CO_2 concentration in the exhaled gas can be reduced to 5 mbar, which is an acceptable level for breathing gas. Therefore, the CO_2 removal

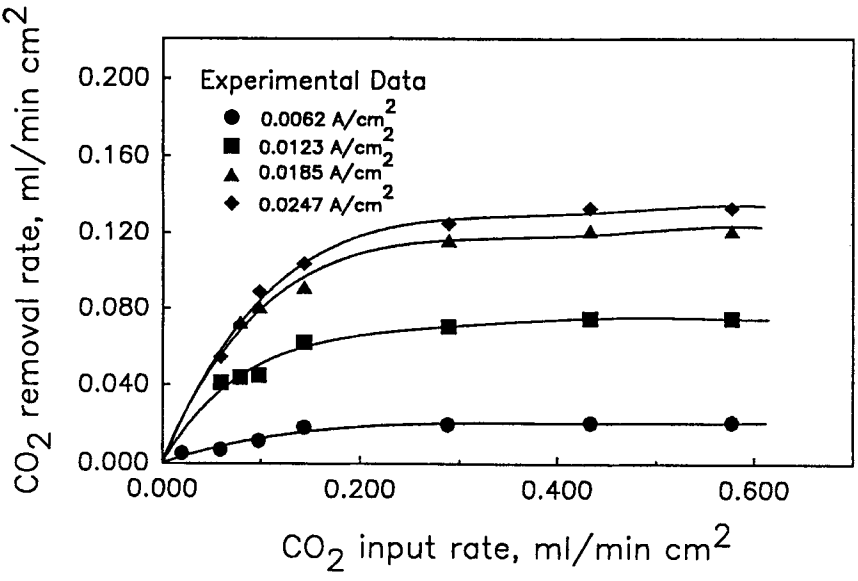

FIG. 2. Effect of CO_2 input rate on CO_2 removal rate based on the experimental results. The solid lines represent the best fitted curves.

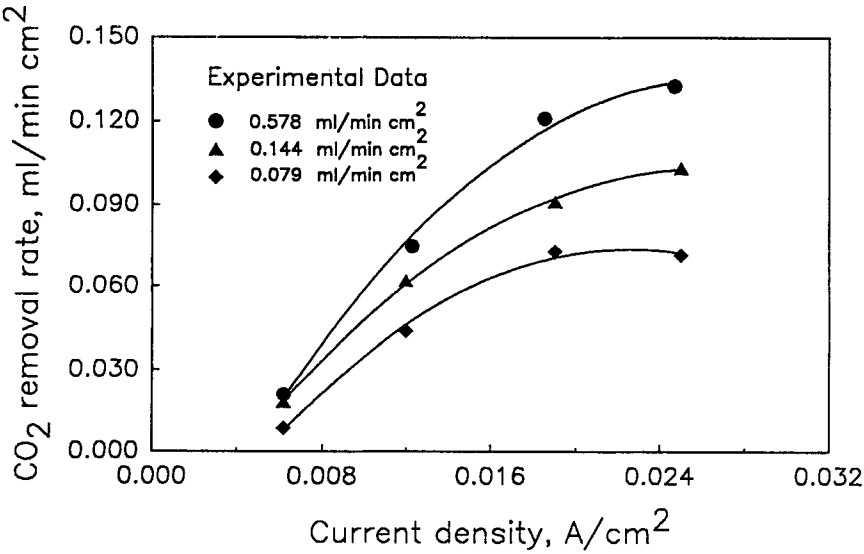

FIG. 3. Effect of current density on CO_2 removal rate based on the experimental results. The solid lines represent the best fitted curves.

rate and the CO_2 concentration in the depleted stream are the main interests of this study and are presented in Figs. 2, 3, and 4.

Figure 2 shows the effect of the CO_2 input rate on the CO_2 removal rate. The CO_2 input rate is expressed in milliliters of input CO_2 per minute and square centimeters of the effective membrane area (mL/min · cm^2), while the CO_2 removal rate is defined as milliliters of CO_2 removed per minute and square centimeter of the effective membrane area (mL/min · cm^2). It can be seen from Fig. 2 that as the CO_2 input rate is increased, the CO_2 removal rate is improved but only up to a certain value of the CO_2 input rate, which we term the maximum effective CO_2 input rate. Any further increase in the CO_2 input rate after this effective CO_2 input rate does not result in better CO_2 removal, as shown in Fig. 2. This behavior is also true for different current densities. It is interesting to note that the effective CO_2 input rate, in this case about 0.3 mL/min · cm^2, remains almost identical and does not seem to be dependent on the current density.

In Fig. 3 the effect of current density on CO_2 removal rates is shown for different CO_2 input rates. It can be seen that, in general, an increase in current density results in better CO_2 removal; however, the CO_2 removal

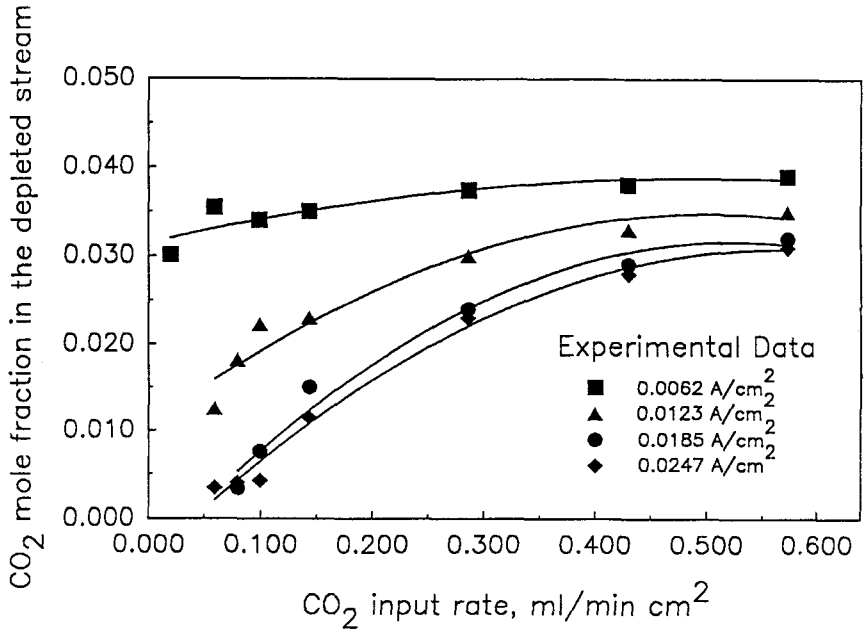

FIG. 4. Effect of CO_2 input rate on CO_2 concentration in the depleted stream based on the experimental results. The solid lines represent the best fitted curves.

rate becomes relatively independent of current density at current density values greater than 0.024 A/cm^2. This behavior is particularly pronounced when the CO_2 input rate is at 0.079 mL/min · cm^2.

Figure 4 depicts the CO_2 depletion curves resulting from the electrochemical membrane process for various CO_2 input rates and different current densities. It can be seen from Fig. 4 that the CO_2 concentration in the depleted stream decreases with a decrease in the CO_2 input rate. The required CO_2 level, i.e., less than 0.5%, in the depleted stream can be achieved at a current density of 0.0247 A/cm^2 and a CO_2 input rate of 0.1 mL/min · cm^2 or less. This means that the electrochemical membrane cell used in this study can be successfully employed for CO_2 removal from a breathing gas mixture.

It has been shown (*5*) that a diver exhales approximately 1 L/min of CO_2 when he is doing moderate work under water. If the effect of scale-up on the CO_2 concentration in the depleted stream is assumed to be negligible, a total electrochemical membrane area of 1 m^2 or 123 electrochemical membrane cells (used in this study) connected in parallel would be required for the diver.

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