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New mobile pressure control system for pneumatic actuators, using reversible chemical reactions of water

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ABSTRACT

Recently, the need for mobile gas sources and portable gas controllers that are silent and have high efficiency for pneumatic actuators has become important. Conventional air compressors and their control systems are large, heavy, noisy, and of low efficiency. This paper proposes a new mobile pressure control system using reversible chemical reactions. This device, consisting of a proton-exchange membrane fuel cell and a current controller, can control gas pressures using an electric current. This report shows the basic mechanism and experimental results using the first prototype based on the electrolysis/synthesis of water; this new idea has great potential. The prototype system achieved a pressure of 0.5 MPaG, which can drive most general pneumatic actuators.

1. Introduction

Pneumatic actuators such as pneumatic cylinders and pneumatic rubber actuators are widely used in industrial products and welfare equipment because of their unique characteristics, such as low cost, simple structure, light weight, and compliance [1–5]. However, conventional pneumatic actuators have three serious problems.

1. Driving pneumatic actuators generally needs an air compressor. This results in difficulties in using conventional pneumatic actuators in portable IT equipment and mobile welfare-robots.
2. The energy efficiency is low as a result of the conventional method of driving, in which compressed air with high physical energy is released to the atmosphere during return of the motion of the actuator, without energy recovery.
3. They are noisy. This limits the use of pneumatic actuators to industries and makes home use difficult.

Although pneumatic actuators have various excellent properties, these three problems make their application fields very limited.

This research aims to develop a new, small gas pressure controller, which drives pneumatic actuators easily, in the same way as electric motors are driven by batteries.

In the past, several prototypes of portable gas power sources using physical or chemical reactions have been studied. Examples are a gas source using carbon-dioxide phase-transition at the triple point [6], a prosthesis using monopropellant hydrogen peroxide [7,8], a gas source using the neutralization reaction of sodium bicarbonate and tartaric acid [9], and a gas source using an explosive chemical reaction [10].

However, these are not very good gas sources, for several reasons. The first problem is that their motions are controlled by mixing chemicals or by heating, and they cannot be controlled electrically. This is unsuitable for servo-actuators in mechatronics equipment. The second point is that the total quantity of generated gas is limited because they only generate gas from chemical materials mounted in the device. Other problems are their low energy efficiency and noise caused during exhaust. In addition, driving them needs several additional pieces of equipment and solvents. This results in the volume ratio of generated gas/equipment not being as high as expected in principle.

In this paper, we propose a new gas generation/absorption method using reversible chemical reactions that can be controlled by an electric current. Neagu et al. have developed a gas-actuated micro-electro-mechanical systems (MEMS) device based on the same idea [11,12], but their method is for small MEMS devices and the response time is very low. The goal of our research is to produce a silent and highly efficient gas generation/absorption system with practical response times for general pneumatic actuators, using a proton-exchange membrane (PEM) electrolyzer.

The system achieves pressure control through gas generation and absorption, with electric current control, and it also recovers energy during gas absorption. This means that the system

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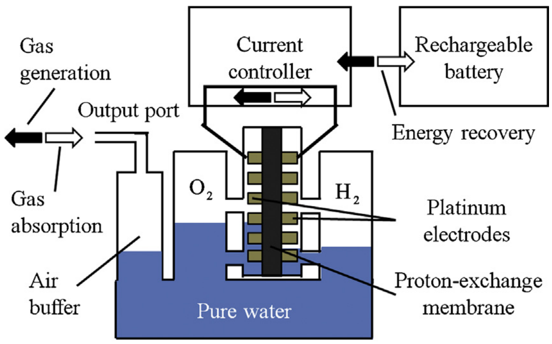

Fig. 1. Schematic diagram of proposed mobile pressure control system.

work continuously because the chemicals are recycled in the system.

As the first steps in our research, we have focused on the electrolysis/synthesis of water, developed a new gas control system, and experimentally showed its potential as a mobile gas controller for pneumatic actuators.

2. Working principle and prototype design

2.1. Basic working principle

The electrolysis/synthesis of water, which we have focused on, is represented by the following formula:

$$2H_2O \leftrightarrow 2H_2 + O_2 \quad (1)$$

Fig. 1 shows a schematic diagram of the proposed pressure control system. It consists of two platinum electrodes, a PEM, a water vessel filled with pure water, a current controller, and a rechargeable battery. A controlling electric current achieves reversible reactions of liquid to gas and gas to liquid.

Applying the electric current generates oxygen gas at the anode and hydrogen gas at the cathode. The two gases push down the water, and the air in the air buffer is compressed and expelled. To decrease the air pressure, this system operates as a type of fuel cell. Oxygen and hydrogen gases are absorbed on each electrode, and an electric current is produced, which can be recovered to a rechargeable battery. In this paper, we do not discuss energy recovery in detail but simply point out its potential.

2.2. Gas/liquid reaction cell structure

The prototype system uses a PEM electrolyzer; it works at room temperature and is suitable for miniaturization. This device is widely used as a power source for various kinds of mobile equipment and domestic electrical appliances. The PEM device generating gases by water electrolysis is shown Fig. 2, and its operation as a fuel cell to absorb gases is shown in Fig. 3.

During gas generation, the device works as an electrolyzer. The electrodes are connected to a DC power supply. Eq. (2) shows the chemical reaction at the anode, i.e., the left-hand side electrode in Fig. 2. Electrons move out from the anode, and oxygen and ionic water are produced from water. At the other electrode, i.e., the cathode, the chemical reaction shown in Eq. (3) occurs, in which electrons move toward the electrode, and hydrogen gas and water are generated. Through these two reactions, oxygen and hydrogen gases are generated as shown in Eq. (4), increasing the pressure in the chamber.

$$6H_2O - 4e^- \rightarrow O_2 + 4H_3O^+ \quad (2)$$

$$4H_3O^+ + 4e^- \rightarrow 2H_2 + 4H_2O \quad (3)$$

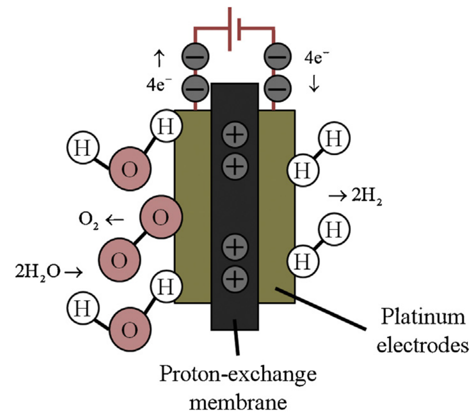

Fig. 2. Proton-exchange membrane device generating gas with electrolysis of water.

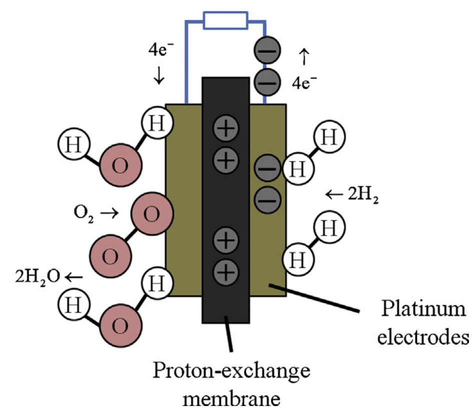

Fig. 3. Proton-exchange membrane device working for gas absorption with synthesis of water.

$$2H_2O \rightarrow 2H_2 + O_2 \quad (4)$$

During gas absorption, the device works as a fuel cell. The electrodes are connected to a resistor to enable current flow. Eq. (5) shows the chemical reaction at the cathode, i.e., the electrode shown at the right-hand side of the membrane in Fig. 3, in which water is generated from oxygen, ionic hydrogen, and electrons. At the other electrode, i.e., the anode, the chemical reaction shown in Eq. (6) occurs, in which ionic hydrogen and electrons are generated from hydrogen. The reaction of oxygen and hydrogen gases to form water, as shown in Eq. (7), results in a decrease in pressure.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (5)$$

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (6)$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad (7)$$

In this way, the pressure in the chamber is controlled reversibly by switching the electrical connections between the device, the power supply, and the resistor. Fine-structured platinum electrodes are used in the PEM, as shown in Fig. 4. They increase the interfacial area between gases and ions, promoting the reaction, resulting in a rapid pressure control response.

2.3. Theoretical characteristics

The pressure is calculated theoretically using Eqs. (8) and (9). Eq. (8) is the gas equation, where p, V, n, R, and T represent controlled pressure, total gas volume, total number of moles of oxygen and hydrogen gases, gas constant, and temperature, respectively. The