Development of Manipulator Using a Gas–Liquid Phase-Change Actuator*

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The purpose of this study is to develop a manipulator driven by a miniaturized artificial muscle in which a tiny compressor can be installed. Pneumatic actuators, such as pneumatic artificial rubber muscles (PARMs), have been widely used in many industrial and robotic research applications because they are compact and lightweight. However, the compressors driving such actuators are relatively large, and the peripheral devices such as filters and valves also tend to be large. To solve this size problem, the authors have been researching soft actuators driven by gas–liquid phase changes (GLPCs). In this research, a manipulator using an artificial rubber muscle driven by GLPCs was fabricated and a gripping experiment was conducted.

Keywords: Pneumatic artificial rubber muscle, Gas–liquid phase change, Pressure control, Manipulator

1. Introduction

The purpose of this study is to develop a manipulator driven by a miniaturized artificial muscle in which a tiny compressor can be installed. Pneumatic actuators, such as pneumatic artificial rubber muscles (PARMs) (Fig. 1 (a)), have been widely used in many industrial and robotic research applications. PARMs are a type of pneumatic actuator driven by air pressure used to imitate muscle contractions. Air pressure supplied to the inside of a PARM results in its expansion in the radial direction and contraction in the axial direction. This process generates a displacement, as shown in Fig. 1 (a). PARMs are flexible and lightweight, and they can generate a pulling force several times that generated by an air cylinder of the same diameter. In addition, PARMs have beneficial properties such as explosion proofing, action holding, and applicability to robots that require soft-touch operation. The use of PARMs in manipulators and power-assist devices has also been studied

However, the compressors driving such actuators are relatively large, and the peripheral devices such as filters and servo valves (Fig. 1 (b)) also tend to be large. To solve this type of problem, some studies have been reported in which pneumatic actuators are driven with the power generated by volume changes of liquids other than water

Colleagues of the authors have investigated the use of soft actuators driven by gas–liquid phase changes (GLPCs) of fluorocarbons; however, the response of the actuator was very slow (the time constant was greater than tens of seconds). Therefore, in recent years, by applying feedback control of the inner pressure generated by GLPCs, we have been trying to realize a relatively high-response actuator with a time constant of several seconds.
In this paper, the feedback control method of a PARM driven by GLPCs is summarized. Then, the design and fabrication of a manipulator using a PARM driven by GLPCs are explained. Finally, a performance test of the manipulator is presented.

2. Nomenclature

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\begin{align*}
E & : \text{Voltage} \quad [V] \\
F & : \text{Force} \quad [N] \\
P & : \text{Pressure} \quad [Pa] \\
P_{\text{ref}} & : \text{Reference pressure} \quad [Pa] \\
t & : \text{Time} \quad [s] \\
\varepsilon & : \text{Contraction ratio} \quad [-]
\end{align*}
\]

3. Concept of Actuator Driven by Gas-Liquid Phase Changes

3.1 Gas-liquid phase change (GLPC)

GLPC is a phenomenon in which a substance transitions from liquid to gas or from gas to liquid. When a liquid is heated, it begins to boil and transitions to the gas phase, and this transition causes its volume to expand and the pressure in the container to increase. When the substance is removed from the heat source, it loses its energy and returns to the liquid phase because of the heat transfer from inside the container to the ambient environment. Consequently, the substance volume contracts and the pressure decreases.

3.2 Actuator driven by GLPCs

Fig.2 illustrates the concept of an actuator driven by GLPCs. The actuator takes advantage of the phenomenon of volume expansion during the liquid-to-gas phase change. A working fluid is added to an actuator such as a PARM, and an electric heater (e.g., constantan heater) is installed. When the heater in the actuator is powered on, the heated liquid expands and boils into gas. The actuator is driven by the pressure generated by the volume expansion due to thermal expansion of the liquid and the following GLPC. When the heat source is removed, the generated gas returns to liquid and the volume contracts. Because the GLPC actuator does not require a compressor and other peripheral pneumatic components, it is possible to miniaturize the entire apparatus for driving the actuator.

3.3 Working fluid

In this study, the fluorocarbon C$_5$F$_{11}$NO (3M Company, U.S.A., Fluorinert, PF-5052) was used as the working fluid. Its characteristics are compared with those of water in Table 1. Because this fluorocarbon has a low boiling point of 50 °C at atmospheric pressure and a heat of vaporization of 104.65 kJ/kg, which is 1/22 that of water (2260 kJ/kg), a small thermal energy supply can induce the liquid-to-gas phase change. The coefficient of thermal expansion of the fluorocarbon at 20 °C is 0.00154 °C$^{-1}$, which is approximately seven times that of water. Moreover, it is non-poisonous, incombustible and its properties are not changed by heating (according to its product manual issued by 3M Company). As such, this working fluid is very suitable for the GLPC actuator.

4. PARM Driving Experiment Using GLPCs

4.1 Experimental configuration

A PARM driving experiment was conducted on the configuration shown in Fig.3. The PARM used in this research is MXAM-5-AA, made by Festo, Germany, and its specifications are shown in Fig.3. Beneath the PARM, a fixed container with a volume of 3.93 cm$^3$ is installed. The PARM and the container are filled with the fluorocarbon working fluid. The working fluid in the container is heated and boiled by powering the constantan heater (Tokyo Wire Works, Ltd., diameter: 0.231 mm, resistance per length: 16.02 Ω/m, total resistance: 20.6 Ω) at the bottom of the device. In addition, a pressure sensor (SMC Corporation, PSE510-R06) is installed between the PARM and the container.

The control signal (voltage: 0–10 V) is generated by the digital signal processor (DSP) (MTT Corporation, s-BOX). By inputting the control signal into the power source, a voltage of 0–35 V is applied to the heater. The working fluid in the container is heated by the heater to induce the GLPC.
The pressure generated by the GLPC is measured by a pressure sensor and the measurement is sent back to the DSP as the feedback control, as shown in Fig.4.

### 4.2 Experimental procedure and result

In this experiment, the PI control gains were set as follows: proportional gain: 1000 V/Pa, integral gain: 3 V/(Pa·s). The reference pressure $P_{\text{ref}}$ was initially set at 0.3 MPa (gauge). At 40 s, $P_{\text{ref}}$ was increased to 0.35 MPa and then at 80 s, it was decreased back to 0.3 MPa. The generated pressure $P$ was measured by the data logger.

The experimental result is shown in Fig.5. The time constants were 0.51 s when the pressure was increased from 0.3 to 0.35 MPa, and 0.37 s when the pressure was decreased from 0.35 to 0.3 MPa. During the period of 40 s to 80 s, the pressure was almost steadily kept at 0.35 MPa.

According to our former report [5], the pulling force generated by the PARM differs depending on its contraction ratio, shown in Fig.6. At the inner pressure of 0.35 MPa, when the contraction ratio is 0.04, the pulling force generated by the PARM is approximately 20 N.

### Table 1 Characteristics of working fluid compared to water

| Working fluid (Chemical formula) | Boiling point (1 atm) [°C] | Heat of vaporization [kJ/kg] | Coefficient of thermal expansion [°C⁻¹] |
|----------------------------------|-----------------------------|-------------------------------|---------------------------------------|
| Fluorocarbon ($C_5F_{11}NO$)    | 50                          | 104.65                        | 0.00154                               |
| Water ($H_2O$)                  | 100                         | 2257                          | 0.00021                               |

The pulling force generated by the PARM differs depending on its contraction ratio, shown in Fig.6. At the inner pressure of 0.35 MPa, when the contraction ratio is 0.04, the pulling force generated by the PARM is approximately 20 N.

### 5. Manipulator Driven by PARM Using GLPCs

#### 5.1 Design and fabrication of manipulator

In this section, a manipulator whose driving force is generated by a PARM using GLPCs is designed and fabricated. The fabricated manipulator is shown in Fig. 7. Most of the components used in this manipulator are the same as those in Fig.3. The manipulator consists of a container (3.93 cm³), a constantan heater (Tokyo Wire Works, Ltd., diameter: 0.231 mm, total resistance: 3.7 Ω), a pressure sensor (SMC Corporation, PSE510-R06) and working fluid (fluorocarbon). At the top of the PARM, a manipulating hand was newly attached. According to the kinematic calculation, when the pulling force generated by
the PARM is 18 N, the hand can generate a gripping force of about 2.55 N.

5.2 Manipulator driving experiment (Gripping)

The experimental configuration for the manipulator driving experiment is shown in Fig.8. As stated in Section 4.2, the PI control gains were set as follows: proportional gain: 1000 V/Pa, integral gain: 3 V/(Pa·s). The reference pressure $P_{\text{ref}}$ was initially set at 0.3 MPa (gauge). At 40 s, $P_{\text{ref}}$ was increased to 0.35 MPa and then at 80 s, it was decreased back to 0.3 MPa. The gripping force was measured by a load cell (Tokyo Sokki, TCLZ-20NA, Dynamic Strain Meter DA-18A). The generated pressure $P$, gripping force $F$, and voltage to the heater $E$ were measured by the data logger.

The experimental results are shown in Fig.9. The time constants were 0.18 s when the pressure was increased from 0.3 to 0.35 MPa, and 1.35 s when the pressure was decreased from 0.35 to 0.3 MPa. During 40 s – 80 s, the pressure $P$ was almost steadily kept at 0.35 MPa, and therefore the gripping force was kept at around 2.6-2.5 N. The decrease in the measured grip force may be derived from the slip between the bolt (screwed to the load cell) and the hand of the manipulator, as the bolt and the hand were not rigidly fixed.

6. Conclusions

In this paper, the feedback control method of a PARM driven by GLPCs is summarized. Then, the design and fabrication of a manipulator using a PARM driven by GLPCs are explained. Finally, a performance test of the manipulator is presented.

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