A DUAL-CHAMBER RECIPROCATING AIR SUPPLY DEVICE USING ELECTROMAGNETIC ACTUATION FOR PORTABLE PEMFCS

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Abstract: In this study we proposed an air supply device using reciprocating motion of electromagnetic actuators and validated possibility for fuel cell applications. The electromagnetic actuator is characterized in terms of root mean square flowrate and current with various parameters like voltage, frequency, and materials for core of solenoid. They all showed a linear dependency on an applied root mean square voltage. Maximum flowrate was obtained around 20 Hz. We compared performance of PEMFC using flowmeter and electromagnetic actuator and about 70% of output power using flowmeter could be obtained using electromagnetic actuator. Based on that, we calculated parasitic ratio of air supply device so we can estimate whether we can supply air to PEMFC by our device without any external power supply.

Keywords: Electromagnetic actuator, Proton exchange membrane fuel cell,

INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are considered as power sources for various applications from portable electronic devices to small scale power plants [1]. Especially, the application to portable devices such as cellular phones and tablet PCs has been a very attractive issue owing to simple structure of PEMFCs without moving parts but its commercialization has some problems like hydrogen storage and minimization of balance of plant (compressors, humidifiers, and heat exchangers) [2].

Air supply of PEMFCs for portable application is important, because it directly affects the performance. Most of them have been developed for an air-breathing type (natural convection system) which has no external device to supply air and easy to reduce the size and power consumption [3]. However, it has low performance than the forced convection system [4~6].

Lack of suitable air supply devices which can be applied in portable way is a main obstacle to application of forced convection system.

Seen in the previous study using electroosmotic pump as air supply device for fuel cell, with portable, efficient external air supply device, we will be able to elevate the output power by sufficient air supply to the PEMFC [1]. Since we need low working voltage and power, predictable and controllable pumping motion, and fast response, we focused on electromagnetic mechanism. Yamahata et al. [7] suggested diaphragm-deflection pumping using electromagnetic actuation for valveless liquid micropump, and Lee et al. [8] and Chang et al. [9] performed analysis and optimization for similar type of valveless liquid micropumps. We suggest reciprocating electromagnetic actuator with dual chamber for gas supply in our previous study [10].

We used reciprocating motion of permanent magnet attached to flexible membrane directly for air pumping. If AC current is loaded to solenoids, permanent magnet starts reciprocating motion. When the permanent magnet is on downstroke motion, polyurethane membrane deflects down causing volume increase of upper air chamber and because of that air flows into cathode of PEMFC attached to upper chamber (Fig. 1). Simultaneously, N_2 and other residual gases after reaction at PEMFC are flows out from cathode of PEMFC attached to bottom chamber because of the downstroke motion. These two simultaneous flows occur repeatedly so we can supply air for both two independent PEMFC modules at the same time.

EXPERIMENTAL SETUP

Fig. 2 shows the schematic of the electromagnetic actuator. The electromagnetic actuator is composed of a flexible polyurethane membrane, solenoid with core at center, and NdFeB permanent magnet. The material of overall housing structure is acrylic. NdFeB permanent magnet is bonded to flexible polyurethane membrane by using common epoxy and correctly located between two air chambers. Flowrate of electromagnetic actuator was measured by air flow

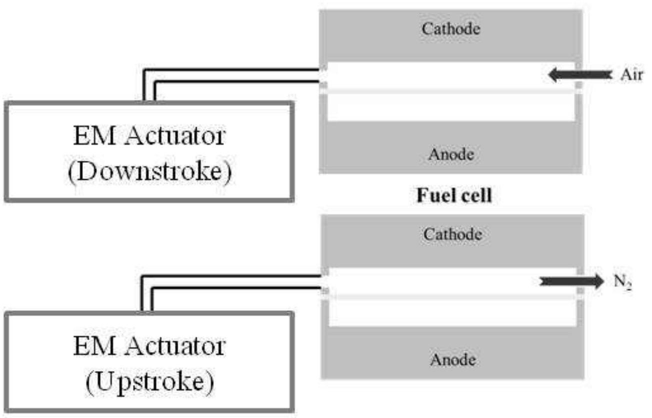

Fig. 1 "Breathing-motion-like" air displacement operation of an EM actuator to deliver air to a PEMFC.

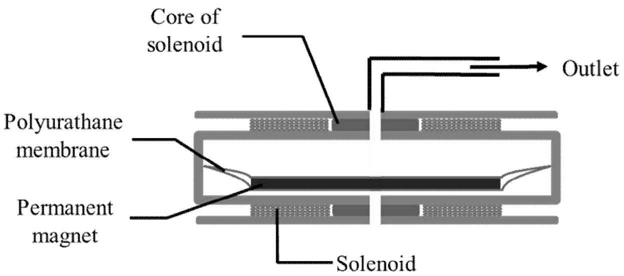

Fig. 2 Schematic of dual chamber reciprocating air supply device utilizing electromagnetic actuation

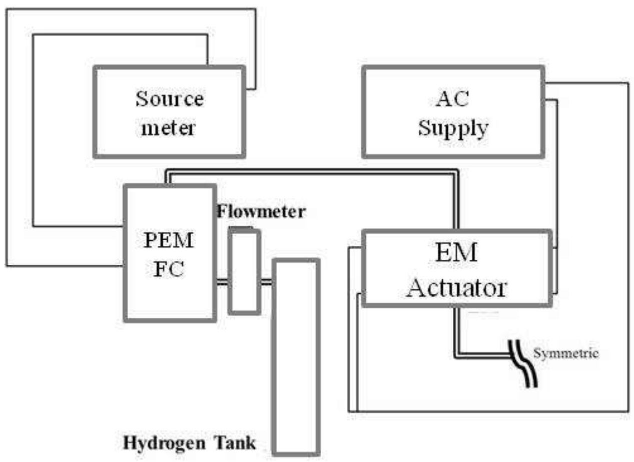

Fig. 3 Schematic of experimental setup

sensor (Sensirion ASF 1430).

Fig. 3 shows the schematic of experimental setup for measuring the performance of PEMFC integrated with the dual chamber reciprocating air supply device. This setup includes the AC powersupply (Agilent 6410), mutlimeter (Agilent 34405), sourcemeter (Keithley 2410), and flowmeter. An air chamber of electromagnetic actuator supplies air to cathode of PEMFC. Hydrogen directly flows into anode of PEMFC from gas tank through flowmeter. Sourcemeter connected to electrodes of PEMFC provides voltage to PEMFC and measure current and voltage loaded to PEMFC simultaneously.

In case of PEMFC, we used commercial proton exchange memebrane (Dupont Nafion211) with 0.3mg/cm^2 Pt catalyst loading and carbon paper gas diffusion layer (GDL), which has 1cm^2 active area. We used multiple straight open shape flowchannels for cathode to ease the air flow in and out. For the anode, we used single serpentine shape flowchannel to maximize the hydrogen contact area.

RESULTS & DISCUSSION

1. Performance of electromagnetic actuator

Fig. 4 shows the change of maximum flow rate of electromagnetic actuator with two different solenoid cores each made of steel and permalloy when the loaded voltage increases. Flowrate linearly increased with increasing voltage. Actuator with permalloy core which has higher relative permeability than steel core

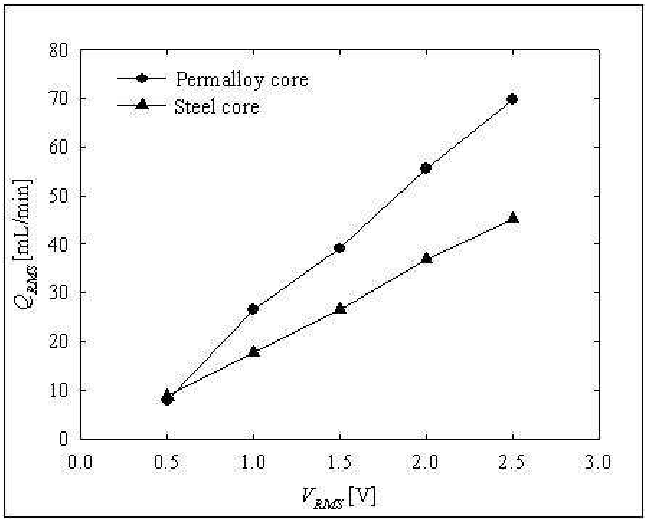

Fig. 4 RMS flowrate versus RMS voltage with materials of solenoid core

showed better performance when the same voltage was loaded. The effect of high relative permeability for increasing flowrate is also covered at our previous study [10].

Fig. 5 to Fig. 7 shows various parameters of electromagnetic actuator with increasing voltage and frequency. RMS current of electromagnetic actuator tends to linearly increase with increasing voltage at each frequency but almost stead with increasing frequency at each voltage (Fig. 5). As the resistance of solenoid is constant because of the fixed size of solenoid, the current linearly increases with increasing voltage because of the Ohm's law.

RMS flowrate of electromagnetic actuator also increased with increasing voltage. It was peak at frequency of 20Hz with same voltage range (Fig. 6).

The modeling equation for maximum volume change of electromagnetic actuator was covered in our previous study [10].Yang et al. [11] modeled force between solenoid and permanent magnet (Eq. 1). The maximum volume change mainly proportional to the force between solenoid and permanent magnet along z axis.

$$F_z = \frac{\pi}{8} \times \frac{B_p \times \mu_c^3 \times r_p^2 \times r_c^3 \times N}{(r_s - r_c)(\mu_c r_c + \mu_s r_s)^2} \times \ln\left(\frac{r_s + \sqrt{r_s^2 + 4l^2}}{r_c + \sqrt{r_s^2 + 4l^2}}\right) \times \frac{I}{z^2} \tag{1}$$

B_p is surface magnetic flux density of permanent magnet, and *r* is relative permeability and radius, respectively. Subscript *c*, *p* and *s* each represent the core of solenoid, permanent magnet and solenoid. *N* is number of turns of solenoid, *I* is current load to solenoid, and *z* is the gap between solenoid and permanent magnet along z axis.

Maximum vertical deflection of flexible membrane can be expressed as Eq. 2 based on the modeling of Lee et al [3] and Chang et al [4].

$$w_{max} = \left(\frac{F_z r_p^2}{16\pi D}\right)\left\{k^2 - \ln k - \frac{3}{4}\right\} \qquad (2)$$

D is flexural rigidity of flexible membrane and k is the ratio of radius of flexible membrane to radius of permanent magnet.

Maximum volume change was expressed as Eq. 3 by Chang et al [4].

$$V_{max} = w_{max}\left(\frac{\pi r_p^2}{4k^2 - 4\ln k - 3}\right) \times \left\{\frac{2}{1+v_m} - \frac{2(2k^2-1)}{(1+v_m)k^2} + k^4 - k^2 - k^{-2} - 4\ln k + \frac{4}{3}\right\} \qquad (3)$$

v_m is Poisson's ratio of flexible membrane.

In Eq.1, the force between permanent magnet and solenoid is proportional to the value of current I. As current increases with increasing voltage, RMS flowrate also increases with voltage. In case of frequency, if the frequency is too low, the reciprocating motion of permanent magnet is not frequent enough to get high flowrate. On the contrary, if the frequency is too high, the stroking direction of permanent magnet changes during the stroke, so it is unable to get enough displacement of permanent magnet to push air outside the air chamber.

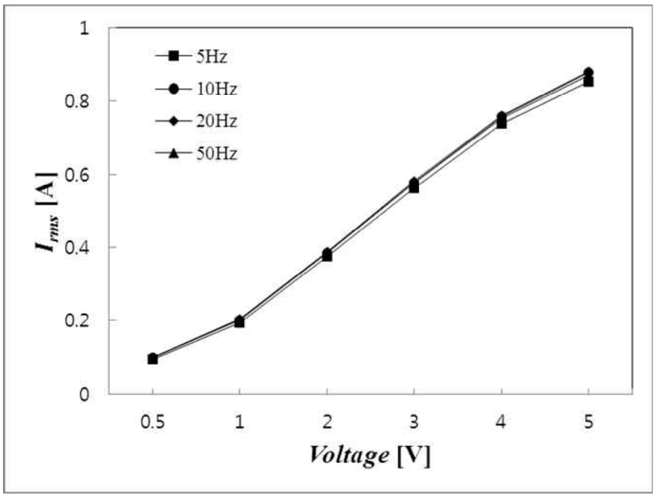

Fig. 5 RMS current versus voltage and frequency

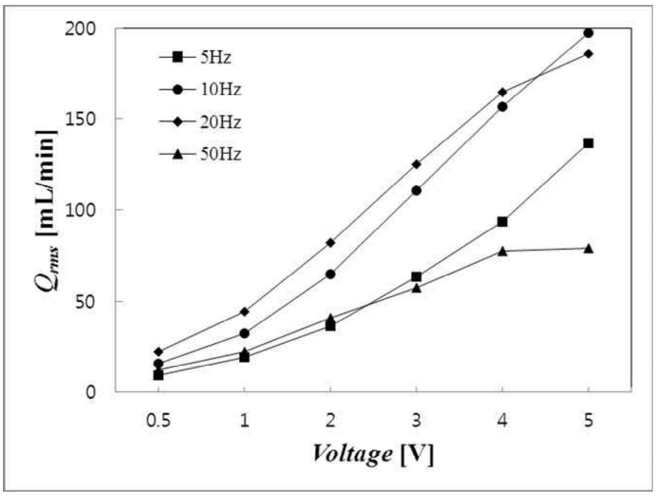

Fig. 6 RMS flowrate versus voltage and frequency

Combining these two results, RMS flowrate per power consumption of electromagnetic actuator is depicted at Fig. 7. It had higher value when voltage gets lower and was peak at frequency of 20Hz. The peak frequency was same as the frequency for highest flowrate, but the flowrate per power consumption had high value when the loaded voltage is relatively low, because the increase of current squared power consumption of electromagnetic actuator.

2. Application to PEMFC

The power density curve of the PEMFC integrated with an electromagnetic actuator in Fig. 8. The power density increased while voltage loaded to electromagnetic actuator increasing and had the highest value at 10Hz, the second highest at 20Hz. The tendency with frequency is similar to the RMS flowrate of electromagnetic actuator which represents the performance of electromagnetic actuator, the oxidizer supply from external air supply device, is mainly affects the output power of the PEMFC.

Fig. 9 is the graph of parasitic ratio, the ratio of power consumption of electromagnetic actuator to output power of PEMFC. Lower parasitic ratio means

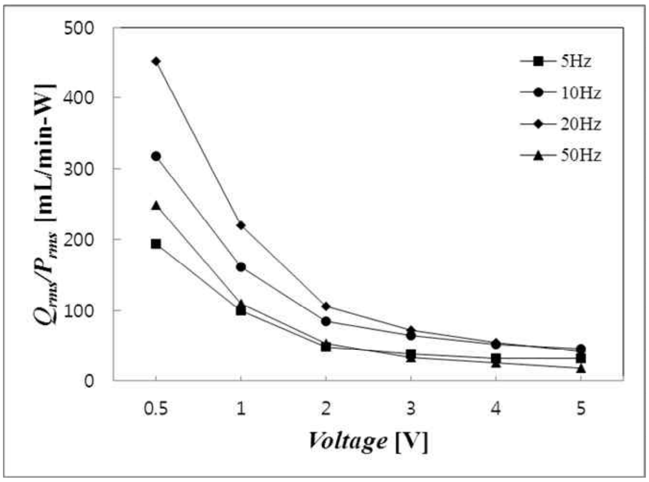

Fig. 7 RMS flowrate per power consumption versus voltage and frequency

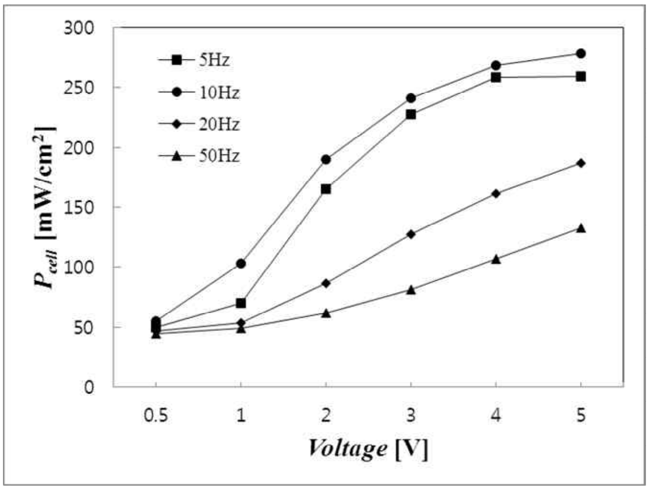

Fig. 8. Power density versus voltage and frequency load to electromagnetic actuator

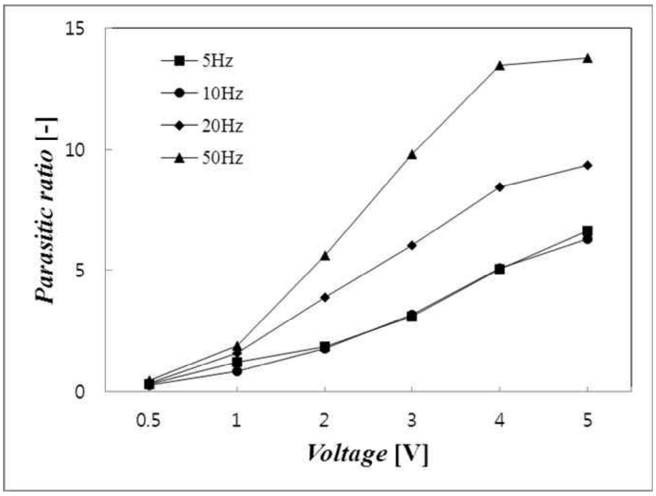

Fig. 9 Parasitic ratio of electromagnetic actuator versus voltage and frequency

the less power is consumed from PEMFC output power by external air supply device, the electromagnetic actuator. The frequency that has minimum parasitic ratio was 10Hz. Parasitic power ratio also decreases with decreasing voltage.

The main issue of this research was reducing parasitic ratio so that we can us electromagnetic actuator as an external air supply device for PEMFC without using any extra power supply from outside. If high voltage is loaded, the flowrate of electromagnetic actuator elevates the output power of PEMFC to the level using flowmeter as an air supply. On the contrary, high voltage also increases RMS current of electromagnetic actuator so that makes high power consumption which occurs increase of parasitic ratio. Our electromagnetic actuator has dual-chamber mechanism which has the benefit that can use the power from two PEMFC modules while supplying oxidizer to them. Nevertheless, it was difficult to reduce parasitic ratio under 0.3, when the loaded voltage was 0.5V and 10Hz of frequency.

CONCLUSION

In this study we characterized electromagnetic actuator with various parameters such as voltage, frequency, and the material for core of solenoid. RMS flowrate increases with voltage and has peak value when the frequency is 20 Hz. The output power of the PEMFC was also showed similar tendency. Elevating power consumption of electromagnetic actuator with increasing voltage made high parasitic ratio unless voltage is very low. To use electromagnetic actuator as an external air supply device without any external power supply, it is important to balance the frequency and loaded current to lower the parasitic ratio.

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