Performance Improvement of IPMC (Ionic Polymer Metal Composites) for a Flapping Actuator

Soon-Gie Lee, Hoon-Cheol Park*, Surya D. Pandita, and Youngtai Yoo

Abstract: In this paper, a trade-off design and fabrication of IPMC (Ionic Polymer Metal Composites) as an actuator for a flapping device have been described. Experiments for the internal solvent loss of IPMCs have been conducted for various combinations of cation and solvent in order to find out the best combination of cation and solvent for minimal solvent loss and higher actuation force. From the experiments, it was found that IPMCs with heavy water as their solvent could operate longer. Relations between length/thickness and tip force of IPMCs were also quantitatively identified for the actuator design from the tip force measurement of 200, 400, 640, and 800μm thick IPMCs. All IPMCs thicker than 200μm were processed by casting Nafion™ solution. The shorter and thicker IPMCs tended to generate higher actuation force but lower actuation displacement. To improve surface conductivity and to minimize solvent evaporation due to electrically heated electrodes, gold was sputtered on both surfaces of the cast IPMCs by the Physical Vapor Deposition (PVD) process. For amplification of a short IPMC's small actuation displacement to a large flapping motion, a rack-and-pinion type hinge was used in the flapping device. An insect wing was attached to the IPMC flapping mechanism for its flapping test. In this test, the wing flapping device using the 800μm thick IPMC could create around 10°~85° flapping angles and 0.5~15Hz flapping frequencies by applying 3~4V.

Keywords: Artificial muscle, flapping device, Ionic polymer-metal composites (IPMCs), IPMCs actuator, Nafion™.

1. INTRODUCTION

The IPMC (Ionic Polymer-Metal Composites) is an electrically activated polymer (EAP) actuator [1]. The actuator can be made by using a Nafion® membrane following chemical deposition of platinum as the source of electrodes [2-5]. When an electric field is prescribed through the thickness of an IPMC, cations inside the membrane carry solvent molecules toward the cathode and the movement creates bending providing the source of actuation force [6,7].

The IPMCs can create a large bending motion under relatively low input voltage (1~3V), which is a unique merit over the other class of EAP actuators [8]. However, conventional water-based IPMCs significantly lose their solvent content when operated by higher than 1.22 input voltages in the air. This fact should be overcome for various potential applications such as artificial muscle actuators for insect mimicking flapping devices.

As an effort to prevent the solvent loss, replacement of the water solvent with ionic liquid has been studied [9,10]. The IPMC with ionic liquid showed an extended operation time. However, its time response was significantly slowed down, which means the actuator is not appropriate for a flapping actuator. For the improvement of actuation force without significant sacrifice to the rapid actuation response, a thicker membrane can be used. In references [11,12], thick membranes were cast by using Nafion™ solution for enhancement of the actuation force of an IPMC. However, the actuation displacement of the thick IPMCs (~1mm) was noticeably reduced in this case, even though the actuation force was improved.

In this work, we aim to develop an IPMC that can be used as an actuator for a flapping mechanism operated in the air. Therefore, trade-off in the response speed, actuation force, solvent loss, and actuation

---

Manuscript received January 4, 2006; accepted June 27, 2006. Recommended by Editorial Board member Hyoukryeol Choi under the direction of Editor Jae Weon Choi. This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund) (KRF-2004-005-D00045).

Soon-Gie Lee and Hoon-Cheol Park are with the Department of Advanced Technology Fusion, Konkuk University, 1 Hwayang-dong, Gwangjin-gu, Seoul 143-701, Korea (e-mails: {abraxalee, hcpark}@konkuk.ac.kr).

Surya D. Pandita is with the Artificial Muscle Research Center, Konkuk University, 1 Hwayang-dong, Gwangjin-gu, Seoul 143-701, Korea (e-mail: surya @konkuk.ac.kr).

Youngtai Yoo is with the Department of Materials Chemistry and Engineering, Konkuk University, 1 Hwayang-dong, Gwangjin-gu, Seoul 143-701, Korea (e-mail: ytyoo@konkuk. ac.kr).

* Corresponding author.

displacement is inevitable for the actuator design. For investigation of solvent loss characteristics and actuation force, IPMCs with various combinations of cations and solvents have been processed and the actuation force, endurance, and solvent loss of each IPMC are compared. Thick membranes have been fabricated by casting Nafion™ solution to improve actuation force. The surface conductivity of the platinum electrodes was improved by gold sputtering. In the sputtering process, the Physical Vapor Deposition (PVD) process [13,14] has been used. The gold coating was confirmed to improve actuation displacement and force at the same time [2,15,16]. The gold-coated thick IPMC was used to actuate a flapping device. In this device, the bending motion created by the IPMC was transferred to a large flapping motion through a rack and pinion system.

2. SOLVENT LOSS AND ACTUATION FORCE

The movement of ions with solvent molecules is the source of actuation force generation in IPMCs. In the conventional IPMCs, deionized water has been widely used as the solvent. Therefore, when higher than 1.22V is applied through the thickness of an IPMC, solvent content of the IPMC can be reduced due to electrolysis in addition to evaporation. As a cation, H^+ is widely used for IPMCs. If cations such as Li^+ and Cu^{++} with larger ion sizes are used in an IPMC, actuation force of the IPMC tends to be improved [2,16-18]. On the other hand, maximum frequency of the IPMC was lowered due to reduced mobility of the cations, even though the measured data are not included in this paper.

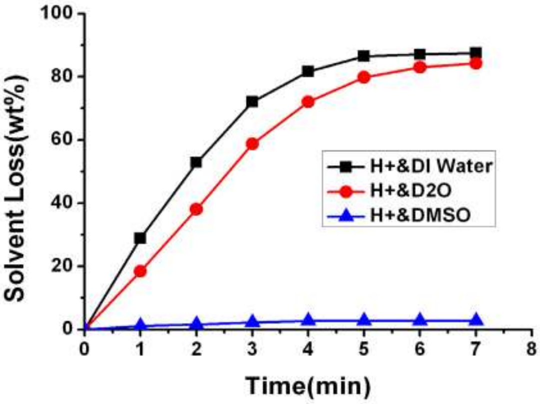
Since the available operation time of an IPMC is primarily dependent on the solvent loss [19], solvent uptake and loss have been investigated for various IPMCs. To examine solvent uptake characteristics, H^+-, Li^+- and Cu^{++}-form IPMCs made of Nafion® 117 were immersed in DI water, D_2O or DMSO (dimethyl sulfoxide) for 24 hours and then solvent uptake of each IPMC was measured. Any ionic liquid was not considered for the solvent because of their low actuation response. Table 1 summarizes the solvent uptake of each IPMC. The IPMCs with DMSO swelled too much, and the others demonstrated similar solvent uptake.

For measurement of solvent loss of IPMCs, each IPMC was operated at 2.5V input voltage with square wave input [20,21] of 5Hz. The solvent loss is defined as the lost weight percentage of solvent divided by solvent uptake. IPMCs with nine combinations of cations and solvents were tested and the results are compared in Fig. 1.

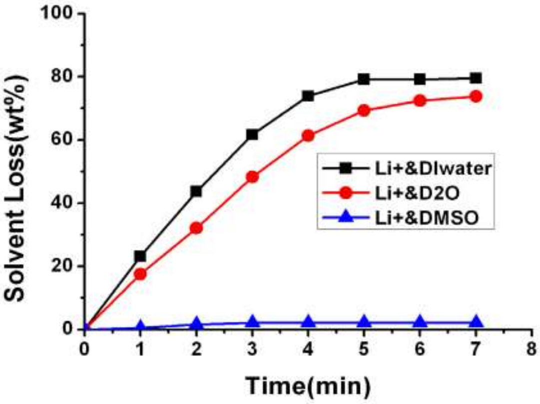
The graphs in Fig. 1 indicate that the IPMC with heavy water (D_2O) can extend the operation time around 2 minutes for 75%~80% solvent loss. The IPMC with combination of Cu^{++} and heavy water shows the best endurance in this test, even though the

Table 1. Solvent uptake at 25℃ (wt%).

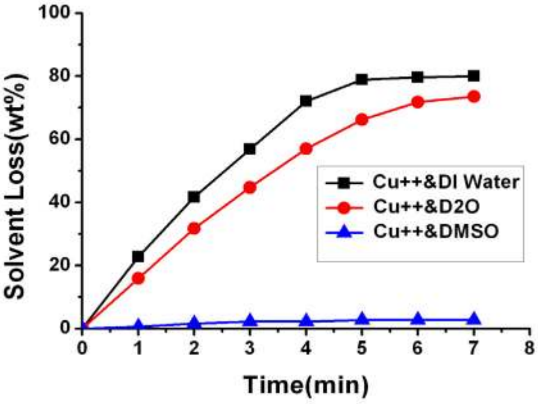
Ion form	DI water	D_2O	DMSO
H^+	24.50	24.70	108.20
Li^+	26.50	26.60	110.30
Cu^{++}	26.10	26.30	109.50



(a) H^+-form IPMCs with different solvents.



(b) Li^+-form IPMCs with different solvents.



(c) Cu^{++}-form IPMCs with different solvents.

Fig. 1. Solvent loss of various IPMCs.

amount of solvent loss was not significantly changed for the water-based IPMCs with the other two cations. The IPMC with DMSO as a solvent demonstrates more than 100 wt % solvent uptake from Table 1 and very small solvent loss from Fig. 1. However, the IPMC immersed in DMSO swelled too much, so it could not generate actuation force. Even though an IPMC with Cu^{++} and heavy water shows the best solvent loss performance, it was observed that the actuation response was noticeably reduced during the experiments.

The 10mm×5mm size water-based IPMCs with H$^+$, Li$^+$, or Cu^{++} were prepared for the tip force measurement [21]. A load cell and LABVIEW data acquisition system was used for the measurement. Fig. 2 shows the schematic diagram of the tip force measurement system. The tip force generated by the Li$^+$-form IPMC was larger than the others as shown in Fig. 3. This is because lithium has higher electropositive value than hydrogen, which means that lithium turns into cations more easily than hydrogen. Since the ionic mass of lithium is less than that of copper, the mobility of Li$^+$ must be better than Cu^{++}. Therefore, Li$^+$ and water are recommended as cation and solvent, respectively, for a flapping actuator with higher frequency and stronger actuation force.

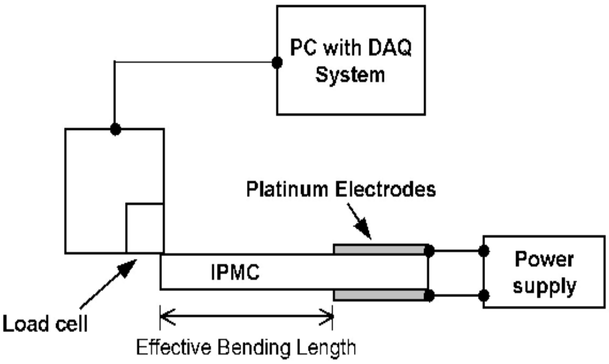


Fig. 2. Schematic diagram of tip force measurement.

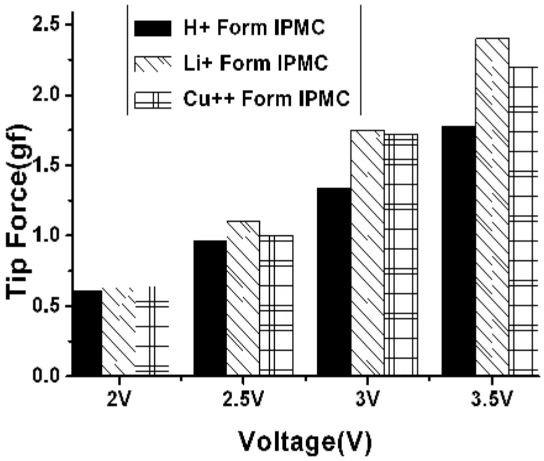


Fig. 3. Tip force for various input voltages.

3. IMPROVEMENT OF ACTUATION FORCE

For successful application of an IPMC to the flapping device, the IPMC should produce a larger actuation displacement and force with reasonable actuation frequency. The actuation force is directly related with an actuator's suitable size, thickness, and applied voltage. A long IPMC can create a large displacement, but it cannot produce a high tip force. Whereas a short IPMC can produce a high tip force, it can create only small tip displacement. Even though a thick IPMC can generate a high tip force and work for a relatively longer time, the IPMC's response speed and tip displacement are decreased. When the applied voltage is increased, tip displacement and tip force are also increased. In this case, however, electrolysis is accelerated and, at the same time, evaporation increased by the heat generated by the IPMC resulting in shorter endurance.

Therefore, trade-off in the actuation force, actuation displacement, response speed, and endurance must be considered in the flapping actuator design by using IPMCs. In a flapping device, a set of wing structures needs to be attached at the tip of the actuator and the wing must flap with reasonable frequency. Because the maximum attachable mass for the wing structure is limited by the maximum generative tip force, improvement of tip force performance is very important. In this work, therefore, actuation force and response speed become primary concerns and the other factors are secondary. Limited actuation displacement of an IPMC can be amplified by implementing a mechanical design.

Reduced surface resistance of platinum electrodes in an IPMC also contributes to improvement of actuation displacement and force at the same time. Effects of gold coating on the actuation tip force and actuation displacement are also examined in this section.

3.1. Effect of length

The length of an IPMC directly affects the tip force.

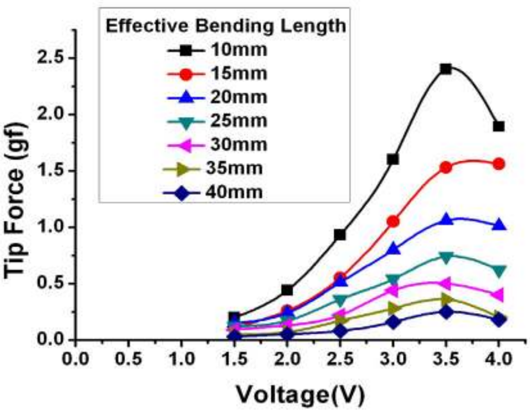


Fig. 4. Tip force with effective bending length.

To discover the effect of length on the actuation force, the tip forces of 200μm thick IPMCs made of Nafion® 117 with various lengths have been measured by using the same method described in Fig. 2. In Fig. 4, the effect of length of the IPMCs was quantitatively identified. As expected, a shorter IPMC could produce a higher tip force for a given electric field. Therefore, a shorter IPMC is recommended as a flapping motor. As indicated in Fig. 4, the tip force was still generated even though electrolysis started over 2V.

3.2. Effect of gold coating

In a platinum plated IPMC, the solvent in the IPMC is lost through the platinum electrodes and side edges, which is caused by electrolysis and evaporation. During this process, the pores in the membrane are closed gradually. Theses pores act as a transport channel, which was described in the cluster network model [22]. This contraction by the drying out increases surface conductivity. At the same time, however, it blocks the ion channel through which cations and solvent molecules are moving, resulting in reduction in actuation force. For the improvement of actuation performance of IPMCs [3,15,16] coating another conductive metal such as gold over the platinum electrode can be a plausible approach.

Fig. 5 shows a SEM (Scanning Electron Microscope) image of the platinum-electrode surface in a Li^+-based IPMC. The platinum electrode was plated using the chemical deposition process [2-5]. When the SEM image of a crack area shown in Fig. 5 is magnified 50,000 times, the pores can be clearly identified as shown in Fig. 6.

Repeated contraction and relaxation during bending actuation of an IPMC creates more cracks on the surface of the electrode and it deteriorates surface conductivity of the IPMC. If the surface electrode of an IPMC has a large surface resistance, the cations and solvent molecules inside the membrane will move toward the outer electrodes connected to the power supply due to the induced gradient in the electric field, as described in Fig. 7(a). As shown in Fig. 7(b), since the surface resistance is relatively low in the gold coated IPMCs, the alternating electric voltage applied through the outer electrodes will be almost constant over the entire surface electrode and the cations and solvent molecules will mostly move up and down through the thickness. However, if the electric voltage is lowered due to high surface resistance at the tip, then the mobile molecules can be attracted toward the outer electrodes from the tip of the actuator. This explains why the dry-out of a solvent always begins from the tip of an IPMC, and the actuation displacement and force become reduced.

To avoid this situation, the surface resistance needs to be reduced by coating conductive materials over the platinum electrodes. In this work, gold was sputtered

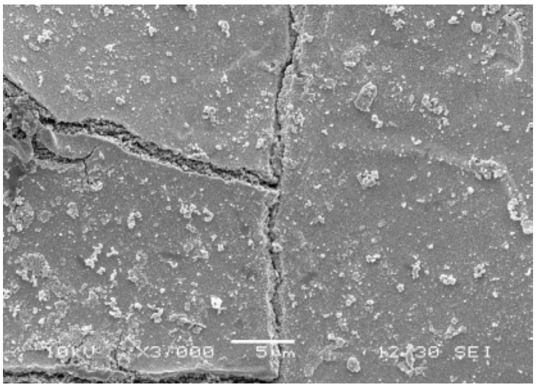


Fig. 5. SEM surface image of an IPMC.

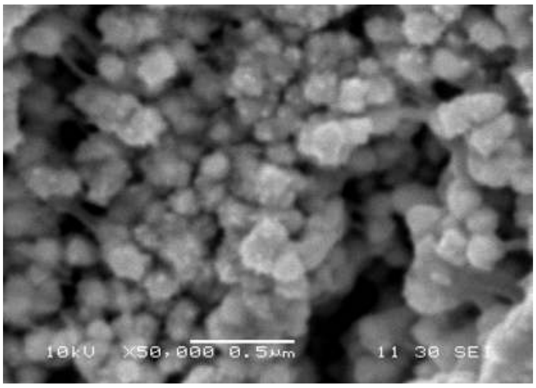
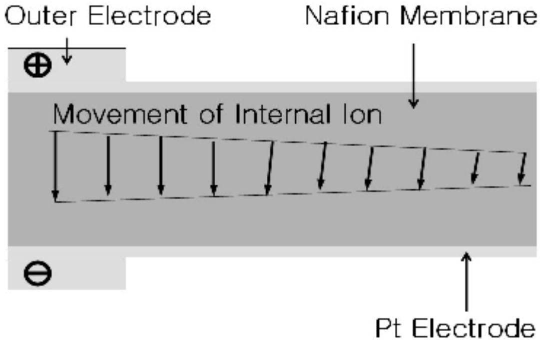
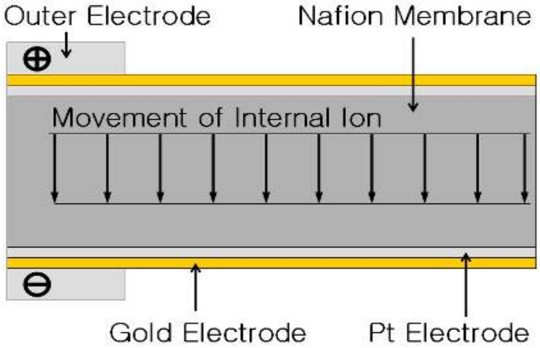


Fig. 6. SEM image of the IPMC surface crack.



(a) For a normal IPMC (high surface resistance).



(b) For a gold sputtered IPMC
(low surface resistance).

Fig. 7. Movement of internal ions in IPMCs.

over the platinum electrode using the PVD (Physical Vapor Deposition) process to improve the surface conductivity of a flapping actuator. Fig. 8 displays the cross-section of a SEM image in the gold sputtered IPMC made of Nafion® 117. The upper white portion is the gold-coated surface and the second gray layer stands for the gold layer. It is clearly seen that 1~2 micro meters of the gold layer was sputtered over the platinum electrodes of the IPMC surface. Compared to the chemical deposition of the gold coating [3,15,16], the process of PVD is easier to handle and the time required for the coating is significantly reduced.

The gold layer is so soft that it reduces cracks on the surface of an IPMC. In addition, the low surface resistance results in low heat generation over the electrodes and less evaporation. As a result, the movement of cation and solvent is much confined toward the thickness direction due to the relatively constant electric field over the electrodes, and dry-out due to evaporation is abridged thanks to the reduced surface cracks and low heat generation. Therefore, the gold sputtered IPMC can provide higher actuation force, larger actuation displacement and extended endurance at the same time.

Dry surface resistances of the 5mm×30mm size normal and gold sputtered IPMCs were measured by changing the distance of two probes. Fig. 9 indicates the measured surface resistance of a dry IPMC with gold coating and without gold coating, where it can be clearly confirmed that the gold sputtered IPMC has lower surface resistance than the normal IPMC. It is also noticeable that the gold sputtered IPMC has low surface resistance even when the distance of the two probes is increased. The low surface resistance contributes to reduce the heat generation during operation, which can minimize solvent evaporation.

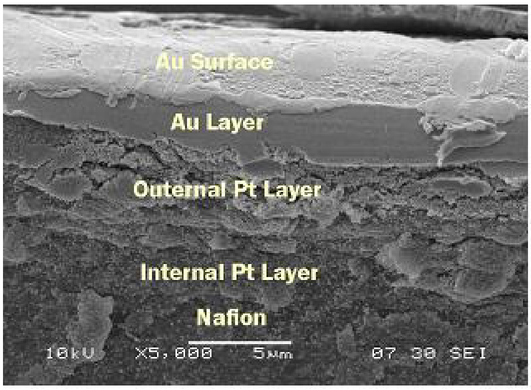


Fig. 8. SEM image of Au sputtered IPMC cross section.

3.3. Effect of membrane thickness

To investigate the actuation performance of thick IPMCs, various thick membranes were fabricated by casting Nafion™ solution. The general procedure for the casting is well explained in References [11,12]. After the casting, the thick membranes were processed such that Li^+-form membranes with DI water as the inner solvent can be fabricated. We have chosen Li^+ and DI water as cation and solvent, respectively, because the IPMC with them demonstrates a reasonable response speed even though solvent loss is significant as described in the previous section. Gold was also sputtered over the platinum electrode of thick IPMCs for higher actuation force and large actuation displacement.

Tip forces of the thick IPMCs were measured by the same test set-up shown in Fig. 2. The size of each IPMC was 10mm (effective bending length)×5mm (width), and dry thickness of each IPMC was 200, 400, 640, and 800μm. Fig. 10 shows the measured maximum tip force of the various thick IPMCs. Relatively high voltage (4V) was intentionally prescribed to find out how much tip force can be generated even with electrolysis. It can be found that the gold sputtered 800μm thick IPMC can create about 10 grams of force for 4V, which is more than 30% larger tip force than can be generated by 800μm thick IPMC without gold coating.

Fig. 11 shows the measured maximum tip forces of gold sputtered IPMCs for various input voltages. For a

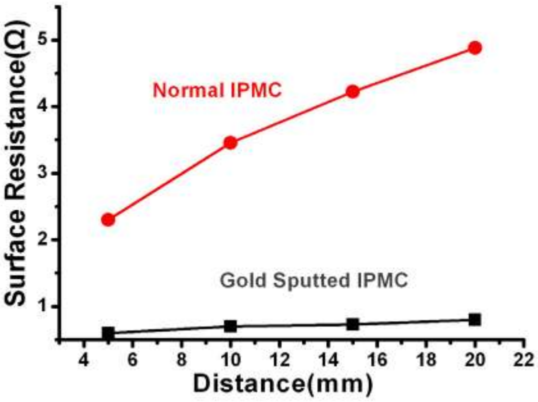


Fig. 9. Surface resistance of dry IPMCs.

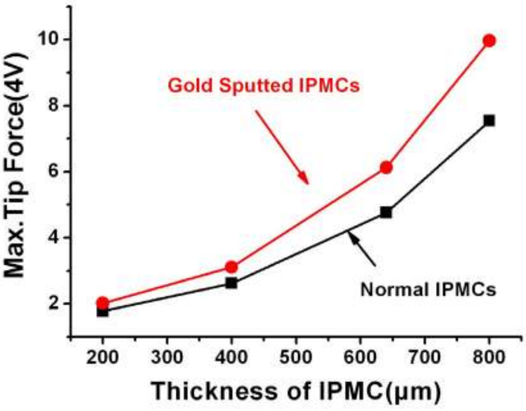


Fig. 10. Tip force of gold-coated thick IPMCs.

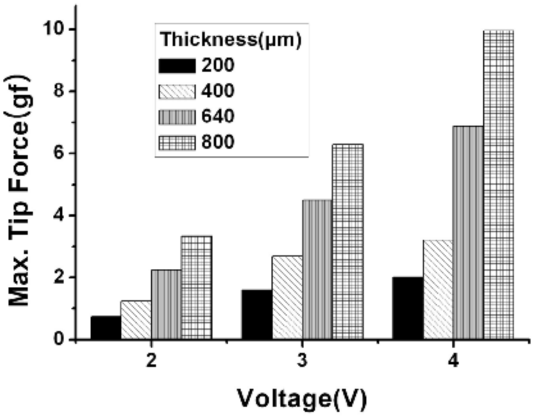


Fig. 11. Maximum tip force of gold-coated thick IPMCs for various voltages.

low applied voltage, the tip force increment is almost proportional to the thickness increment. The tip force becomes nonlinearly increased for anything higher than 2V input. These data should be very useful for the design of a flapping device.

4. FLAPPING DEVICE

4.1. External electrodes

In the design of a flapping mechanism, many aspects need to be considered even though actuation performance of an IPMC is much improved. One of them is the external electrodes needed to supply the electric field to the IPMC. The actuation can be retarded due to a chemical reaction between the external electrodes and the surface electrodes of the IPMC that contains solvent and cation. Platinum electrodes are widely used for the external electrodes to prevent the chemical reaction. Since the platinum plate is quite expensive, 100nm thick platinum was sputtered by the PVD process [13,14] on one side of the 25μm thick copper plate, where the surface electrode of an IPMC will be contacted. To prevent deformation of the thin electrodes, the platinum sputtered electrodes were attached to a 5mm× 5mm×1mm size balsa wood plate as shown in Fig. 12.

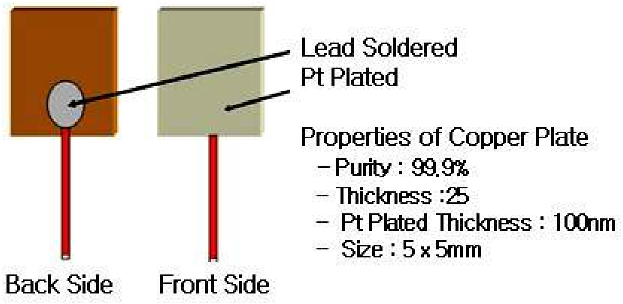


Fig. 12. Schematic diagram of the movement.

4.2. Actuation system

In the actuation system of a flapping device, a 15 mm long, 5mm wide, and 800μm thick IPMC was selected for the actuation because the primary concerns in the design are actuation force and response speed. However, the actuation system should be able to produce a desired flapping angle for a successful flapping device. A rack-and-pinion system shown in Fig. 13 was devised to transfer the actuation force from the IPMC actuator to a wing system and to amplify the flapping angle at the same time. The rack was attached at the end of the IPMC actuator in the vertical position and two pinions 3mm in diameter were placed such that they were tightly contacted with the vertical rack. The rack created an up-and-down motion due to the bending motion of the IPMC and the pinion produced a rotating motion. Since the wings were attached at the outer surface of the pinion, the wings could flap with large flapping angles.

Fig. 14 and Fig. 15 show the assembled flapping wing at the ends of the upstroke and downstroke. The applied voltage was 3~4V in the square wave form with 0.5~10Hz frequency. The maximum flapping angle of 85 degree was produced for 1Hz input. However, the flapping angle was reduced for higher input frequency, and it reached a 15 degree flapping angle for 3V, 15Hz input. The slow response may be

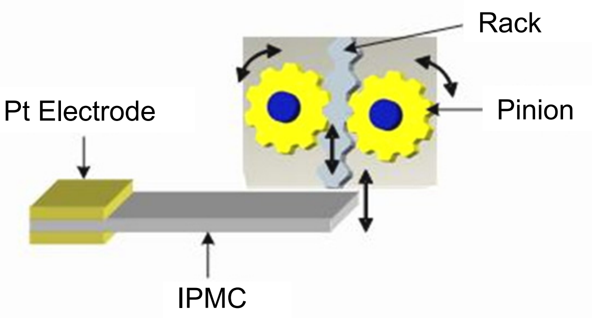


Fig. 13. Schematic figure of IPMC with rack-and-pinion device.

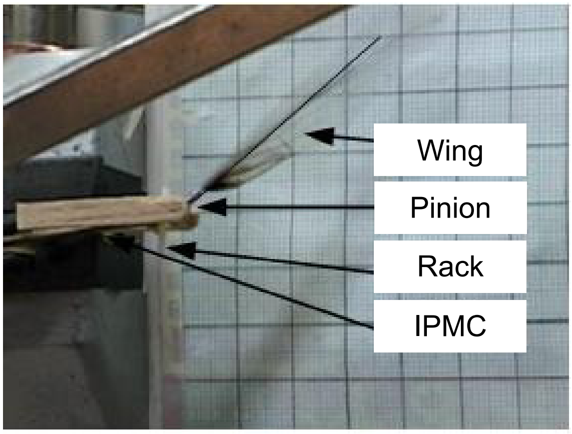


Fig. 14. Upstroke of the flapping wing.

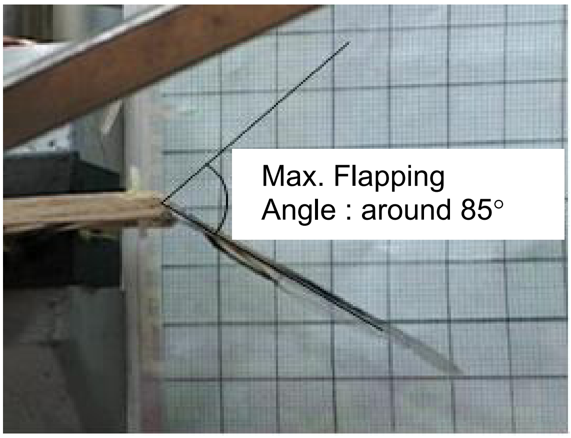


Fig. 15. Downstroke of the flapping wing.

caused by the increased distance that cations travel through the thickness in a thick IPMC. Therefore, the flapping device should be useful for mimicking an insect that flies in low frequency with relatively large wings.

5. CONCLUSION

In this work, performance improvement of IPMCs was attempted focusing on the solvent loss and actuation force. For reduction of solvent loss and improvement of actuation force, IPMCs with various solvents (DI water, D_2O, DMSO) and cations (H^+, Li^+, Cu^{++}) were tested for measurement of solvent loss and actuation force. From the test, the IPMC with D_2O as solvent and Cu^{++} as cation presented the lowest solvent loss and largest actuation force. To achieve larger actuation force from an IPMC, thick IPMCs were fabricated by casting Nafion™ solution and gold was sputtered over the platinum electrode of the IPMC by the Physical Vapor Deposition process. The coating was very effective for preventing solvent loss due to evaporation and improvement of actuation force. Even though the IPMC could produce a larger actuation force, the time response was slowed down due to increase in the thickness of the IPMC. For a trade-off, therefore, water was used for solvent and Li^+ for the cation in the thick IPMC for a faster flapping actuation. A flapping device was designed and fabricated using an 800µm IPMC and rack-and-pinion system. The device could produce a large flapping angle of about 85 degrees for a low frequency input (3~4V at 0.5Hz). The angle reached about 15 degrees for a 3V, 15Hz input. The flapping device should be useful for mimicking an insect flying at low frequency.

REFERENCES

[1] Y. Bar-Cohen, *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential, and Challenges*, Bellingham, WA, USA, 2001.

[2] M. Shahinpoor and K. J. Kim, "Ionic polymer-metal composites: Fundamentals," *Smart Materials and Structure*, vol. 10, pp. 819-933, August 2001.

[3] K. J. Kim and M. Shahinpoor, "Ionic polymer-metal composites: II. Manufacturing techniques," *Smart Material and Structure*, vol. 12, pp. 65-79, January 2003.

[4] J. J. Park, S. E. Cha, H. J. Ahn, and S. K. Lee, "Fabrication of ionic polymer metal composites by electroless plating of Pt," *Proc. of the 32nd Intl. Symp. on Robotics*, April 2001.

[5] S. E. Cha, J. J. Park, and S. K. Lee, "Fabrication process and characterization of ionic polymer-metal composite actuators by electroless plating of platinum," *Trans. of KIEE*, vol. 51, no. 9, pp. 455-463, 2002.

[6] M. Shahinpoor, "Continuum electromechanics of ionic polymeric gels as artificial muscles for robotic applications," *Smart Materials and Structure*, vol. 3, pp. 367-372, September 1994.

[7] R. Kanno, S.Tadokoro, T. Takamori, and K. Oguro, "3-Dimensional dynamic model of ionic conducting polymer gel film (ICPF) actuator," *Proc. of IEEE International conference on Systems, Man and Cybernetics*, pp. 2179-2184, 1996.

[8] K. Oguro, K. Asaka, and H. Takenaka, "Actuator element," *US Patent Specification* 5, 268, 082, 1993.

[9] M. D. Bennet and D. J. Leo, "Ionic liquids as stable solvent for ionic polymer transducers," *Sensors and Actuators A: Physical*, vol. 115, pp. 79-90, February 2004.

[10] T. E. Sutto, P. C. Trulove, and H. C. Delong, "Investigations of the effects of lithium ion and polymer type on the electrochemical behavior of ionic liquid / polymer gel electrolytes," *Proc. of the 13th International Symposium on Molten Salts*, The Electrochemical Society, Philadelphia, PA, May 2002.

[11] B. K. Kim, B. M. Kim, J. W. Ryu, I. H. Oh, S. K. Lee, S. E. Cha, and J. H. Park, "Analysis of mechanical characteristics of the ionic polymer metal composite (IPMC) actuator using cast ion-exchange film," *Smart Structures and Materials*, vol. 5051, pp. 486-495, July 2003.

[12] L. A. Zook and J. Leddy, "Density and solubility of Nafion®: Recast, annealed, and commercial films," *Analytical Chemistry*, vol. 68, no. 21, pp. 3793-3796, 1996.

[13] D. M. Mattox, *The Handbook of Physical Vapor Deposition (PVD) Processing (Materials Science and Process Technology Series)*, Park Ridge, NJ, USA, 1998.

[14] J. E. Mahan, *Physical Vapor Deposition of Thin*

Films, New York, NY, USA, 2000.

[15] K. Onish, S. Sewa, K. Asaka, N. Fujiwara, and K. Oguro, "Biomimetic micro actuators based on polymer electrode / gold composite driven by low voltage," *Proc. IEEE 13th Annual Intl. Conf. on Micro Electro Mechanical Systems*, pp. 386-390, 2000.

[16] S. Nemat-Nasser and Y. Wu, "Comparative experimental study of ionic polymer-metal composites with different backbone ionomers and in various cation forms," *Journal of Applied Physics*, vol. 93, pp. 5255-5267, May 2003.

[17] Y. Abe, A. Mochizuki, T. Kawashima, S. Yamashita, K. Asaka, and K. Oguro, "Effect on bending behavior of counter cation species in perfluorinated sulfonate membrane-platinum composite," *Polymer Advanced Technology*, vol. 9, pp. 520-526, December 1998.

[18] K. Onish, S. Sewa, K. Asaka, N. Fujiwara, and K. Oguro, "The effects of counter ions on characterization and performance of a solid polymer electrolyte actuator," *Electrochemistry, Acta*, vol. 46, no. 8, pp. 1233-1241, 2001.

[19] C. Yang, S. Srinivasan, A. B. Bocarsly, S. Tulyani, and J. B. Benziger, "A comparison of physical properties and fuel cell performance of Nafion and zirconium phosphate / nafion composite membrane," *Journal of Membrane Science*, vol. 237, pp. 145-161, March 2004.

[20] A. Asada, K. Oguro, Y. Nishimura, M. Mizuhata, and H. Takenaka, "Bending of polyelectrolyte membrane-platinum composites by electric stimuli, I. Response characteristics to various waveforms," *Journal of Polymer Sci.*, vol. 27, no. 4, pp. 436-440, 1995.

[21] M. Mojarrad and M. Shahinpoor, "Ion-exchange-metal composite artificial muscle actuator load characterization and modeling," *Proc. of SPIE*, vol. 3040, pp. 294-301, February 1997.

[22] T. D. Gierke and W. Y. Hsu, "The cluster-network model of ion clustering in perfluorinated membranes, in: A. Eisenberg, H. L. Yeager (Eds.), Perfluorinated Ionomer Membranes," *American Chemical Society*, pp. 283-307, Washington DC, USA, 1982.

Soon-Gie Lee received the B.S. (2002) degree from Konkuk University. He is currently a Master's Student at the Department of Advanced Technology Fusion and a Research Assistant at the Artificial Muscle Research Center in Konkuk University, Seoul, Korea. His research interests include technology fusion among bio-technology, nano-technology and aerospace-technology.

Hoon-Cheol Park received the B.S. (1985) and M.S. (1987) degrees from Seoul National University in Seoul, Korea and the Ph.D. (1994) degree from the University of Maryland at College Park, MD, USA. He joined the Department of Aerospace Engineering, Konkuk University in Seoul, Korea in 1995, and he is currently a Professor in the Department of Advanced Technology Fusion. His professional experience includes Kia Motors (1986-1988) and the Korea Aerospace Research Institute (1994-1995). His specialty is finite element analysis and his recent research topic is mainly focused on biomimetics.

Surya D. Pandita is currently conducting research as a Research Fellow at the Artificial Research Muscle Center, Konkuk University, Seoul, Korea. He received the M.S. (1994) degree in Physical Chemistry from Institut Teknologi, Bandung, Indonesia, and the M.S. (1995) and Ph.D. (2002) degrees in Metallurgy and Materials Engineering, Katholieke Universiteit, Leuven, Belgium.

Young-Tai Yoo received the B.S. (1979) and M.S. (1981) degrees from Seoul National University and the Korea Advanced Institute of Science and Technology in Korea, and the Ph.D. (1988) degree from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. His professionnal experience includes the Korea Institute of Energy and Resources (1981-1984) and Eastman Kodak Company (USA 1989-1991). Following that, he joined the Department of Materials Chemistry and Engineering, Konkuk University in Seoul, Korea where he is currently a Professor. His field of research is polymeric actuators and sensors.