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Multi-scale Electrochemical-mechanical Modeling of Fast Response of Ionic Metal-Polymer Composite Actuator

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Abstract

Ionic Polymer-Metal Composite (IPMC) strips are very thin actuators in the form of a sandwich composite with an electroactive polymer in the core and two metal electrodes on its sides. In this paper, a multi-scale electrochemical-mechanical analysis of the actuation time response of an IPMC composite strip is performed. First, the electrochemical response of the primary motion stemming from the electrostatic force, the viscous force of ionic cluster motion in the polymer solvent, and the diffusive force caused by the concentration potential are obtained by a hydraulic model. The solution methods include finite element method in the space domain, and Euler's integration method in the time domain. Then, the solvent transport equation is written, and the rate of eigen strain and bending moment of the IPMC actuator is obtained. By extracting the amount of the cluster concentration in the boundary layer of cathode and anode, the displacement response of the beam end is determined. The results are validated with previous available studies. The results confirm that the presented model provides the prediction of the fast response of an IPMC strip.

Keywords: Ionic Polymer-Metal Composite, Actuation response, Electrochemical-mechanical model, Finite element method.

1. Introduction

Ionic Polymer-Metal Composite (IPMC) is one of the electro-active polymer materials in medical applications, robotics, light microelectronic machines, and entertainment devices [1-3]. Improvements in the sensing and operating properties of IPMC materials depend on how these properties are measured as well as how they are modeled [4-6].

In the hydraulic models for IPMC, the migration of water between the ionic clusters in the polymer causes the material swelling and subsequent bending [2]. Ref. [7] presented a model that connected the water pressure gradient with the overall electric field as electro-thermodynamic forces. Asaka and Eguru [8] presented a model in which the water flow resulting from the pressure gradient and electroosmotic flow generates stress and actuator swelling. Nemat Nasser and Lee [6] also provided a model in which the electric field, elastic deformation, ion and water transport, were the reasons of the IPMC bending. In addition to these hydraulic models, Nemat-Nasser looked into a hybrid model that took into account the electrostatic, osmotic, and elastic effects [6].

In this article, a multi-scale electrochemical-mechanical analysis of the actuation time response of an IPMC composite strip is carried out. The aim is to obtain the ion and water concentration distributions through the IPMC thickness and its relationship with the fast response. The concentration distribution equation is written based on the electrical potential excitation and solved by the finite element method. By using the analytical relation between the eigen strain rate and the bending moment, the fast response of the IPMC cantilever is obtained.

2. Methodology

Here, as shown in Figure 1, the IPMC strip is assumed to bend under a small voltage due to the water redistribution within the material [9].

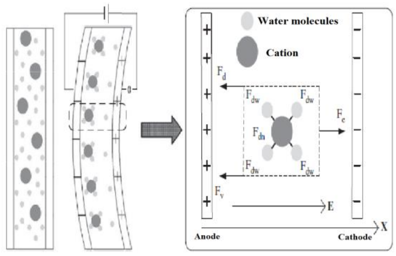

Figure 1. Acting forces on the ion cluster via applying the electric potential [9]

Three forces, including the electrostatic force F_{es}, the viscous force F_{vis}, and the diffusive force F_{dif} are applied to each moving ion cluster [10]. According to the Newton's second law, Eq. (1) is written:

$$F_{es}(x,t) - F_{vis}(x,t) - F_{dif}(x,t) = m_p \frac{dv(x,t)}{dt} \tag{1}$$

forces are obtained according to Refs. [10, 11]. The inertia term is smaller and ignored, so Eq. (2) results [9]:

$$\eta \frac{\partial q(x,t)}{\partial t} - KT\left(\frac{\partial^2 q(x,t)}{\partial x^2}\right)(1+n) - e\left\{\frac{V(t)}{d} + \frac{2}{\kappa_e . S_x}[q(x,t) - q_0(x)]\right\}\frac{\partial q(x,t)}{\partial x} = 0 \tag{2}$$

where η and d are, respectively, the viscosity and thickness of a hydrated Nafion, $q(x,t)$ is the electric charge at the distance x from the anode and at time t, and n is the number of water molecules attached to the cation. Also, K is the Boltzmann constant, $V(t)$ is the external applied voltage, κ_e is the equivalent dielectric permeability, and S_x is the cross-sectional area of the material in the x direction.

The initial and boundary conditions of Eq. (2) are as follows:

$$\begin{gathered} q(x,0) = N_a e S_x C_0 x \\ q(x,0) = 0 \\ q(d,t) = N_a e S_x C_0 d \end{gathered} \tag{3}$$

where C_0 is the concentration at the initial time and place, and e is the electric charge of an electron.

From the RC model for a voltage step of 1 volt, and considering the purpose of this article is also to derive the response of this material to a 1 volt potential, the electric current is obtained in the form of:

$$i(t) = 0.0515e^{-15.23t} \tag{4}$$

To solve Eq. (2), the finite element method is used. The elements are one-dimensional linear Lagrangian, and the shape function N is used to represent the change q in each element as

$$[A]\{\dot{q}\} + [B]\{q\} = 0 \tag{5}$$

$$[A] = \eta \int_{\Omega} [N][N]^T dx \tag{6}$$

$$[B] = KT\int_{\Omega} \frac{\partial [N]}{\partial x}\frac{\partial [N]^T}{\partial x} dx + \frac{2e}{\kappa_e S_x}\int_{\Omega} [N]\frac{\partial [N]^T}{\partial x}\left\{\int_0^t i(\tau)d\tau + q - q_0\right\} dx = 0$$

By solving Eq. (5) using the Euler`s method, the concentration distribution along the thickness of the strip is obtained, and then continuity equation implies:

$$\frac{\dot{w}}{w+1} + w\nabla . v = 0 \tag{7}$$

For the approximate solution of Eq. (7), first, the bending moment created by the volumetric deformation due to the solvent transport is given, then an approximate solution of (7) is presented.

With fully hydrated clusters, the volumetric strain rate $\dot{\varepsilon}_v$ is related to the rate of absorbed water by:

$$\dot{\varepsilon}_v = \frac{\dot{w}}{1+w} = \frac{\partial \ln(1+w)}{\partial t} \tag{8}$$

The bending moment rate is defined assuming the absence of external mechanical force and only for the ionomer (without considering the electrodes):

$$\dot{M}^e(t) = \int_{-h/2}^{h/2} \dot{\sigma}^* z dz = \int_{-h/2}^{h/2} Y_b \dot{\varepsilon}^* z dz \tag{9}$$

Y_b is the effective Young's modulus of the hydrated polymer (ionomer), and h is the polymer thickness.

In this article, the unknowns related to the boundary layer of anode and cathode were obtained according to Ref. [2], and finally, the deflect of the end of the IPMC strip was obtained as:

$$\frac{u_3}{L} = \frac{M^e L}{2(YI)_{eff}} \tag{10}$$

where Y is the effective stiffness of the strip. L is also the length of the strip. I is the moment of inertia, and u_3 is the deflection of the end of the strip, too.

3. Results and Discussion

The computer program of the differential equation (5) has been written and executed by MATLAB software for an IPMC strip with a thickness of 200 micrometers. 32 elements through the thickness of the strip is adopted. The Euler's method has also been used for the time integration. It should be noted that in order to compare with Ref. [17], the parameters of the problem corresponding to this reference have been selected. The polymer, cation, and solvent used are Na^+, water and

Nafion, respectively. The time step of the Euler solution is considered to be Δt=0.0005 s.

In Figure 2, the ion concentration distribution is depicted at the time of 0.11 s, for the present analysis and the results of Ref. [12].

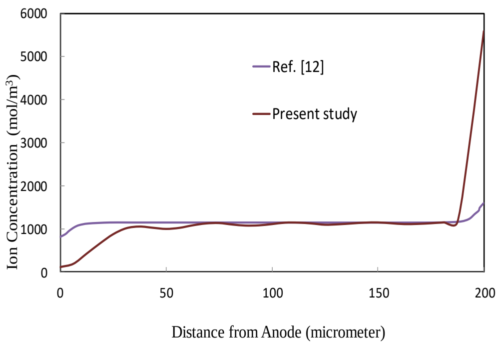

Figure 2. Ion concentration through the IPMC thickness after applying 1 Volt excitation

The results of Ref. [12] is different with the results of Tadakura [10] and with the results of Nemat Nasser's hybrid nonlinear model [6]. The rate of the migration of ions near the anode and cathode in the diagram of Ref. [12] changes in the same way, while this is contrary to the results of Ref. [6] and the present results.

In Figure 3, a parametric study is examined on the effect of the applied electrical potential on the actuation of IPMC near the anode. The concentration of ions in the induction time of 0.05 sec is presented under two electric potentials of 1 and 1.5 V.

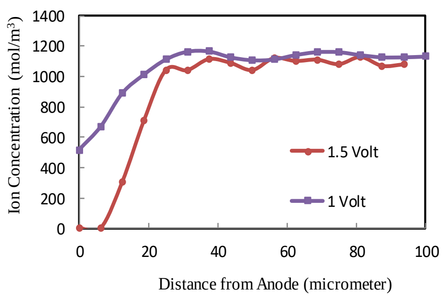

Figure 3. Ion concentration under excitations 1 V and 1.5 V near the anode

As can be seen from Figure 3, by increasing the applied voltage from 1 V to 1.5 V at a distance of less than 10 micrometers from the anode electrode, all existing cations migrate and the cation concentration becomes zero.

Figure 4 displays the time response of the deflection of the IPMC strip end, and the present results validated with the experimental results of Ref. [6].

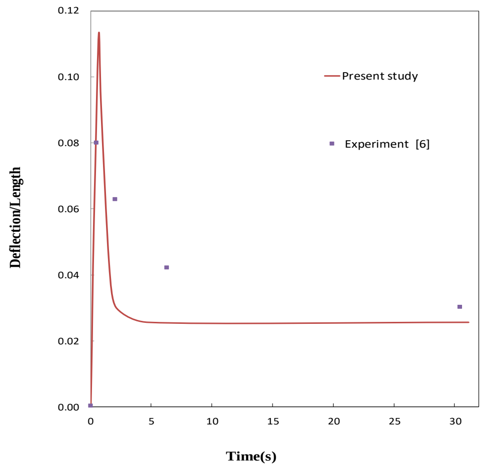

Figure 4. Deflection of the end of the IPMC strip

The behavior of the actuator shown in Figure 4 indicates that the primary motion of the IPMC is very fast. This movement is towards the cathode and the reason for it is the bending moment resulting from the electric potential. The results shown for the strip end displacement are dimensioned by dividing it by the IPMC length, predicting a maximum displacement of 2 mm. After this fast movement, the material returns to the anode, and the final deflection of 0.5 mm remains in the material.

4. Conclusions

The actuation behavior of an IPMC strip was predicted by an electrochemical-mechanical model. After applying electric voltage, the ion and water concentration distribution was formulated in terms of the electric charge. The equation was solved by the finite element method. The time integrals of the equation were solved by the Euler's method. Then, using the relation between the bending moment rate in terms of eigen strain, the bending moment and the deflection of the strip were obtained. The results obtained from the model were compared and validated with the available experimental results. The important role of the anode and cathode boundary layers was proved. It was observed that with an increase in the excitation voltage, the amount of migrated ions and water is higher, and as a result, more bending is observed. The results showed that despite the simplicity and low computational cost, the presented model predicts the fast response of the IPMC strip in an acceptable way.

5. References

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