Nonlinear numerical analysis of actuation response of ionic polymer metal composite cantilever considering coupled electrical, chemical, and mechanical fields

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ABSTRACT

Ionic-Polymer-Metal-Composite (IPMC) actuators are thin sandwich strips with an electroactive polymer in the middle and two metal electrodes on the sides. The coupling of electric, chemical and mechanical fields causes bending deformation, as applying voltage to the electrodes leads to the ions migration through the thickness. A nonlinear coupled electrochemical mechanical analysis of the actuation response of an IPMC cantilever is performed. From the coupling of chemical and electric fields, the electrochemical response equation is solved by the finite difference and Newton-Raphson methods. This response inserts into the mechanical field. Using the solvent transfer equation, the eigen strain and bending moment rates are obtained. Cantilever's tip deflection is determined by extracting the water coverage in the boundary layer of cathode and anode. The results are compared and validated with previous available studies. The results show a fit between the response of the actuator and the electrical excitation, and confirm the presented model provides the fast response prediction of the strip. Under 1 Volt excitation, the maximum and residual deflections of the cantilever's end were found 0.11 and 0.04 of the strip length, respectively, and the cation concentration in the middle of the thickness was calculated to be 1150 mol/m^3.

KEYWORDS

Ionic Polymer-Metal Composite, Actuation response, Electrochemical-mechanical model, Finite difference method, Newton-Raphson method.

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].

Traver et al. [4] investigated the dynamics and control of a synthetic flagellar eukaryotic swimming robot whose parts are made of IPMC and presented a dynamic model based on the frequency response analysis. Sampur et al.

[5] also presented a nonlinear dynamic viscoelastic model for IPMC actuators based on the viscoelastic structural equation and energy-based variational approach. Nemat Nasser moreover investigated a hybrid model for this material that included the electrostatic, osmotic and elastic effects, and compared the results of the model with the results of his own laboratory work [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 difference method. Futhermore, by using the analytical relation between the eigen strain rate and the bending moment, the fast response of the IPMC cantilever is obtained.

Methodology

The J^+ cation flux changes due to the change in the local concentration of C^+ at time t according to Eq. (1) [7]:

$$\dot{C}^+ + \nabla.J^+ = 0 \qquad (1)$$

The local concentration of C^+ is defined as the cation mole per volume of water hydrated IPMC. Cation flux is expressed due to the presence of μ^+ electrochemical potential gradient and fluid displacement flow according to Eq. (2) [7] as

$$J^+ = -\frac{D^+ C^+}{RT}\frac{\partial \mu^+}{\partial x} + C^+ v \qquad (2)$$

The chemical potential in relation (2) is defined in Eq. (3):

$$\mu^+ = \mu_0^+ + RT\ln(k^+ C^+) + z^+ \phi F \qquad (3)$$

The electric field expresses the interaction between the electric potential (which the operator applies to the IPMC electrodes) and the charged particles of fixed anions and mobile cations. Equation (4) related to this field is known as Poisson's equation [8].

$$\Delta\phi = -\frac{F}{\kappa}(z^+ C^+ - C^-) \qquad (4)$$

In order to obtain the relative water hydrating rate, it is necessary to consider the cluster pressure. For this purpose, the momentum equation (Euler's equation) is used as Eq. (5) [8]:

$$\dot{v} + (v.\nabla)v + \frac{1}{\rho_L}\nabla p_{cluster} = 0 \qquad (5)$$

The concentration change function is obtained after discretizing the electrochemical equations by the finite difference method and applying the boundary conditions. Then, it is entered in Eq. (6).

$$w(x,t) = w_1 + w_2 + nC(x,t) \qquad (6)$$

Assuming a constant density ρ_L for the solvent, the mass conservation law and the continuity equation are written as Eq. (7):

$$\frac{\dot{w}}{w+1} + w\nabla.v = 0 \qquad (7)$$

For the approximate solution of Eq. (7), first, the bending moment created by the volumetric deformation due to the solvent transfer is given, then an approximate solution of Eq. (7) is presented. With fully hydrated clusters, the volumetric strain rate ε_v is related to the rate of absorbed water by:

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

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

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

where 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 are adopted according to Ref. [1], and finally, the deflection of the IPMC cantilever is obtained as:

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

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

Results and Discussion

In Figure 4, the results of numerical modeling in COMSOL software and finite difference modeling showing the cation concentration in the twelfth second in the middle of the cantilever thickness are presented. The analytical results of Ref. [6] are also included in the figure.
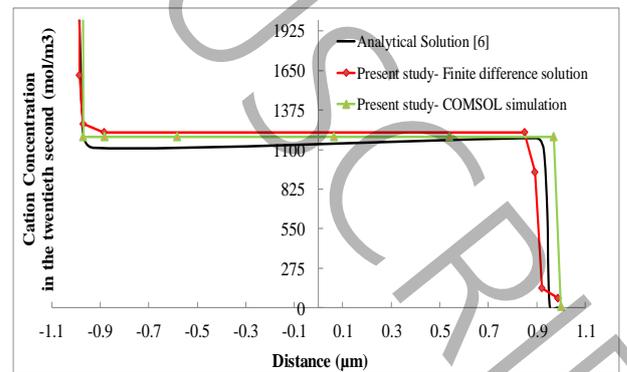
Figure 1. Ion distribution in the IPMC thickness by applying 2V voltage

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It can be observed from the figure that the analytical solution [6] and the other two presented models illuatrate the cation concentration of 1150 mol/m³. Also, the presented numerical models predict the concentration changes near the cathode and anode well. According to Ref. [6], the gradient of cation concentration near the anode and cathode changes rapidly and as a result of this increase in the concentration, the mechanical actuation is observed in the metal-polymer composite.

As anther validation study on the presented nonlinear numerical analysis, an IPMC cantilever with 6 µm thick platinum on the both sides of the strip is considered. The initial water coverage is assumed to be 0.533, and the applied electric potential is 1 Volt. The present results are compared with the experiment of Ref [6], and illustrated in Figure 2. It is worth mentioning that the results of Ref. [6] were obtained from the laboratory evaluation of the mechanical response of the IPMC actuator with different cations and in different water concentrations.
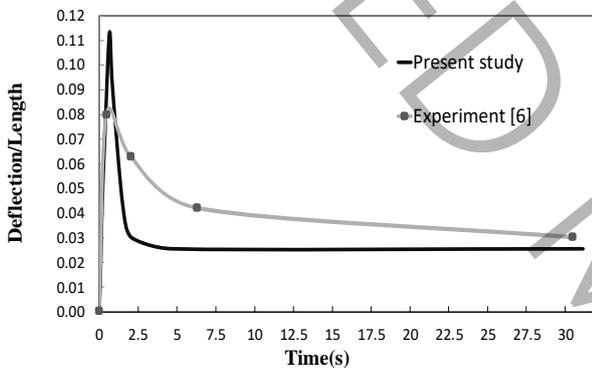
Figure 2. The deflection of the IPMC strip end under an excitation of 1 V

The behavior of the actuator shown in Figure 2 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.

Conclusion

In this paper, a nonlinear coupled electrochemical mechanical modeling was carried out on the actuation response of an IPMC cantilever. The equations were solved by the finite difference and Newton-Raphson methods. The bending moment rate was obtained using the solvent transfer equation. Then, the cantilever deflection was found via extracting the water coverage in the cathode and anode boundary layers. The results

showed that despite the solution's simplicity and low computational cost, the presented model predicts the fast response of an IPMC cantilever in an acceptable way. The important role of anode and cathode boundary layers was confirmed as the area determining the volume strain. In the simulation, it was observed that with the increase of voltage, the amount of displaced ions and water is higher, and as a result, more bending is seen in the IPMC cantilever. The summary of the obtained results is listed below:

• By applying one volt excitation, the dimensionless residual and maximum tip deflection of the cantilever are obtained as 0.04 and 0.11 respectively, which are less than 10% error with the experimental results.

• From the parametric study, it was found that by increasing the excitation voltage from 1 to 1.5 V, the cation concentration reaches zero up to a distance of 6 micrometers, and this shows the direct effect of the voltage change on the concentration changes in the cantilever thickness.

• A good agreement was observed between the current modeling and previous researches. In such a way that both of them obtained 1150 mol/m³ ion concentration in the middle of the metal-polymer composite with a slight difference, and at the end, they reported the singularity of the cation concentration change.

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