Finite element simulations of the bending of the IPMC sheet

D. Pugal[a,b], H. Kasemägi[a], M. Kruusmaa[a], A. Aabloo[a], K. J. Kim[b]

University of Tartu
University of Nevada

ABSTRACT

Finite Element method is used to build and simulate an IPMC sheet. The physical bending of the realistic Nafion sheet due to the drift of counter-ions (e.g Na+) and dragged water in applied electric field are simulated . The other effects like viscous resistance and diffusion of water, also the porous nature of the environment inside the Nafion are taken into account. The effect of the concentration of water and counter-ions near the electrodes are tried to relate to the physical bending of the IPMC sheet. Some additional effects like voltage drop at more distance points from contacts instead of constant electric field and electrolysis for more complex model are discussed. Also some electrochemical reactions leading to self oscillations are discussed and simulated.

Keywords: Electroactive polymers, EAP, Finite element method, Electrochemical-mechanical analysis, Actuator, Coupled problem, Self-oscillating systems

1. INTRODUCTION

EAP-based electromechanical actuators are valuable for use in a number of applications starting with miniature robotics up to military and space. These actuators have light weight, noiseless motion, simple mechanical construction; large controlled displacement and good damage tolerance along with an ability to perform different movements like bending and contractions makes possible to use them as artificial muscles. In this letter we consider simulation of ionic polymer-metal composite (IPMC) materials with finite element method (FEM).

IPMC materials are highly porous polymer materials such as Nafion, Fleminon, Teflon, filled with some kind of ionic conductive liquid. There are water based IPMCs which operate in aquatic environment and conduction is caused by ions such as Na+, K+ dissociated in water. Ionic liquid based IPMCs do not need wet environment for operating. The sheet of the ionoic polymer is coated with thin metal layer, usually platinum or gold. In applied electric field the freely movable cationsinside the polymer migrate towards an electrode, causing expansion of the material at the one end of the sheet and contraction at the other end, which leads to bending of the sheet.

For simulating actuation of an IPMC sheet we need to solve coupled problems due to the complex nature of IPMC actuation. It involves working in different domains such as mechanical, electrostatic and mass transfer. XXX and YYY have already simulated mass transfer and electrostatic effects. We have used similar approach for these problems. However, new approach is introduced for mechanical bending of IPMC strip. By coupling those domains together we get enough accurate finite element model for an IPMC muscle sheet. It allows us using the model as a base for solving more complex problems, thus we have also introduced simulation of electrochemical reactions.

1.1. Electrochemical oscillations

Spontaneus oscillations are common fenomenon in nature and it has been studied for many experimens, including electrochemical systems such as oxidation of organic materials and metals [REF]. Electrochemical systems exhibiting instabilities often behave like activator-inhibitor systems, where the potential of the electrode is an essential variable and takes on the role either of the activator or of the inhibitor. Under certain conditions the system can generate oscillations. We have conducted series of tests, where IPMC sheet have immersed into acidic formaldehyde, HCHO, solution and exposed to constant outer potential. However, measurements show current oscillations, which in turn result in oscillating bending of the IPMC sheet. Hence we have also introduced a model in this paper for describing such systems coupled with other physicals domains.

Further author information: (Send correspondence to Alvo Aabloo)
Alvo Aabloo: Email: alvo.aabloo@ut.ee

2. SIMULATION DETAILS

An IPMC sheet consists of backbone polymer and metal coating. We have used Nafion 117 coated with thin layer of platinum. Although, as it is written in the introducion that simulations in multiple physical domains are needed for getting bending model for an IPMC, only one mechanical domain, backbone polymer, is used for simulations as shown in [FIGURE1]. Platinum coating is considered neglibly small.

Most simulations are done for IPMC strip, 1cm long, xxx cm thick, with cantilever configuration - one end of the strip is not allowed to move. Gravitational forces are not considered in following simulations.

2.1. Migration of cations

Nernst-Planck equations describes diffusion and convection and migration of charged particles under electric field. General form of the equation is

$$\frac{\partial C_i}{\partial t} + \nabla \cdot (-D_i \nabla C_i - z_i \mu_i F C_i \nabla \phi) = -\vec{u} \cdot \nabla C_i \tag{1}$$

where subscript i denotes species and C is concentration of species, μ is mobility of species, D is diffusion constant, T is absolute temperature, R is gas constant and ϕ is electric potential. This equations must be solved only for freely movable cations. As voltage is applied to the electrodes of the IPMC, all freely movable cations start migrating towards anode???, causing current in circuit. As ions cannot move beyond boundary of Nafion, charges start to accumulate, resulting in increase of electric field of opposite direction to applied one. So the electric field caused by charge distribution is described by Gauss' Law:

$$\nabla \vec{E} = \frac{F \cdot \rho}{\varepsilon} \tag{2}$$

where ρ is charge density, ε is absolute dielectric constant and E is the strength of the electric field and can be expressed also as $\nabla \phi = -E$. Steady state of the cations forms when electric field created by distribution of cations cancels out applied electric field, i.e. electric field strength inside the polymer is zero as shown in Figure 1 . Charge distribution for Na+ ion concentration of $1200 \frac{mol}{m^3}$ is shown in Figure . It is interesting to notice that there are anomalies in charge distribution only in really thin boundary layers.

Variable	Value	Dimension

Table 1. Values used in simulations.

All values used to simulate previously described equations are shown in Table 1.

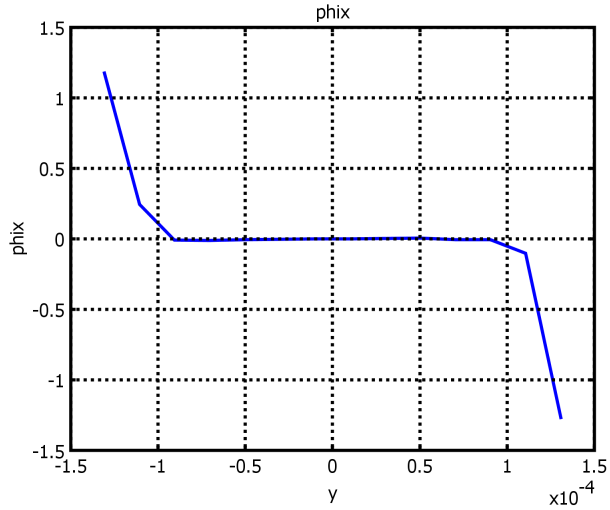

Figure 1. Electric field strength inside the IPMC in charge balance state. (TODO better figure)

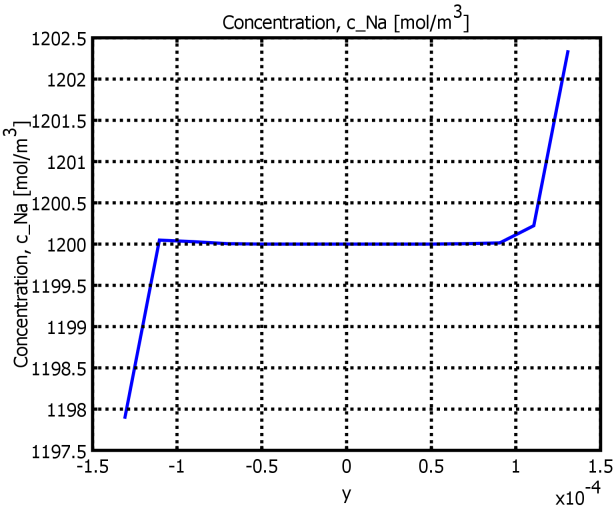

Figure 2. Cation distribution in charge balance state. (TODO better figure!)