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Recent advances in ionic polymer–metal composite actuators and their modeling and applications

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ABSTRACT

This paper presents a comprehensive review of ionic polymer–metal composite (IPMC) actuators. Recently, strong emphasis has been put on investigating various ionic polymer membranes for high-performance IPMC actuators and overcoming some drawbacks of ionic polymer actuators to improve stability and reliability. The paper gives an overview of different types of sulfonated ionic polymer membranes. Various emerging materials that exhibit notably good deformation, stability, and efficiency are extensively considered. A thorough comparison of different state-of-the-art ion exchange membranes is presented. Along with the material study, recent trends in modeling and control approached of IPMC actuators are presented. Although fundamental models of IPMC were proposed over a decade ago, physics-based models are still being developed in order to study specific aspects of the actuators and to develop a control design for practical applications. Therefore, this paper considers the latest actuation models and control designs of IPMC actuator and various promising prototype applications that lead the way in using the materials for real applications in future.

Contents

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1. Introduction

For ionic polymer–metal composites (IPMCs), the type of the ionomers is a critical component. Generally, perfluorinated polymers, such as sulfonated (Nafion) or carboxylated (Flemion), are employed for IPMCs. Perfluorinated sulfonic acid ionomeric polymers are synthesized by copolymerization of sulfonyl fluoride vinyl ether and tetrafluoroethylene [1–3]. Nafion is a perfluorinated sulfonic acid ionomer membrane that has a Teflon-like backbone and short side-chains terminated by sulfonic acid group, with counter ions such as H^+, Li^+, Na^+ and K^+, and hydrophobic fluorocarbon and hydrophilic ionic phases. Nafion is important in electromechanical actuators because it is easy to produce, and exhibits light weight, flexibility, large bending deformation, quick bending response, softness, low actuating voltage [4,5]. Electroless plating is the best process to fabricate IPMCs based on Nafion membranes, using conductive metal ions (platinum or gold) (see Fig. 1).

However, these perfluorinated ionomers have some limitations on performance and cost for application. Hydrocarbon backbone polymers could offer a solution to overcome these drawbacks because the change of two or more different structural unit monomers can be easily controlled, especially via manipulation of block copolymers.

In Section 2 of this article, we review the physics of Nafion based IPMCs, and then various types of novel hydrocarbon ion-exchangeable membranes are introduced. Also, membrane preparation, enhancement methods and considerations for high-performance actuation are followed. Next, an overview of the latest physics based models and control design of the IPMC actuators is discussed in Section 3. Various models have been proposed to describe the actuation mechanism of IPMC material. A diffusion equation describing the evolution of solvent concentration and resulting strain on polymeric gel materials was already proposed in 1992 [6]. Attempts to formulate the electromechanical theory of IPMCs were made in the following years. Nafion based IPMCs are widely used in artificial muscles, actuators and sensor transducers [7–14], biomimetic micro-collector [15], active catheter systems [16], micropump [17,18]. Thus the ionic polymer–metal composite (IPMC) has considerable potential in applications. Several review articles on the applications of the IPMC actuators have been published [9,10,19,20]. The last section reviews the most recent developments of the application researches of the IPMC actuators including sensor/actuator integrated systems, biomimetic robots, biomedical devices, human friendly applications, aerospace applications, etc.

2. Novel ionic exchangeable membranes for IPMC

2.1. Nafion-IPMC

An actuation mechanism of Nafion-IPMC under an electric field might involve an ion cluster flux and electro-osmotic flow of water that moves from anode to cathode through hydrophilic and ionic channels, resulting in a bending motion of the IPMC [22]. Moreover, the mobility of the ion-water clusters in the IPMC causes a contraction of one side and expansion of other side, as shown in Fig. 2 [22–25].

The water channels in the Nafion membranes have diameters between 1.8 and 3.5 nm [26,27], which causes hydrophilic domains with sulfonic acid groups. Further, counter ions in the Nafion, H^+, Li^+, Na^+ and K^+ are solvated by water with sizes of 3–5 nm (see Figs. 3 and 4).

Under an applied electric voltage, redistribution of the charges in an IPMC membrane causes changes in the electrostatic, osmotic, and elastic interaction forces within and outside of the clusters. This in turn results in localized volume change in the clusters, which together with the change in the water content causes either stretching or relaxation of the polymer chains. These effects are prevalent in producing the initial fast bending response of the IPMC, followed by slower relaxation.

Nemat-Nasser [28] has proposed a model that incorporates hydraulic, electrostatic, osmotic, and elastic forces in the actuation of IPMCs. The study showed that the electrostatic and osmotic forces in the clusters with balancing elastic force of the backbone ionomer cause the actuation. In a Nafion-based IPMC, the redistribution of cations appears to contribute to the back relaxation of the IPMC strip. Direction of the back relaxation depends on the composition of the backbone ionomers and the nature of the counter-ions. In the anode side, the reduction in the cation concentration decreases the osmotic pressure inside the clusters. Moreover, the reorientation of the remaining water molecules in the clusters tends to increase the effective electric permittivity of the clusters and hence reduces the electrostatic repulsive forces among the fixed charges within the clusters. Due to the cation depletion, repulsive