In situ studies MRI of soft actuators during operation for RTB web page

Soft actuators are devices constructed of polymer or gel materials that are able to undergo dramatic and reversible shape deformation in response to the application of an electrical potential or chemical stimulus. One class of soft actuator is made from elements of ionic polymer, such as cation-exchanged Nafion, soaked with a solvent, usually water, and coated with high surface area metal electrodes on opposite faces. Such IPMCs are of great scientific and technological interest because of their unique properties and wide range of potential applications in medical, mechanical, electrical and aerospace engineering. IPMC materials are relatively inexpensive, light, compact and flexible, and can be cut to any desired size and shape. They can undergo very large bending deformations, require only very small applied potentials (typically around 5 V) compared to piezoelectric ceramic (several kV) or polymer actuator technologies (tens of hundreds of V), and exhibit relatively short (from ms to s) response times. Induced strains are also several orders greater in IPMCs than in piezoelectric ceramics. These properties make IPMCs suitable for potential applications in artificial valves and muscle in medicine as well as in actuators for manipulation of fragile objects in robotics and as micro-actuators in MEMS devices.

A typical IPMC consists of a thin, cation-exchanged ionic polymer membrane with metal electrodes deposited chemically at both faces. The best electrodes are made up of small, interconnected metal particles, generally platinum or gold, that penetrate into the polymer membrane. The IPMC must be impregnated with an electrolyte solution, which is usually aqueous. Nafion is a suitable ionic polymer membrane for use in IPMC actuators.

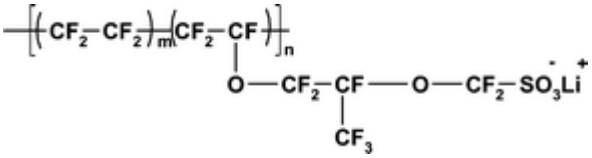

Fig. 1 Chemical structure of Li^+-exchanged Nafion.

Fig. 2 is a schematic diagram of the bending deformation of an IPMC. On application of a small d.c potential across its thickness, the IPMC actuator bends dramatically and reversibly toward its positively charged surface. This is a result of the electrically induced movement of cations – together with their solvation shell of water molecules – through the ionic polymer network, towards the negatively charged electrode (cathode). The anionic sulfonate groups are tethered to the polymer and so are unable to move in the applied electric field. The resulting net movement of water towards one face of the polymer is sufficient to cause the polymer to swell at this face and to contract at the opposite face, so giving rise to a dramatic, reversible bending motion.

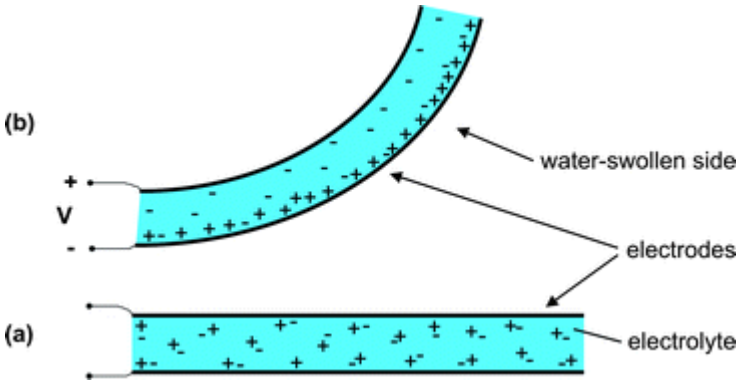

Fig. 2 Schematic diagram of the bending actuation in an IPMC. (a) No potential applied; (b) with potential applied.

The VIDEO (Fig. 3) shows an IPMC device operating in our laboratory. A 6 Volt a.c. potential was applied in this case.

Fig. 4 shows maps of how proton density and proton spin–spin relaxation time (T_2) varied across the cross-section of the IPMC with no potential applied and with a potential applied in different directions. Proton density can be related directly to the concentration of water in the polymer (there are no other Hs in the sample since Nafion is perfluorinated). The proton relaxation time, T_2, gives a measure of the rotational freedom of the water molecules in the polymer - that is, how strongly or weakly they interact with their immediate surroundings. The + and – symbols indicate the sense of the applied potential.
Proton density is uniform initially but then shows higher values near the negative electrode (cathode) and low values near the anode. We believe that this is because of the movement of solvated $[Li(H_2O)_x]^+$ ions through the polymer structure and towards the cathode, under the influence of the applied electric field. As the direction of the potential is switched, the position of the new cathode changes and the areas of high and low proton density also swap around. In the T_2 maps, the initial distribution is not uniform because of the effect of the Pt electrodes. When the potential is applied, higher T_2s (indicating “freer” water molecules) are seen near the cathode and lower values near the anode. For detailed discussion of these effects, please see our papers.

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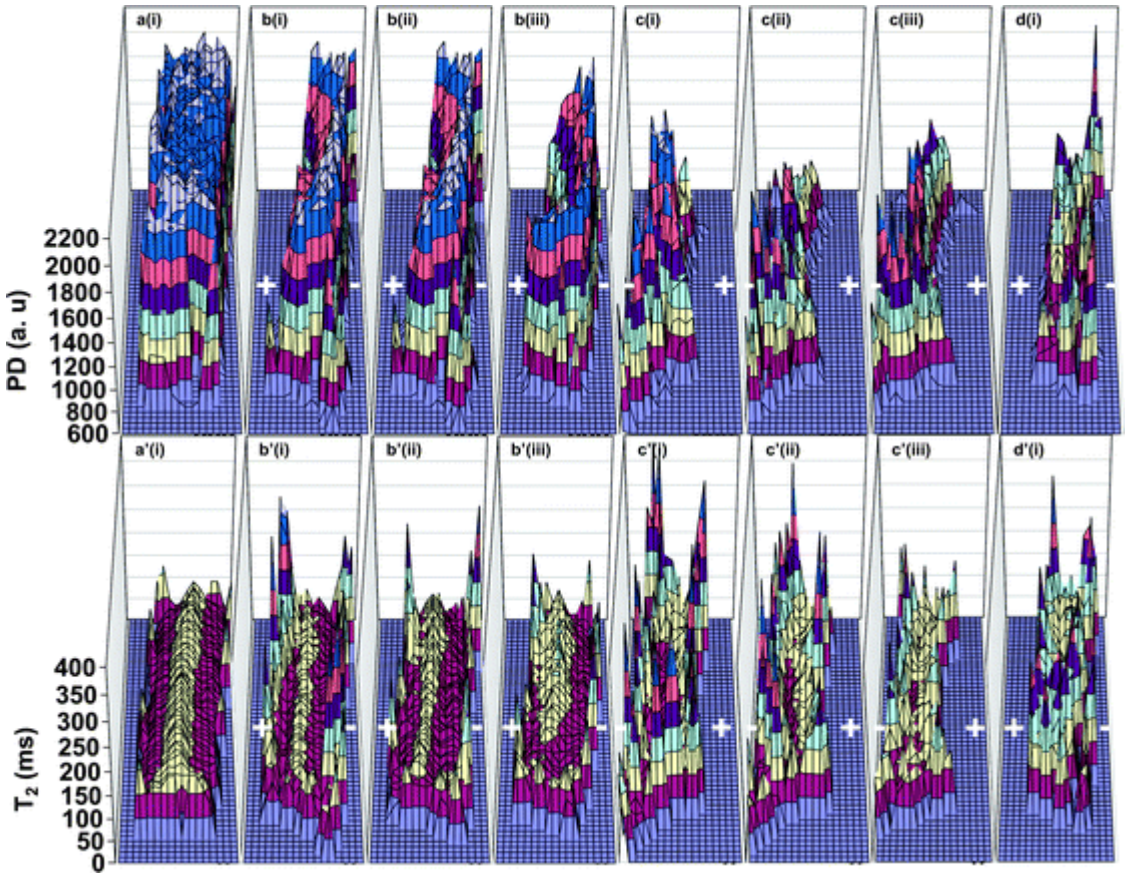

Fig. 4 PD (top maps) and T_2 (lower maps, primed labels) of the IPMC sample obtained: (a, a′) (i) with no potential applied; (b, b′) (i) 0; (ii) 29; and (iii) 89 min after application of a 3 V d.c. continuous potential in the sense indicated; (c, c′) (i) 0; (ii) 29 and (iii) 89 min after the first reversal of the polarity; and (d, d′) (i) 0 min after the second reversal of the polarity of the potential. The "−" and "+" symbols indicate the cathode and anode sides of the sample, respectively.

In related work, Diffusion-Weighted Imaging was employed to spatially map the distribution of the diffusion coefficient of water, *D*, in an IPMC soft actuator element, prepared from Nafion by impregnation with Pt electrodes. *D* was evaluated in two orthogonal directions: along one of the long dimensions of the sample (D_x) and through its thickness (D_z). *D*-maps of the IPMC element were obtained both in the absence of an applied potential and *in situ* during the application of a 3 Vd.c potential across the thickness of the sample. In the bare Nafion, *D*-maps showed uniform values of both D_x and D_z of about 6×10^{-10} m^2s^{-1}. In the IPMC two effects were observed: (i) *D* at the electroded surfaces of the IPMC was higher than at the centre of the sample; (ii) This difference was much greater in D_z than in D_x. Both effects were explained by the influence of the impregnated Pt electrodes on polymer structure. The *D*-maps in the electrochemical measurements showed high values of *D* (up to 8×10^{-10} m^2s^{-1}) at the cathode and low values (from 1×10^{-10} m^2s^{-1}) at the anode. This was explained in terms of the effect on the Nafion nanostructure of the forced electro-migration of $Li(H_2O)_x^+$ species towards the cathode.

The application of a potential across the thickness of the sample caused a clear effect on the distribution of D_x and, to a lesser extent, D_z. High *D* values were always observed near the cathode and low values near the anode, even after reversal of the potential. These phenomena were compared with the studies of T_2 and *PD* in previous work and were explained as the effect of the forced migration of solvated Li^+ ions from the vicinity of the anode into that of the cathode. This would both extend the volume of the hydrated phase of the polymer and decrease its tortuosity at the cathode while having the opposite effects at the anode. Both factors would increase *D* at the cathode and decrease *D* at the anode.

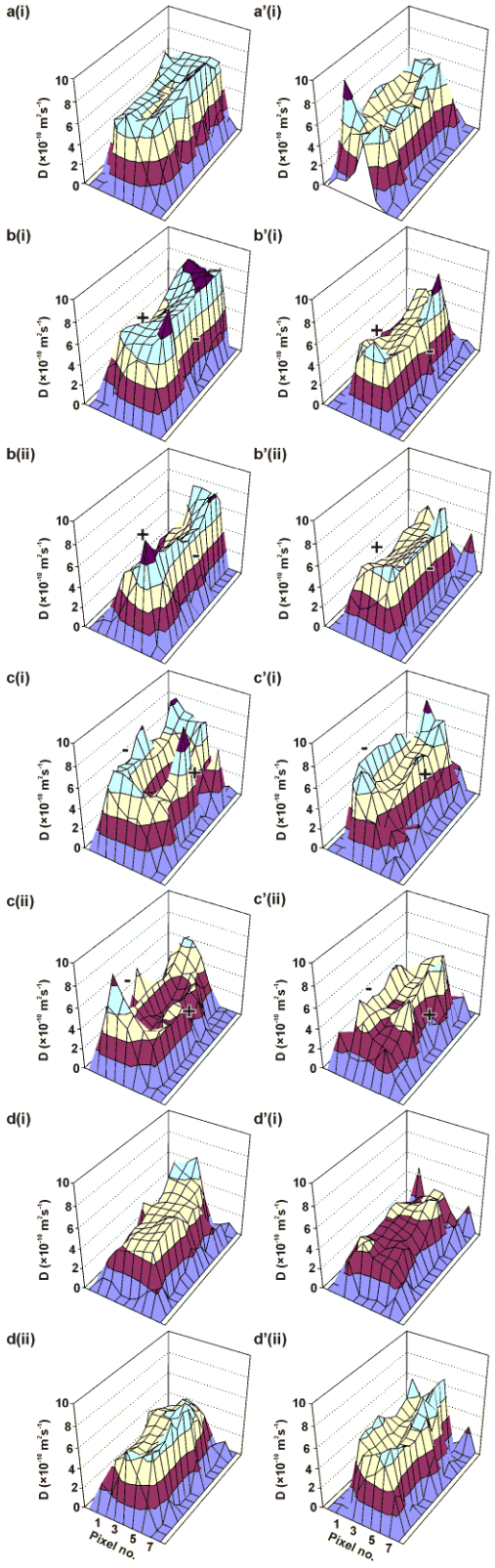

Figure 7. D_x-maps and D_z-maps of IPMC sample: (a)(i) with no potential applied; (b)(i) 0 min.(ii) 21 min. after application of a 3 Vd.c. continuous potential in the sense indicated; (c) (i) 0 min.(ii) 42 min. after reversal of the polarity of the 3 V d.c. potential; (d) (i) 0 min. and (ii) 65 h. after the potential was switched off. The "-"and

“+” signs indicate the cathode and anode sides of the sample, respectively.

References

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