**Electroactive polymer actuators with carbon aerogel electrodes**

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**Abstract**

Electroactive polymers (EAPs) are soft materials whose shape is modified in response to the voltage stimulus. They can be used as actuators or sensors. Several researchers have introduced different materials and methods for assembling EAPs. Now it is generally accepted that the porous structure of electrodes with possibly high specific area can greatly improve the actuation performance. In this paper, a carbon aerogel is introduced as a new material for making nanoporous electrodes for EAP actuators. Using the direct assembly process (DAP), actuators with either activated or non-activated carbon aerogel electrodes are synthesized. Their electrochemical and electromechanical characteristics are presented and compared to our recently reported actuators based on carbide-derived carbon and activated carbon electrodes. The results shows that our newly developed actuators with non-activated carbon aerogel electrodes and activated carbon aerogel electrodes have maximum strains of 1.3% and 1.1%, respectively, which are comparable to our previously reported actuators and also any other low-voltage driven EAP actuators.

*Keywords*: Actuator; Electroactive polymer; EAP; Ionic Polymer Metal Composite; Nafion; Carbon Aerogel; Carbon Electrode; Carbide Derived Carbon.

**1. Introduction**

Electroactive polymer (EAP) actuators have been extensively studied during the recent years. Their soft, flexible structure and ability to respond quickly with large linear deformations makes them attractive for a wide range of applications including biomimetics, robotics, micro-electromechnaical systems, and medical devices[[2]](#endnote-1). EAPs may have several configurations and can be manufactured using variety of different materials,

**2. Experimental**

*2.1 Chemicals and materials*

Carbon aerogels (activated and non-activated) were provided by Tallinn University of Technology and used *as received*. Nafion™ 117 membrane (product of DuPont) was purchased from FuelCellStore.com™. Gold foil from Gold-Hammer (24-carat, 80x80 mm2) was used as contact material on electrode surface.

All reagents were of analytical grade and used without further purification: 1-ethyl-3-methylimidazolium trifluoromethanesulfonate (EMI-TF, Fluka); lithium perchlorate (LiClO4, Fluka); 2-Propanol ((CH3)2CHOH, 99.9%, Sigma Aldrich); ethanol (CH3CH2OH, 96%, Sigma Aldrich); hydrochloric acid (HCl, 36%, Stanchem). All solutions were prepared using deionised water (18 MΩ ∙ cm)

The physical properties of electrode materials used are listed in Table 1.

*2.2 Preparation of the IPMCs*

Bare Nafion™ 117 membrane was pretreated by roughening both sides with emery paper in order to remove the outer polymer surface layer, which due to its relatively high hydrophobicity interacts weakly with the solutions used further on. Roughening also enlarges the polymer-electrode interface area, thereby providing better adhesion. Both sides of the membranes were roughed until the surface appeared to be non-transparent, after which the membranes were washed by boiling in 1 M hydrochloric acid for 30 minutes, followed by boiling in de-ionized water for 1 h to remove acid residuals.

In order to prevent degradation of the ionomer during the relatively long drying procedure at elevated temperature[[3]](#endnote-2), the membranes were ion-exchanged by boiling for 2 h in a 1 M LiClO4 solution. The membranes were then dried in vacuum at 150o C for 12 h. Thereafter, the membranes were instantly immersed in neat ionic liquid (Emi-Tf) and heated for 5 h at 150o C. Afterwards, the uptake of Emi-Tf is expected be near 60% of the dry weight of the membrane[[4]](#endnote-3).

The electrodes were applied to the membrane using DAP[[5]](#endnote-4); *i.e.,* a conductive powder with high specific area was mixed with an ionomer solution and painted directly on the diluent-swollen membrane and sandwiched between two gold foils followed by hot-pressing. A 5 wt% Nafion 1110 dispersion was prepared by heating the ionomer in an autoclave for 3 h at 210o C under continuous stirring in the presence of a 50% ethanol/water solution. Thereafter, the ionomer dispersion was mixed with conductive powder. For RuO2 electrodes, the mixture was prepared containing of 6 wt% ruthenium (IV) oxide powder, 47 wt% of Nafion solution (5%) and 47 wt% of isopropanol. The mixture for carbon electrodes was adjusted to contain 1.7 wt% of carbon powder, 48.3 wt% of Nafion solution and 50 wt% of isopropanol. All mixtures were then sonicated for 1 to 3 h to disperse the conductive powder particles.

The conductor/ionomer mixtures were applied to the membrane using an SB-1107 Sumake airbrush operated by compressed-air. Volatile solvents were removed under an infrared lamp (150 W, Philips) after application of each layer. Typically 8 to 15 layers of the conductor/ionomer mixture were sprayed on each membrane to achieve uniform thicknesses – the RuO2 solutions had higher viscosity than the carbon based, therefore resulting in better covering. After painting on the electrodes, a layer of 5% Nafion solution was applied onto the sprayed electrode to provide better surface adhesiveness to the gold foil. Thereafter, the membranes were placed under IR light for an additional 15 minutes. Finally, the membranes were sandwiched between two gold foils (270 nm thick) and fused together by hot-pressing at 150o C under 3.5 MPa for 5-10 s. This decreases the surface resistance of painted layers to less than 1 Ω/cm, according to measurements.

By this process, four sets of samples with three membranes in each set were prepared with different electrode materials: TiC derived carbon (here referred to as carbon (1)), coconut shell based activated carbon (carbon (2)), anhydrous RuO2 (1) and hydrous RuO2 (2). All samples were 40 mm in length × 8 mm in width.

*2.3 Electromechanical Characterization*

For electromechanical characterization, the experimental setup described in [26] was used. A National Instruments PCI-6034 DAQ with an SCC-RTD01 module was used to measure the resistances of the surfaces using a four-probe system. This method eliminates inexactnesses caused by the inconsistent current density and the resistances of the contacts. The SCC-RTD01 is a dual-channel resistance-temperature detector (RTD) module that accepts 2, 3, or 4-wire RTDs. Each channel of the SCC-RTD01 has an amplifier with a gain of 25 and a 30 Hz lowpass filter. In addition, the module has a 1 mA excitation source for powering the RTDs. The range of the module allows reliable measurement of resistances from 0 to 200 Ω. In order to connect the four probes simultaneously to the IPMC strip, a special flexible contact strip was made by fixing four contacts made of gold foil onto the surface of a thin ribbon of PTFE. The distance between the test-contacts was kept at 21 mm.

A schematic of the experimental setup for the characterization of the actuator strain and speed is shown in Figure 1. The actuators were clamped in vertical cantilever position and measurements were done in the dry state in air. Rectangular or sinusoidal driving pulses were applied via a fixed contact U and a ground contact made of gold. The measurements were conducted with National Instruments LabView7 control software. The driving voltage was generated by a NI PCI-6703 DAQ board and amplified by electric current from a NS LM675 power op-amp. The voltages with respect to the ground were measured with a NI PCI-6034 DAQ board. One input contact of the IPMC sample was also connected to the ground. The electric input current of the sample was measured as a voltage drop over the resistor R. The value of the resistor should be chosen as low as possible, but still sufficiently high with respect to the value of the current and the sensitivity of the measuring equipment. In the course of the experiments described here, the value of the resistor R was 0.5-1 Ω. Electric current was calculated according to Ohm’s law.

The bending motions of the actuator were recorded with a firewire camera, Dragonfly Express from Point Grey Research Inc., recording images at 30 frames per second. The direction of the camera was set transverse to the actuator and the experiment was illuminated from the background through a frosted glass and a graph paper. In this camera position, the recorded image of the actuator consists of a single curved contrast line.

The resistances (conductivities) of both electrodes were measured using a four-probe system. The values of the shunt conductivity parameters were determined using impedance spectroscopy with variable-voltage step pulses as described in [27]. Blocking force was measured at zero displacement using the Panlab MLT0202 load cell. Sample stiffness was determined by a 3-point bending test [28].

*2.4 Scanning electron microscopy*

Scanning electron micrographs were obtained on all samples using a Hitachi Tabletop Microscope TM-1000 in standard backscattered electron (BSE) image mode with 15 keV primary electron energy.

**3. Results and discussion**

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| **Electrode material** | **Maximum peak-to-peak stain (mε)** | **Maximum strain rate (mε/s)** | **Capacitance (mF/cm2)** | **Electrode surface resistance (Ω/cm)** | **Blocking force (mN)** | **Stiffness (MPa)** |
| Non-activated carbon aerogel | 12.8 | 1.5 | 8 | 0.4 | 1.7 | 99 |
| Activated carbon aerogel | 11.5 | 1.3 | 14 | 0.3 | 1 | 100 |

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| --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **Maximum peak-to-peak stain (mε)** | **Maximum strain rate (mε/s)** | **Capacitance (mF/cm2)** | **Electrode surface resistance (Ω/cm)** | **Blocking force (mN)** | **Stiffness (MPa)** |
| Carbon (1) | 20.4 (±11%) | 2.3 (±9%) | 16 (±9%) | 0.7 (±17%) | 3.6 (±9%) | 97 (±8%) |
| Carbon (2) | 10.3 (±11%) | 1.6 (±9%) | 51 (±11%) | 0.6 (±17%) | 3.1 (±12%) | 103 (±10%) |
| RuO2 (1) | 9.4 (±11%) | 0.93 (±6%) | 20 (±12%) | 0.6 (±17%) | 3.3 (±10%) | 88 (±12%) |
| RuO2 (2) | 6.9 (±10%) | 1.7 (±9%) | 36 (±9%) | 0.5 (±20%) | 3.5 (±11%) | 95 (±8%) |

**4. Conclusions**

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