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Biomimetic, low power pumps based on soft actuators

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Abstract

A new biomimetic miniaturized pump based on soft materials is reported. The pump consists of a soft chamber made of polyurethane or polydimethyl siloxane (PDMS) tubes and a set of two soft electro-mechanical actuators in a cantilever configuration. The soft actuators were constructed using Nafion as an ionic polymer and polypyrrole as conducting material to make the electrodes by chemical in situ polymerisation. To our knowledge this is the first time this type of actuator has been reported. This choice of electrode material permits the pump to be actuated using lower potentials than when using platinum (±3 V as opposed to ±5 V when electroding using platinum). This leads to a much lower power consumption, which averaged to approximately 69 mW per stroke for an actuator that measured 3 cm length by 0.3 cm wide (as opposed to 227 mW when electroding with platinum). As the potential steps are applied to the actuators, they bend and produce a change of volume in the soft pumping chamber that generates the flow movement. The pumps developed in the present work were capable of flow rates of up to 1.6 μL/s, and could cope with backpressures of up to 0.025 Bar. This biomimetic pump is suitable for long term field deployable platforms, such as reagent based analytical platforms, since it is low power, corrosion resistant and also resistant to particle ingress due to its soft nature.

Keywords: Biomimetics; Soft actuators; Pumps; Polypyrrole-Nafion; Microfluidics

1. Introduction

As analytical chemistry advances, more compact and miniaturized devices are being developed to achieve both lower volumes of waste and lower detection limits. Another objective of more compact and miniaturized devices is deployment in different environments while remaining inconspicuous. These devices often implement microfluidic systems. However, the pumps used with these systems are traditionally several orders of magnitude larger than the device itself and they consume large amounts of energy. New miniaturized pumps have been recently reported in the literature, which are based on different types of actuators, the most successful ones being those based on piezoelectric actuators [1,2]. However, piezoelectric actuators consume large amounts of energy, which is a great limitation for the development of autonomous field deployable sensing platforms based on microfluidic devices. Moreover, the pumps reported in this paper are based on soft actuators and have the advantage of overcoming the problems generated by solid particles that would block and/or damage other rigid pumps.

In the present work we report the development of a miniaturized pump based on an ionic polymer (Nafion®) coated with polypyrrole that requires low amounts of energy to operate. To our knowledge this is the first time that this type of actuator (Ppy-Nafion-Ppy) has been reported. Traditionally Nafion has been used as a base material to construct ionic polymer–metal composites (IPMC) for various applications, e.g. as artificial muscles [3,4]. Their preparation involves the chemical reduction of platinum on both surfaces of the Nafion film which is both costly and time consuming. In this work polypyrrole was used as conducting material instead of Pt to form the electrodes on both sides of the Nafion. By doing this, the cost and time of preparation of the actuator were greatly reduced and in addition much lower power was required to actuate it.

This type of actuator is normally allowed to swell in an aqueous electrolyte solution. When a potential is applied between the two platinum electrodes, the hydrated cations that are interacting with the sulfonic groups of the Nafion migrate to the anode, dragging some water molecules with them. This migration causes an increase of volume on the anode and a decrease of

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volume on the cathode, which produces the macroscopic effect of bending the material [5]. However, after a limited amount of cycles, these actuators begin to dehydrate due to evaporation and hydrolysis of water arising from the voltages required. In this case the actuators were maintained in an aqueous environment during the trials in order to avoid dehydration, as this leads to a decrease in actuation strength and a consequent reduction in observed flow rate.

2. Materials and methods

The actuators were constructed using Nafion-117 films obtained by casting 150 ml of a 50% vol. mixture of dimethylformaide (DMF), purchased from Sigma and used as received, and a 5% Nafion-117 solution of saturated alcohols, also obtained from Sigma, in a 9 cm diameter circular-flat bottom mould. The electroding was performed using either platinum or polypyrrole (Ppy).

When platinum was used, the procedure for electroding the Nafion film was the same reported previously [6]. The surface of Nafion-117 was roughened using sand paper and sonicated for 15 min in Milli-Q water to remove any residues. The film was then swollen by boiling it first in HCl 2 M (from Riedels de Häen) for 30 min, which also saturates the Nafion-117 with H^+, followed by boiling in Milli-Q water for 30 min Finally the Nafion-117 film was placed in a solution containing 2 mg of Pt(II)/ml ions overnight to allow the platinum cations to penetrate the ionic polymer. This solution was prepared using $[Pt(NH_3)_4]Cl_2$ in water. The total volume of solution was calculated so that there was 3 mg of Pt per cm^2 of membrane area. The platinum cations trapped in the Nafion-117 were then chemically reduced to Pt^0 using $NaBH_4$ (5%, w:v solution). To ensure optimum conductivity of the Pt electrodes, a second electroding was performed by reducing more Pt(II) (also from a 2 mg of Pt/ml solution prepared using $[Pt(NH_3)_4]Cl_2$ salt) on the existing Pt^0 electrodes using hydrazine (5%, w:v solution) and hydroxylamine hydrochloride (20%, w:v solution). The IPMCs constructed in this fashion were stored in LiCl 2 M for 3 days, to saturate the sulfonic groups of the Nafion-117 with Li^+, which was previously shown to produce stronger IPMCs [7].

When the electrodes were formed using polypyrrole (Ppy), the polypyrrole was synthesised by chemical oxidation of pyrrole on the Nafion film using a procedure reported previously [8]. A Nafion-117 film was pre-treated as above, i.e. it was first roughened using sandpaper and then sonicated for 15 min in Milli-Q water. The Nafion-117 film was then boiled in HCl 1 M for 30 min and in Milli-Q water for another 30 min to swell it. The polypyrrole was synthesised in situ by chemical oxidation and polymerisation. The Nafion-117 film was dipped in a 0.2 M pyrrole solution containing 0.005 M naphthalene-1,5-disulfonic acid disodium salt (NDSA) and a solution of 0.2 M $FeCl_3$ was then slowly added while constantly stirring the solution. Once all the $FeCl_3$ solution was added, the mixture was allowed to react overnight. The actuator was then washed in Milli-Q water and stored in LiCl 2 M for 3 days before use.

Two pumps were developed. Pump A was made using a soft polyurethane tube (2 cm long, 1 mm i.d.) as shown in Fig. 1. The configuration of this pump was very simple, consisting of a pump chamber (the soft polyurethane tube), a reservoir for the liquid pumped and a 1 mm i.d. hard polyurethane tube through which the fluid was pumped. The absence of valves or any other method of control of the direction of the flow resulted in no overall flow movement; however, this set-up permitted to evaluate the pump itself. Pump B was made using a PDMS tube (1.5 cm long, 6–7 mm i.d. and 100 μm thick walls) as shown in Fig. 2. The configuration of this pump consisted of a pump chamber (the PDMS tube), and conical inlet and outlet (made using 0.5–20 μm

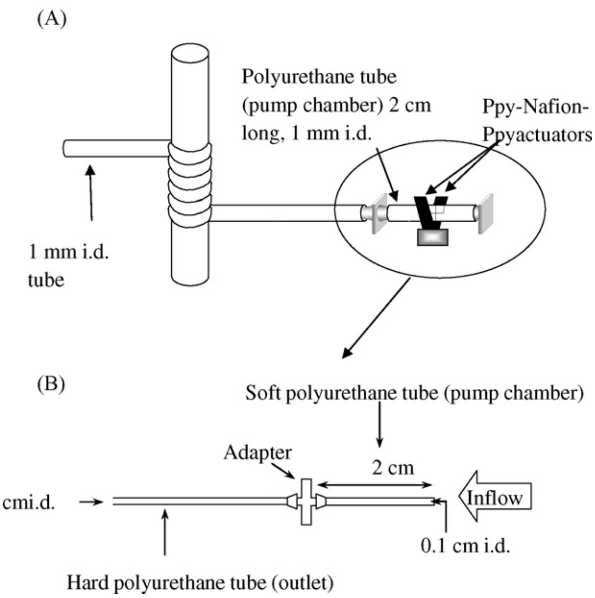

Fig. 1. (A) Diagram of the biomimetic pump constructed using a 1 mm internal diameter polyurethane tube as pump chamber (pump A). (B) Schematics with dimensions of pump A.

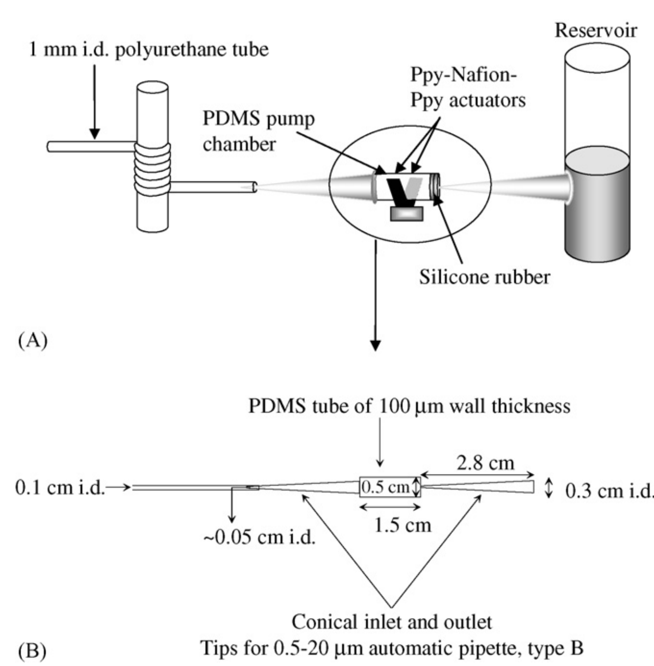

Fig. 2. (A) Diagram of the biomimetic pump constructed using a PDMS tube as pump chamber (pump B). (B) Schematics with dimensions of pump B.