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Design and characterization of low power, low dead volume electrochemically-driven microvalve

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ABSTRACT

We report here, the design and characterization of a low power, low dead volume electrochemically driven micro valve. The valve can be operated with AAAA battery (0.125 mA-h/actuation at 1VDC) and is portable enough to fit inside a drug delivery device (size ~18 mm × 18 mm × 13 mm). The electrochemical nature of the actuator allows for precise control of the valve diaphragm just by controlling the actuation voltage. The initial prototype is shown to withstand backpressure up to 5 psi, and is stable for more than 10 h of continuous operation. Three different design iterations are discussed with progressive improvement in terms of power and actuation time. The valve design and choice of material allows it to be mass manufactured by molding and easily sterilizable.

1. Introduction

Valves and pumps are the backbone of all the fluidics related instrumentation, both in macro or micro scale. While the valve technology is quite mature and sophisticated in macro-scale [1–3], corresponding development in microscale is still faced with considerable hurdles. Actively controlled miniaturized valves [4] are required in microfluidic systems, and there is a simultaneous need for time controlled actuation, reduction of power, reduced overall size and minimum dead volume. The challenge of designing a valve that can address all these requirements in a single micro-scale embodiment is formidable, as tackling any one of these attributes generally requires a tradeoff in the other.

Fully automated microfluidic systems are becoming very popular. Thanks to astounding developments in the areas of MEMS [5,6], microelectronics and lab-on-chips [7–12], valves have been miniaturized to a great extent. Nevertheless, there is still an unmet need for a microvalve design and development that meets together the desired attributes of low cost of manufacturing, low power requirement, reliable operation, low dead volume and easy integration with other subsystems. Moreover, when these valves are used in biomedical devices [13,14], additional requirements like wetted parts compatibility with drug/biofluid, sterility and stability of valve material must be considered early in the design phase.

In order to design an actively controlled microscale valve that can be used in discrete, wearable medical drug delivery applications, the following design requirements must be taken into account. These valves must be efficient enough to be run with portable power source (coin cell or other small battery) for an extended period of 3–5 days. Further requirement for the size of the valve is to fit, with all other components, within a footprint of approximately ~40 mm diameter × 14 mm thickness (entire drug delivery device with onboard electronics, drug reservoir, and pump and delivery mechanisms) and it should be able to withstand a pressure of 0–5 psi with minimal dead volume possible. Though a passive valve [15] can ameliorate the requirement of power, most of the time it cannot be used in drug delivery device mainly from safety point of view. Passive valves also suffer from other problems like (a) variability in cracking pressure (b) additional pressure required to crack open the valve has to be generated by the pump and (c) susceptibility of valve actuation to sudden pressure gradient that can be generated due to changes in external environment. Furthermore there are design challenges that are present in form of size and shape restriction for extremely portable devices. There are a wide varieties of active valve technology available like piezoelectric, thermal, magnetic field, pneumatic, solenoid driven, shape memory alloy and others, and many of them can and have been miniaturized to fit the above requirement. However in this paper, we present a different technology to actuate these micro valves that can address the above design challenges and will discuss the major advantages (shape, size, low power, stable operation, low dead volume etc.) for using this technology for valve actuation. SFC Fluidics has licensed the ePump® electrochemical pumping technology [16]

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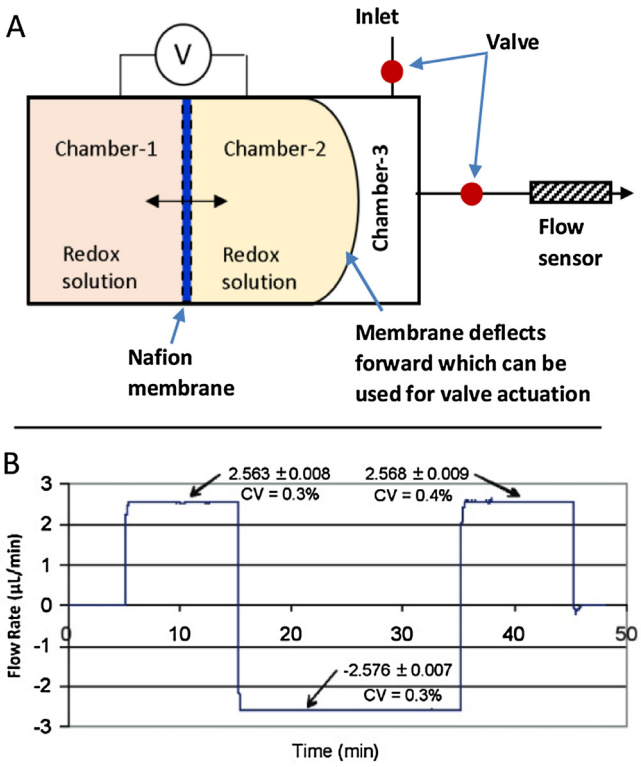

Fig. 1. (A) Illustration of working principle of electrochemical actuator. (B) Typical flow obtained from electrochemical actuator, when used as a pump, showing uniformity in diaphragm movement. The positive flow of 2.56 µL/min is obtained when 1VDC is applied through two mesh electrodes in chambers separated by Nafion membrane. The flow is reversed when the direction of applied potential is reversed.

from University of Colorado, and has improved and fine-tuned the technology to adapt it to a micro valve.

2. Materials and method

2.1. Principle of electrochemical actuator

Electrochemical actuation described here is based on SFC Fluidics' well-established ePump technology [16–19]. Briefly, the actuator has two primary chambers (Fig. 1A) containing a redox couple in solution. The volume of the solution is defined by the required actuation volume of the valve cycle. The diaphragm, which can be made of a flexible elastomer, serves as an impermeable barrier between actuating solution and the fluidic line. Power requirement for this electrochemical actuator is 0–1.5 V, typically obtainable from an inexpensive dry cell battery. The current consumption will depend on the size of the valve and required speed of operation, but ranges from 0 to 200 mA. As electric potential is applied across the semipermeable membrane via mesh electrodes submerged in redox solution, solvated ions will pass through the Nafion (from chamber # 1) and increase the volume of destination chamber # 2. This increase in volume moves a flexible membrane constituting the distal wall of the chamber, essentially converting the electrochemical to mechanical energy. The rate of movement of this solvated ions and thereby the movement of flexible membrane can be controlled to a precise level by controlling the current or voltage applied. The reaction is reversible and application of voltage in opposite direction will lead to movement of fluid back to chamber #1 from chamber 2. The actuator chambers were machined from poly(etheretherketone) (PEEK). The electrode material is platinum, bought from Alfa Aeser. The gaskets to seal the assembly as well as the expansion diaphragm were made of Viton or Chemraz/Kalrez,

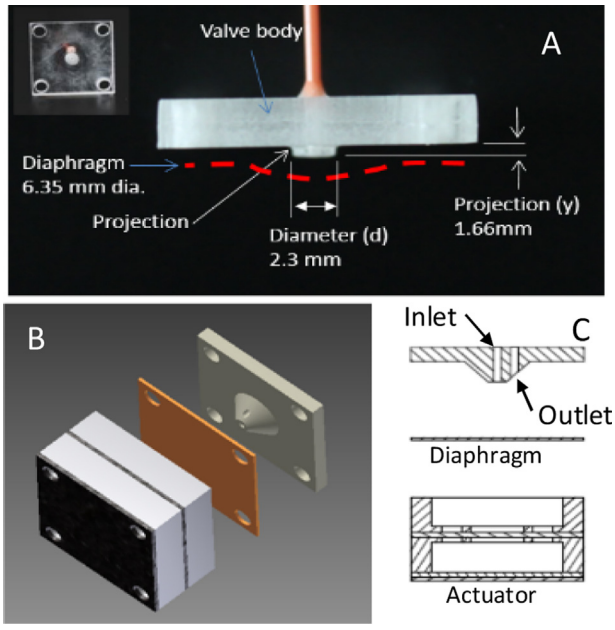

Fig. 2. (A) Valve seat for normally closed valve design. (B) Assembly drawing for valve. (C) 2D drawing for slightly modified valve seat (~120°).

bought from Green Tweed. The semipermeable membrane used is Nafion 117, bought from Dupont. Fig. 1B shows the typical flow obtained from electrochemical actuator when used as a pump. Sensirion flow sensor after the valve is used to measure the flow. An additional chamber (#3) is attached to the right end of the system (Fig. 1A), which serves as temporary reservoir for the user fluid. The fluid will be first pulled in from the inlet line (membrane travels from right to left due to reverse applied voltage) and consequently pushed out through the outlet line (membrane travels from left to right due to forward applied voltage), both of which are controlled by external valves. The high accuracy and precision obtained from these actuators can advantageously be used to operate a diaphragm valve with very tight tolerance and very low dead volume. The actuator used for this paper had a low flowrate. However the actuator design is flexible and flowrate is dependent on the cross section of semipermeable membrane and voltage applied. The actuator design can be easily changed to increase or decrease the flowrate and hence the actuation time of the valve.

2.2. Material for test and fabrication of valve

In this study, the valve body was made of poly(methylmethacrylate) (PMMA). The parts were initially machined for prototype development, but the design was chosen so as to allow mass manufacturing. Alternate elastomeric membrane tested for valve performance were bought from McMaster Carr. The initial control system was developed using Labview to control a benchtop power supply (Keithley 2400). Dual pressure controllers were bought from Alicat (PCD series) and Omega (PRG101). The pressure sensors were bought from Omega (PX309-005GV). Laser sensor for monitoring the position of diaphragm was bought from Aquity (AR2000). The flow sensors (0–55 µL/min, bidirectional, LG16-480) were bought from Sensirion. Syringe pump (Elite 11) was purchased from Harvard Apparatus and fluidic connectors were from Idex. Glass syringes (100–250 µL volume) used in the syringe pump were bought from SGE. The valve is essentially the electrochemical actuator with a valve seat (contains both inlet and outlet lines) designed on top of the deflection membrane. Depending on the design of the valve seat, the valve can be either normally closed (NC) or normally open