CENTIMETER-SCALE HIGH PRESSURE VESSEL PNEUMATIC POWER SOURCE

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Abstract: This paper reports the first use of carbon-fiber composite Centimeter-Scale High Pressure-Vessel (CSHPV) used to MEMS actuators. The design, fabrication and testing of microsystem compatible CSHPV and valves with pneumatic energy densities exceeding those of the traditional lithium battery and electromechanical actuator combination is presented. The pneumatic power sources can provide direct mechanical power to move mechanical elements, enabling pathway for near 100% efficient operation. The 1-2 cc pressure vessels with burst pressures as high as 3250 bars were achieved corresponding to an energy density of 20.5Wh/Kg, comparable to 50Wh/Kg of Lithium batteries with similar volumes. A microfluidic interface from the CSHPV was realized using glass capillaries that provides pathway to deliver fluidic power to microactuators. Electromagnetic coil valves were used to control CO_2 flow from 10-20 micron diameter glass capillaries that could actuate surface micromachined polysilicon micromotors.

Keywords: pressure vessels, pneumatic energy, micromotors, microsystem

INTRODUCTION

The overwhelming actuation paradigm in MEMS is to convert electricity to mechanical motion using electrostatic, piezoelectric, and thermal, among other transduction mechanisms. The conversion efficiency of electrical to mechanical energy can be high for macro-scale engines, but at MEMS scale few actuator mechanisms are greater than 10% efficient, due to high voltage or current needed, and greater internal friction forces at the microscale. While electrostatic and electromagnetic actuators remain popular in MEMS, analysis shows that fluidic actuators develop higher force and power density at the microscale [1]. Examples of various actuators using varying degrees of pressurized air/liquid as a power source as classified in [1]:

- Elastic Membrane Actuators: Elastic or flexible actuators comprise at least one component that deforms elastically under the applied pressure [2,3].
- Piston fluidic actuators: While piston cylinder mechanism is challenging to fabricate on a micro scale due to low friction sealing requirements, they are not entirely uncommon[4,5].
- Drag based fluidic actuators: They make use of drag force between the fluid and the actuator [6,7].

Applications for these actuators exist in fields ranging from microfluidics and bioMEMS to microrobotics. While these actuators are gaining popularity, cm-scale power-sources that generate high pressure and can be used with these actuators do not exist.

In this paper we introduce a unique design for realizing a MEMS compatible centimeter scale high energy density power source using composite overwrap pressure vessels and valves with energy densities exceeding those of traditional lithium battery and electromechanical actuator combination (Fig.1). Pneumatic power sources are an attractive alternative to conventional battery at small scale due to several reasons. Firstly, pneumatic power sources can have comparable energy density to lithium batteries partly made possible by advances in composite technology achieving unprecedented strength to weight ratios[8], and partly due to near-100% conversion efficiency of stored mechanical to actuator energy. Secondly, the stored energy can be released very quickly or very slowly spanning a wide range of operation on the power density to energy density chart as shown in Figure 1. Thirdly, they are potentially high and low temperature compatible as chemical reactions are not required for operation making them suitable for applications involving harsh environments.

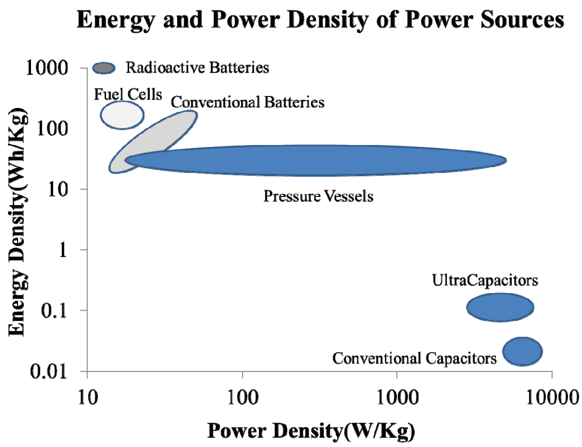

Figure 1. Chart showing the relative merit of various power sources. As can be seen pressure vessels not only having high energy density, but also a wide range of operation for power density due to flexibility in discharge rates.

The remainder of the paper is structured as follows. In the next section we describe the theory and experimental results of CSHPV, flow control using capillary based valves of CSHPV and actuation of micromotor, followed by conclusions.

CSHPV

Theory

Burst pressure of a composite wrapped pressure vessel with a metal liner bursting under hoop stress is given by [9]:

$$P_{burst} = \frac{\sigma_{metal}}{r} t_{metal} + \frac{\sigma_{composite}}{r} t_{composite} \qquad (1)$$

Where σ refers to the ultimate tensile strength of the material, t and r refer to the thickness and radius respectively. While high strength, lightweight aluminum liners can have ultimate tensile strength of 100,000 psi[10], current state of the art carbon composites have an ultimate tensile strength exceeding 1,000,000 psi[8] enabling significant increase in burst pressures with little increase in the composite thickness. Energy density of the vessel is approximately given by:

$$\text{Energy density} \sim \frac{PV}{Weight}. \qquad (2)$$

Figure 2 shows a plot of theoretical burst pressures and the peak energy density versus the composite thickness for a 1-cc volume aluminum liner and TORAY-T1000G carbon overwrap shown in Figure 3. As can be seen the energy density exceeds the lithium battery and electromechanical actuator combination at about 3000 bar.

Flow rates from such high pressure vessels can be significantly high depending on the size of the opening of outlet. Manageable flow rates can be obtained by having small size capillaries as an outlet for the flow. These capillaries provide significant resistance to flow and also serve to reduce the force required to regulate airflow. The flow rate through a tube of radius R and length L for compressible flow is proportional to the fourth power of the radius and can be expressed using Hagen–Poiseuille equation as follows:

$$\text{Flow rate} = \frac{\pi R^4}{16\eta L} \frac{P_i^2 - P_o^2}{P_o} \qquad (3)$$

where P_o and P_i are the inlet and outlet pressures and η is the kinematic viscosity. Constant flow rates can be obtained with gases that liquefy at high pressure. This is due to the fact that as the gas escapes, it is immediately replaced by evaporating liquid keeping the pressure constant. Carbon dioxide (CO_2) is an example of a gas that liquefies at 70 bar at room temperature which enables the flow rate to be constant with time. Figure 4 shows the plot of flow rate as a function of time for various capillary sizes from a 1-cc vessel containing 1 gram of CO2. The flow rate decays

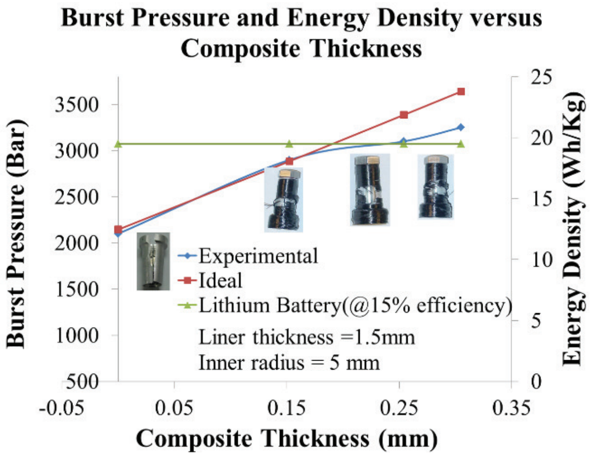

Figure 2. Burst pressures obtained for various composite thicknesses and the energy density of the corresponding vessel. The energy density exceeds lithium batteries at a pressure of 3000 bar

rapidly after all the liquid CO_2 evaporates. The flow rate as a function of time in this region can be obtained by solving (3) and can be given as:

$$\text{Flow Rate} = \frac{\pi R^4}{16\eta L} P_o \left(\left(\frac{1+ce^{-kt}}{1-ce^{-kt}} \right)^2 - 1 \right) \qquad (4)$$

where c is function exclusively of the initial pressure and k is a function of the geometry of the tube and the gas inside the pressure vessel.

To regulate the flow an electromagnetic actuator can be used. The sealing force required for a valve with typical 20 micron capillary is about 3 mg/atm which can easily be achieved with mini magnetic actuators [11].

Experiments

CSHPV was fabricated using high strength to weight Aluminum-7068 alloy as a liner and TORAY T-1000G Carbon fiber as an overwrap. Figure 3 shows the schematic and the pressure vessel with several wrapped layers. The liner was designed to provide a burst pressure of 2000 bar without any overwrap. The cylindrical design enables ease of manufacturing and subsequent wrapping. Threads were included on both sides to facilitate filling of high pressure fluid and controlled release. The liner was designed with an inner diameter of 0.4 inches and an inner volume of 1cc, and the weight being 8 grams. Several layers of the T1000G composite were wrapped in a helical pattern providing strength in the hoop direction. Composite was wrapped using custom made McCLEAN ANDERSON® filament winding machine. A 55%:45% mixture of EPON™ Resin 825 and Huntsman Jeffamine® T-403 was used as a resin. The composite was wrapped and hardened by curing the resin at a temperature of 250°F for 3 hours. The burst pressure of each of these vessels was tested using a NOVASWISS® handpump system rated upto 7000 bar.

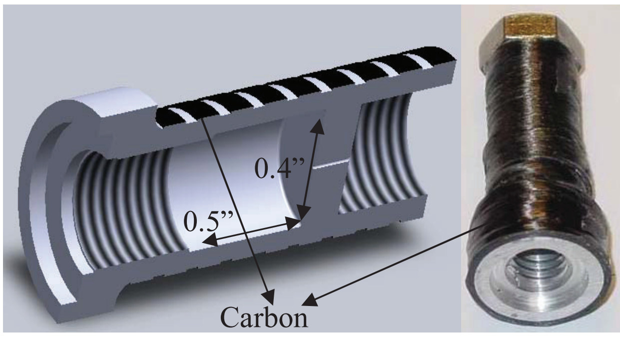

Figure 3. Pressure Vessel Left: A schematic cut section of the pressure vessel showing the chamber and wrapping of Carbon fiber. Right: A wrapped vessel.

The experimentally observed burst pressure as a function of various composite thicknesses is shown in Figure 2. As can be seen from Figure 2, as we increase the composite thickness, the burst pressure does not proportionately increase. Reasons behind this mis-match include the possibility that the assumption of the failure mode to be under hoop stress was violated. As can be seen in Figure 2 the failure mode was a more complicated case of inelastic shear. Another contribution might be due to insufficient bonding between layers of composite.

A microfluidic channel was formed using a micro-drill to incorporate glass-capillaries that provided high resistance so that a small silicon magnetic actuator with hand-wound coil could open and close the flow in continuous or pulsed mode. The capillary was designed to be about 1m in length winding around the pressure vessel and delivering the gas into a hermetically sealed chamber with a magnetic valve (Fig. 5). The outer diameter of the capillary was 350 microns and was chosen to impart sufficient rigidity to the capillary to withstand the force from the valve and not buckle. The normally-closed valve sealing force was 0.1 μN/μm^2/bar with 5-10 mW of opening power consumption. A rubber elastomer was used to effectively seal the contact between the actuator and the capillary.

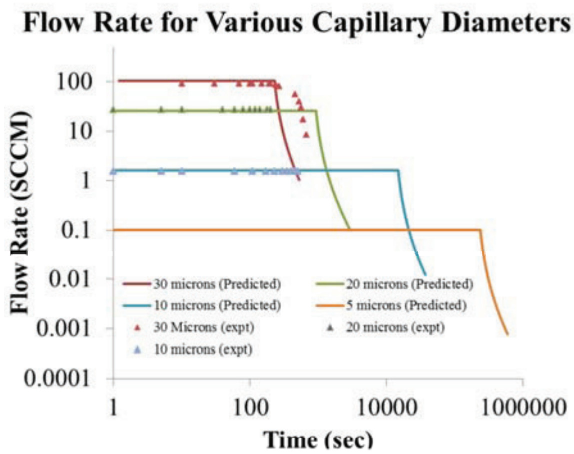

Figure 4. Flow rate as a function of time for 1 gram carbon dioxide in 1-cc vessel for various capillary sizes. Lines represent the predicted flow rate for various diameters. As can be seen flow rate falls rapidly with radius leading to several days of operation for smaller diameter capillaries.

The pressure vessels were filled with solid CO_2 and sealed. The pressure vessel maintains a pressure of about 65 bars at room temperature, the liquefaction pressure of liquid CO_2. The flow rate (Fig. 4) remains constant till the pressure is above liquefaction pressure as the liquid CO_2 vaporizes to keep the pressure constant, and decreases rapidly after all the liquid CO_2 vaporizes. Energy release is controlled by the capillary microfluidic resistance. We have used this controlled force to actuate a MUMPS-fabricated Polysilicon surface micromachined rotor (Fig.6) [12]. Using a 5-micron ID capillary, continuous operation over four days is expected. Using a piezoelectric actuator with a lithium battery, with a 10mW operation would have required a 360 cc lithium battery.

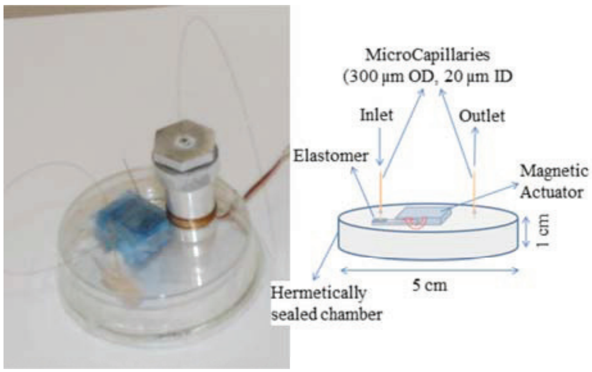

Figure 5: Capillary emerging from the pressure vessel and into the hermetically sealed chamber with magnetic actuator for flow control. Right: Enlarged schematic view of the chamber and magnetic valve.

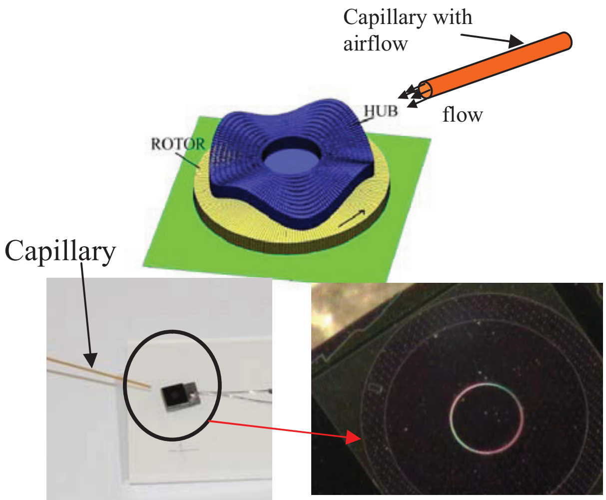

Figure 6. Top: Schematic of Airflow from a pressure vessel being directed to drive a micromotor (not to scale). Bottom right: A micromotor being air driven. Left: An enlarged view of the micro motor with rotor and hub.

CONCLUSIONS

This paper examines the technology components for MEMS compatible pneumatic power sources. It demonstrates all the necessary components for long lasting portable pneumatic power source that can be readily integrated with existing fluidic actuators. Over the last 20 years, numerous fluidic actuators have been developed, many with higher force and power density compared to the more common electrostatic, thermal and piezoelectric actuators. Despite these promising properties, pneumatic and hydraulic actuators are still often overlooked in MEMS partly due to the fact that additional elaborate infrastructure is needed to realize full functionality of these actuators. By shrinking the pneumatic power source to a centimeter scale and keeping the energy density comparable to that of Lithium batteries, current work leads us towards realizing the benefit of pneumatic actuators as easily as electrostatic or piezoelectric actuators.

FUTURE WORK

While current work has valves that are completely external to the pressure vessel, additional compactness can be achieved by placing the valves entirely internal to the pressure vessel. It would also be better suited for applications requiring high pressures. Current valves are low frequency valves. Some applications might require operation at higher frequency. Keeping these applications in mind we would like to work towards internalizing the valve and providing the capability of high frequency operation.

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