MECHANICAL AND THERMAL MODELING OF A PARYLENE ELECTROTHERMAL VALVE FOR MAPPING BRAIN FUNCTION IN FREELY MOVING SUBJECTS

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ABSTRACT

Mechanical and thermal modelling of the first normally-closed Parylene valve operating on electrothermal principles for rapid and wireless drug delivery was investigated. The modelling and experimental results confirm the mechanical robustness of the valve membrane. Valve opening behavior obtained by transient thermal finite element analysis are in accordance with the experimental microscopic images.

KEYWORDS: Parylene, Electrothermal valve, Neuroimaging, MIP

INTRODUCTION

A low power, fast response normally-closed Parylene valve operating on electrothermal principles for rapid and wireless drug delivery was developed to be used in an implantable microbolus infusion pump (MIP) for neuroimaging in freely-moving untethered animals [1]. Functional brain activation is achieved by rapid MIP injection of radiotracer into the circulation following the desired behavioral event, euthanasia administration, brain retrieval, autoradiographic imaging of brain slices, and 3D image reconstruction. Previously, normally-closed electrothermal valves have been developed but only one is suited for implantable drug delivery [2]. This valve consists of a resistive metallic membrane (Pt/Ti/Pt) suspended over a drug reservoir that opens when an applied current melts the membrane (Fig. 1). Here, a Parylene C/Pt composite membrane is used as our valve material to significantly reduce power consumption since Parylene C can be thermally degraded at much lower temperature (125-200°C) and can form large membranes for larger effective valve opening area (330-500 μm).

THEORY

Our valve consists of a platinum resistive element embedded in a flexible Parylene C membrane (10 μm) (Figs. 1a and b). The valve is situated in the lumen of a catheter and two contact pad flaps are wrapped along the catheter for connection to control circuitry (Fig. 1c and d). RF power remotely triggering the valve is applied to initiate Joule heating to thermally degrade or melt the Parylene membrane. When the electrical and mechanical connections are broken, the pressurized reservoir drives rapid release of fluids through the catheter and into the circulation.

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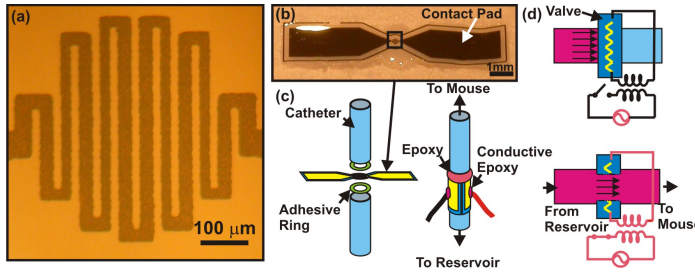


Figure 1. Parylene MEMS electrothermal valve: (a) close-up view, (b) device view, (c) assembly process, (d) operation principle

EXPERIMENTAL

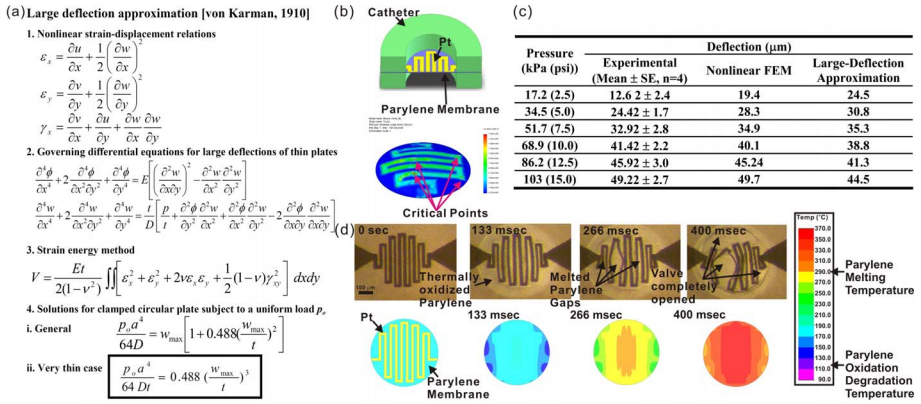
The Pt element and membrane design must account for instantaneous peak pressure from the reservoir (1 atm); their mechanical performance was verified using both large deflection approximation (Parylene only) and nonlinear finite element modeling (FEM) (Parylene/Pt/Parylene) (Fig. 2). Large deflection theory provides a simplified model to investigate the mechanical performance of the Parylene vavle (Fig. 2a). In nonlinear FEM, a circular clamped Parylene/Pt/Parylene composite membrane was subjected to uniform applied pressure (2.5 to 15 psi) (Fig. 2b) and the membrane deflection and stress distribution were obtained. These results were then verified in benchtop experiments. Transient thermal FEM of valve operation was simulated with a 6 mA applied current and thermal contour plots were captured every 133 msec. An experimental comparison was also obtained for the same conditions.

RESULTS AND DISCUSSION

The nonlinear mechanical model indicates the maximum stress of the Pt element under 1 atm pressure (peak under normal operation) was 1.53GPa which is less than its tensile strength (1.83GPa); the electrical connections are expected to survive pressurized conditions during radiotracer loading. Critical stress points in the membrane were identified in the stress distribution diagram. The nonlinear FEM model shows good agreement with load deflection experiments (composite membrane) demonstrating the mechanical robustness of the valve to the operating conditions for the neuroimaging application (Fig. 2b).

Valve opening depends on thermal events which were simulated and captured using time sequence microscopy(Fig. 2c). At 133 msec, a circular thermally oxdized Parylene area was visually observed. The transient FEM results indicated that the majority of the valve area reached over 125°C, thermal oxidation initiation temperature of Parylene. At 266 msec, Parylene began melting and small openings between Pt thermal elements formed and the Parylene melting temperature of 290°C was reached in the central region in FEM. By 400 msec, the valve opening was nearly complete and most of the valve area exceeded the Parylene melting temperature in FEM simulation. Both the expeimental and the transient FEM modeling images demonstrate the valve opening mechanism. However, to achieve complete valve

opening, the entire valve area must exceed the Parylene melting temperature. A more efficient design is underway in which the Pt trace geometry is modified to obtain lower power consumption, higher opening efficiency, and higher heat transfer efficiency into Parylene membrane instead of the surrounding packaging and fluid.



Pressure (kPa (psi))	Deflection (μm) Experimental (Mean ± SE, n=4)	Nonlinear FEM	Large-Deflection Approximation
17.2 (2.5)	12.6 2 ± 2.4	19.4	24.5
34.5 (5.0)	24.42 ± 1.7	28.3	30.8
51.7 (7.5)	32.92 ± 2.8	34.9	35.3
68.9 (10.0)	41.42 ± 2.2	40.1	38.8
86.2 (12.5)	45.92 ± 3.0	45.24	41.3
103 (15.0)	49.22 ± 2.7	49.7	44.5

Figure 2. Modeling and experimental results: (a) equations for large deflection approach, (b) FEM model and results (deflection and stress distribution), (c) comparison of mechanical modelling and experimental results, and (d) experimentally obtained microscope images compared to transient thermal modeling.

CONCLUSIONS

We successfully developed a disposable, low-power Parylene C MEMS valve to enable new neuroimaging approaches. The modeling and benchtop characterization were performed and compared. Mechanical modeling demonstrated valve robustness to operation under 1 atm peak pressure. The themal modeling results suggest an improvement to lower power consumption by redesigning the Pt trace. Also, additional experiments will evaluate the performance of the valve in the presence of the radiotracer agent and *in vivo* in preparation for neuroimaging experiments.

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