DESIGN OF A VALVELESS THERMOPNEUMATIC MICROPUMP WITH EFFECTIVE PARAMETERS ON ACTUATION

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ABSTRACT

A valveless micro pump with thermo pneumatic actuation is designed analytically with two different circular diaphragms for a micro total analysis system and medical applications. The flow rate is about 236 nano liter/stroke with maximum deflection of 10 µm for a flat diaphragm. The same final temperature and flow rate can be achieved with smaller maximum deflection, if the flat diaphragm is replaced by a diaphragm with rigid center.

KEY WORDS: micro pump, thermo pneumatic, diaphragm with/without rigid center, compressible flow

INTRODUCTION

Microfluidics deals with design and development of miniature devices which can sense, pump, mix, monitor and control small volumes of fluids. Principal applications of microfluidic systems are for chemical analysis, biological and chemical sensing, drug delivery, molecular separation such as DNA analysis and amplification.

A typical micropump is a micro electromechanical system (MEMS) device, which provides the actuation source to transfer the fluid (drug) from the drug reservoir to the body (tissue or blood vessel) with precision, accuracy and reliability. A review of MEMS-based micropumps in drug delivery and biomedical applications are given by Nisar et al. [1]. A number of different micropump designs based on silicon microfabrication techniques have been presented over the last two decades [2-4]. A detailed review of these micropumping technologies was compiled very recently [5]. In general, micropumps can be classified as either mechanical or non-mechanical micropumps [6]. Mechanical type micropump needs a physical actuator or mechanism to perform pumping function. The mechanical micropumps with vibrating diaphragms [7,8] have generated the most interest. The most popular mechanical micropumps discussed here include electrostatic, piezoelectric, thermopneumatic, shape memory alloy, bimetallic, ionic conductive polymer film, electromagnetic and phase change.
Micropumps found today can be divided into two groups with and without valve. Number of critical properties like backward flow, pressure drop, slow response time and switching speed has to be kept under tight control to achieve a working micro pump. Moreover, wear and fatigue can be a critical issue, especially in polymer fabricated devices. There is also the risk of valve blocking and fluid leakage by even small particles which instantly degrade the pumping performance. These limit the application range of most valve-based micropumps to filtered media, but the valve less micropump concept can avoid these problems [12].

This paper presents a valveless micropump with thermopneumatic actuation for medical applications. A circular diaphragm with and without rigid center are designed analytically and compared. The effective parameters in actuating diaphragm are discussed.

PRINCIPLE OF OPERATION

Fig.1 represents the conceptual operation of a valveless thermopneumatic micropump. One method to drive an actuator is to use the thermopneumatic principle. A cavity encloses air as the working medium. The cavity forms a closed thermodynamic system. That ideally means no exchange of substances but exchange of energy with environment. An electric heater is implemented in the cavity. By switching on the heater, it dissipates electric power and leads to an increase of temperature in the chamber. Therefore, to refit the thermodynamic equilibrium, the pressure of the air cavity rises. Turning off the heater, the cavity is cooled down. Hence, the cavity pressure relaxes. That way, periodically heating of the air leads to a cyclic pressure change in the cavity.

If one border of the cavity is flexible, a changing pressure is able to move that border, and thus, to displace a certain volume of fluid in an opposite pressure cavity. A fluid channel under the pressure cavity then performs the transport of that displaced fluid. This configuration forms a thermopneumatic volume actuator. These pumps utilize the different pressure drop characteristics of flow through the nozzle and diffuser to direct the flow in one preferential direction. For example in the expansion mode, as the volume of the pumping chamber increases, more fluid enters the pumping chamber from the element on the left which acts like a diffuser (and hence offers less flow resistance) than the element on the right, which acts like a nozzle. On the other hand, in the contraction mode, more fluid goes out of the element on the right which now acts as a diffuser, while the element on the left acts as a nozzle. Hence, net fluid transport is achieved in the pumping chamber from left to right.

HEATING ELEMENT

There are four different concepts for heating the actuator cavity.
1. A copper heater is directly placed on the membrane (thickness 500 nm). To form the heater, the membrane is coated using thin-film technology (sputtering), photo-
lithographically patterned and wet-chemically etched. Because the electric connection of the heater is realized outside the cavity, the heater requires insulation.

2. A commercially available Constantan heater wire (70 µm in diameter) is mounted on the bottom of the actuator cavity by manually threading it through small holes and sealing the holes with epoxy. The two ends of the Constantan wire are soldered on copper pads.

3. A heater is formed by direct use of the patterned copper of a circuit board (thickness 25 µm). The patterning of the heater on the circuit board is done by photo-lithography and wet-chemical etching.

4. A cantilever polymeric carrier coated with Constantan (500 nm Constantan on 8 µm Kapton) is soldered on its two ends on the bottom of the actuator chamber. The Constantan is deposited on the Kapton membrane using thin-film technology (sputtering). Subsequently, the Constantan film is patterned by photo-lithography and wet-chemical etching. After mounting the patterned Constantan-coated membrane on the circuit board by soldering it on copper pads, the remaining uncoated parts of the membrane are removed by using plasma etching (processing gases: CF₄ and O₂). This is possible due to the resistive effect of metallic structures in this plasma etching process. After these steps a released heater (cantilever) is the result.

![Fig. 1 Schematic of a thermo pneumatic micropump and the thicker arrows imply higher volume flow rates.](image)

**PHYSICAL MODELING OF MEMBRANE**

The relation between deflection and back pressure of a flat circular diaphragm with rigid centre is [13]:

\[
P_\infty = \frac{1}{A} \times \frac{Et^3}{R^4} \delta + B \frac{Et}{R^4} \delta^3
\]

where

\[
A = \frac{3(1-\nu^2)}{16} \left[ 1 - \frac{b^4}{R^4} + \frac{b^2}{R^2} \log \frac{b}{R} \right]
\]

\[ (1a) \]

\[ (1b) \]
\[
B = \frac{7 - \nu}{3} \left( 1 + \frac{b^2}{R^2} + \frac{b^4}{R^4} \right) + \frac{(3-\nu)^2 b^2}{1 + \nu \frac{R^2}{b^2}}
\]

\[
(1-\nu)(1-\frac{b^4}{R^2})(1-\frac{b^2}{R^2})^2
\]

where \( t \) is the thickness, \( b \) and \( R \) are the radius of the membrane with and without centre rigid. \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio, respectively. \( \delta \) is the deflection of the membrane's centre. Tachung et al. [14] proposed \( b / R = 0.625 \).

Beams et al. [15] also proposed the following equation for the back pressure of the membrane as:

\[
P_m = \frac{4t\sigma}{R^2} \delta + \frac{8tE}{3(1-\nu)R^2} \delta^3
\]

\( \sigma \) presents the intrinsic tension of the membrane caused by the clamping process. The pressure in the cavity is

\[
P_c = P_m + P_{\text{atm}}
\]

where \( P_c \) is the pressure of the cavity. In an ideal situation, pressure of the reservoir must be at least one atmosphere to have pumping action.

Referring to Fig.1, the shape of the deflected diaphragm is assumed to be fitted by the following polynomial as:

\[
y = ar^3 + br^2 + cr + d
\]

Under the following boundary conditions:

\[
y(0) = \delta \quad (5a)
\]

\[
y(R) = 0 \quad (5b)
\]

\[
\frac{\partial y(0)}{\partial r} = 0 \quad (5c)
\]

\[
\frac{\partial y(R)}{\partial r} = 0 \quad (5d)
\]

The diaphragm shape is as:

\[
y = \delta \left[ 2 \left( \frac{r}{R} \right)^3 - 3 \left( \frac{r}{R} \right)^2 + 1 \right]
\]

The cavity volume expansion due to the heating yields:

\[
\Delta V_c = \int_0^R 2\pi rydr = 0.3\pi \delta R^2
\]
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Combining the above equations and assuming ideal gas behavior for the air, the final temperature of the air in the cavity will be:

\[ \frac{T_c}{T_{co}} = (1 + \frac{P_m}{P_{atm}})(1 + 0.33\frac{\delta}{h}) \] (8)

where \( h \) and \( T_{co} \) are the height and initial temperature of cavity respectively.

Taking into account the thermal effects on physical and mechanical properties of the membrane, the cavity temperature is obtained by multiplying the value of deflection with sensitivity factor defined by [13] as:

\[ S = 1 - \frac{1 + \alpha \Delta T}{1 + C_E \Delta T} \] (9)

\[ E = E_0 (1 + C_E \Delta T) \] (10)

where \( \Delta T = T_c - T_{co} \), \( \alpha \) and \( C_E \) are thermal expansion and modulus elasticity coefficients.

Heating Element: Applying the first law of the thermodynamics to the cavity as a system yields:

\[ \delta Q = \Delta E + \partial W \] (11)

where, \( \delta Q \), \( \Delta E \) and \( \partial W \) are the heat generated by the heating element, change of internal energy and the work done by the system. The work done by the system consists of two parts. One part is related to push away the surrounding air and the other one is associated with the elastic of the diaphragm. In this case the heat generated is equal to:

\[ \delta Q = mC_p \Delta T + (P_m + P_{atm})\Delta V_c \] (12)

where \( m = (P \partial V / RT)_{co} \).

If the working frequency of the diaphragm to be \( f \) Hz, the electrical resistance required to heat up the heater will be:

\[ R = \frac{V^2}{fQ} \] (13)

RESULTS AND DISCUSSION

To observe the displacement behavior of a dynamically moving actuator membrane, a LASER displacement meter (KEYENCE LK-031) can be focused on the centre of the membrane. The exciting of the actuator’s heater and the recording of all measured data will be done by using a PC including LabView software with AT-MIO-16XE-50 as a data acquisition.

A cavity with radius of \( R=5 \) mm and height \( h=800 \) µm includes a membrane with thickness \( t=8 \) µm with physical properties of \( E=3 \) Gpa, \( v=0.4 \) and \( \sigma=5 \) Mpa. It is assumed that the micropump diaphragm is made of polyethylene terephthalate with
deflection of $\delta = 200 \, \mu m$ at the diaphragm centre. The initial temperature and pressure of the cavity air are assumed to be $T_{co} = 308^\circ k$ and $P_{co} = 1.013 \, \text{bar}$ respectively. The diagram of Fig. 3 exhibits dependence of deflection on cavity temperature rise. Fig. 4 shows the centre deflection of membrane against back pressure for two models based on Eq. (1a) and Eq. (2). In the expansion mode the deflection of the membrane by Eq. (2) is higher than that by Eq. (1a) and the result is vice versa in the supply mode. Fig. 5 illustrates a typical deflection curve of an actuator measured at a steady-state. The deflection corresponds (approximately $\delta = 250 \, \mu m$) to a constantly dissipated one watt heating power.

CONCLUSIONS

A thermopneumatic micropump is designed analytically. Variation of the deflection for 5 mm radius circular diaphragm with rigid center versus final temperature of the closed air cavity is calculated. Thermal effects on physical and mechanical properties of the membrane are also taken into account. The results show that the centre deflection of the membrane is about $400 \, \mu m$ due to the cavity temperature rise of $80^\circ C$. The corresponding air flow rate in the flow channel is about 236 nanoliter.

NOMENCLATURE

\begin{tabular}{ll}
\text{A} & constant \\
\text{b} & rigid centre radius \\
\text{B} & constant \\
\text{C} & coefficient \\
\text{E} & modulus of elasticity, energy \\
\text{f} & frequency \\
\text{h} & cavity height \\
\text{P} & pressure \\
\text{Q} & heat \\
\text{r} & r-direction \\
\text{R} & membrane radius \\
\text{S} & sensitivity \\
\text{t} & membrane thickness \\
\text{T} & Temperature \\
\text{V} & Volt \\
\text{V} & volume \\
\text{W} & work \\
\text{y} & y-direction \\
\end{tabular}

Greek Letters

\begin{tabular}{ll}
\text{\alpha} & expansion coefficient \\
\text{\delta} & center deflection of membrane \\
\text{\Delta} & Difference \\
\text{\mu} & micron \\
\text{\nu} & Poisson’s ratio \\
\text{\sigma} & intrinsic tension \\
\end{tabular}

Subscripts

\begin{tabular}{ll}
\text{\atm} & atmosphere \\
\text{C} & cavity \\
\text{Co} & cavity initial condition \\
\text{E} & module of elasticity coefficient \\
\text{m} & membrane \\
\end{tabular}

REFERENCES


Fig. 2 Module of elasticity and expansion coefficient of the diaphragm versus temperature

Fig. 3 Centre deflection of the membrane versus temperature rise of the cavity
Fig. 4 Centre deflection of membrane against back pressure for two models

Fig. 5 Typical movement of an excited actuator membrane for one watt heating power