대한기계학회 2000년도 춘계학술대회논문집 B pp. 108~112 KSME 00S175

Analysis on Phase-Change Based Micro-actuator

Jae Dong Chung* and M. Kaviany**

상변화를 이용한 Micro-actuator에 대한 해석

정재동, M. Kaviany

Key Words: Micro-actuator, Phase change, Thermoelectric heating/cooling

Abstract

This paper presents a mathematical model and simulation of the micro-actuator based on thermally induced liquid-vapor phase-change in a partially-filled closed cavity. The volume expansion by liquid-vapor phase change can generate considerable forces and displacement (~50㎛) required for commercial use. For optimum operation involving many cycles within the closed chamber, active (thermoelectric) heating and cooling is used. The optimization of the system is conducted according to the parameters such as input power and response time. The optimized performance of micro-actuator is reasonable compared to other actuators.

1. INTRODUCTION

In integrated circuit-devices, in order to move or regulate the motion of fluid, relatively large displacements (of the order of 10 ㎛) are needed[1,2]. One of the methods of providing such a force-displacement is by heating an enclosed fluid thus resulting in a rise in the pressure of this enclosure (i. e. cavity)[3]. This fluid can be a liquid, a gas, or a liquid-gas mixture. In order to minimize the electric power consumption, a mixture of liquid-vapor is used. Then the heat added to this enclosed liquid-vapor mixture caused further evaporation and an increase in the cavity pressure. For quick reversal, active (thermoelectric) heating is used, and once the desired pressure is reached during heating, the current is reversed and cooling of the liquid begins. Figure 1 shows a micro-actuator design in which the thin membrane on top of cavity is displaced upon increase in the cavity pressure. This article analyzes the optimum design of micro-actuator thermally driven by phase change using thermoelectric active heating and cooling.

2. ANALYSIS

2.1 Thermoelectric Module

The thermoelectric module is a collection of p-n units with dissimilar characteristics which are connected electrically in series and thermally in parallel, so that two junctions are created[4]. Figure 1 shows the schematic diagram. There are three main contributions to the total heat flux from the device to bottom wall: Peltier heat, thermally conducted heat and Joule heat as described following[4]

* 서울대 기계항공공학부

** Univ. of Michigan

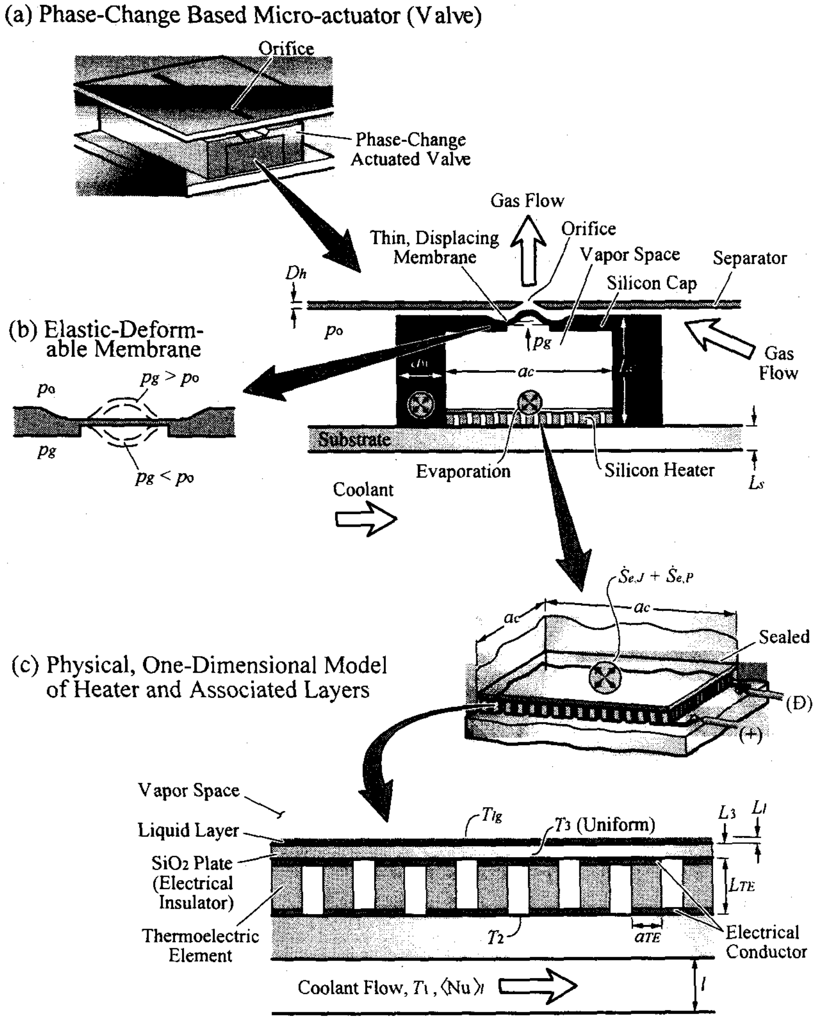

Fig. 1 A schematic of the phase-change based micro-actuator considered

$$Q_b=[-\alpha_s J_e T_b+R_k^{-1}(T_t-T_b)+\frac{R_e J_e^2}{2}]\frac{N_{TE}}{a_c\,a_c} \qquad (1)$$

$$Q_t=[\alpha_s J_e T_t-R_k^{-1}(T_t-T_b)+\frac{R_e J_e^2}{2}]\frac{N_{TE}}{a_c\,a_c} \qquad (2)$$

where the conduction and electric resistance are $(A_k k/L)_p+(A_k k/L)_n$, $(\rho_e L/A_k)_p+(\rho_e L/A_k)_n$, respectively.

2.2 Substrate

Energy conservation applied for substrate is

$$R_{ku}^{-1}(T_b-T_0)-Q_b+\frac{(\rho c_p V)_b}{a_c\cdot a_c}\frac{dT_b}{dt}+\frac{(\rho c_p V)_{Cu}}{a_c\cdot a_c}\frac{dT_b}{dt}=0 \qquad (3)$$

where the temperature of upper and lower portions of the thermoelectric module is assumed to be uniform, then the energy storage of thermoelectric module is approximated as

$$(\rho c_p V)_b=(\rho c_p V)_t\approx\frac{1}{2}[(\rho c_p V)_{Bi_2Te_3}+(\rho c_p V)_{air}] \qquad (4)$$

The high thermal conductivity of copper give credence to the lumped capacity assumption. Heat loss through substrate is modeled as

$$R_{ku}^{-1}=\frac{A_{ku}\langle N\rangle_{D_h}k_f}{D_h}=1.5\times10^4\ \mathrm{W/C} \qquad (5)$$

Here we have used a channel flow with a laminar, fully-developed temperature and velocity fields[4]. Then $\langle N\rangle_{D_h}$ is 7.54 for hydraulic diameter $D_h=15\mu m$. Heat loss through semi-infinite substrate is also possible cooling configuration. In this case, the 1st term of eq. (3) can be substitute by[5]

$$\begin{aligned} q_s'' &= k\frac{\partial T(x,t)}{\partial x}\Big|_{x=0} \\ &= \sum_{i=1}^{n-1}\{[(a_i-a_{i+1})t+(b_i-b_{i+1})]\times \\ &[(\frac{k\rho c_p}{\pi(t-t_i)})^{1/2}-(\frac{k\rho c_p}{\pi t})^{1/2}] \\ &-\frac{\rho c_p}{2\pi^{1/2}}(a_i-a_{i+1})[-(4\alpha(t-t_i))^{1/2}+(4\alpha t)^{1/2}]\} \\ &(a_n t+b_n-T(t=0))(\frac{k\rho c_p}{\pi t})^{1/2}-a_n(\frac{k\rho c_p t}{\pi})^{1/2} \end{aligned} \qquad (6)$$

Preliminary calculation, however, shows the applicability of this cooling type is questionable.

2.3 Working Fluid

A wide variety of working fluid can be used as the phase transform materials. For operation near room temperature and at minimum input power, fluids with near room temperature boiling temperature at one atm such as R11 ($T_{lg}=296.95$ K) will be preferred. Compared with methanol ($T_{lg}=337.85$ K) used in the experiment by Bergstrom et al.[3], R11 would improve device performance because there needs no additional power for heating to its boiling temperature.

The temperature profile in liquid layer is assumed linear. The validity is checked by applying integral method[6] with higher order polynomial. No difference is found between these two. On this assumption, the energy equation in liquid layer is

$$\begin{aligned} -k_l\frac{T_{lg}-T_t}{\delta}-Q_h+\frac{(\rho c_p V)_t}{a_c\cdot a_c}\frac{dT_t}{dt} \\ +\frac{(\rho c_p V)_{si}}{a_c\cdot a_c}\frac{dT_t}{dt}=0 \end{aligned} \qquad (7)$$

Note that small amount of fluid is needed for a fast pressure response but should be enough to maintain a coating on the thermoelectric module.

2.4 Interface Between Liquid and Vapor

Because of the minuscule amount of liquid used, the liquid is not boil and surface evaporation (and condensation) will be the predominant phase change mechanism. The vapor temperature, T_{lg} is assumed spacially uniform, thus the energy equation at the interface between liquid and vapor becomes

$$\begin{aligned} Q_t-R_{ku}^{-1}(T_{lg}-T_0)+q_{side}''\frac{4a_c l_v}{a_c\cdot a_c} \\ +\rho_l\triangle H_{lg}\frac{d\delta}{dt}=0 \end{aligned} \qquad (8)$$

where the 2nd and 3rd terms represent cooling through membrane and side wall, respectively. Membrane cooling is modelled according to eq. (5) with hydraulic diameter $D_h=20\mu m$ ($R_{ku}^{-1}=4958$ W/℃, using air) and side wall is modeled on lumped capacity assumption due to much longer penetration depth compared with side wall thickness. This gives

$$q_{side}''=\rho_{si}c_{p,si}\frac{(2t+a_{c)}^{2-a_c}\cdot a_c\cdot l_v}{a_c\cdot a_c}\frac{dT_{lg}}{dt} \qquad (9)$$

2.5 Vapor

The total amount of liquid and vapor should be conserved as following

$$M_t=\rho_l\delta_0+\rho_{g0}(l_v-\delta_0)=\rho_l\delta+\rho_s(l_v-\delta) \qquad (10)$$

The pressure and temperature are related through the Clausius-Clapeyron relation[7] and the density of the vapor is related to pressure-temperature through ideal gas law.

$$p=p_{ref}\cdot\exp[-\frac{M\cdot\triangle H_{lg}}{R_g}(\frac{1}{T_{lg}}-\frac{1}{T_{ref}})] \qquad (11)$$

$$p = \frac{R_g}{M}\rho_g T_{lg} \qquad (12)$$

Combining these equations gives the relation between liquid thickness δ and vapor temperature T_{lg},

$$\frac{R_g}{M}\frac{M_t - \rho_l \delta}{l_v - \delta} = p_{ref} \cdot \exp[-\frac{M \Delta H_{lg}}{R_g}(\frac{1}{T_{lg}} - \frac{1}{T_{ref}})] \qquad (13)$$

3. RESULTS AND DISCUSSION

Table 1 lists the physical and geometrical properties of the phase-change based micro-actuator considered. The direction of the current flow is reversed to begin immediate cool-down. Heat is added by passing current through the thermoelectric module and when the desired gas pressure is reached, the current is reversed to allow for an active cooling, thus resulting in the return of the membrane to its initial location. In this analysis, inclusion of the change in cavity volume due to membrane deflection is neglected. Preliminary calculation shows its inclusion does not change the final volume by more than 8 percent.

3.1 Optimization

To obtain the maximum coefficient of performance (COP), system optimization is needed. Yamanashi[8] analyzed the optimum design condition of the thermoelectric cooler in a system with heat exchangers to obtain maximum performance, but his work focuses just on the thermoelectric module not including its interaction with whole system.

For the performance evaluation, we define a general dimensionless figure of merit as[9]

$$\Delta x^* = \frac{F \cdot \Delta x}{p \cdot \tau} \qquad (14)$$

where $\Delta F = \Delta p a_c^2$ and Δx are the force and displacement whose relation is available from experiment by Zhang and Wise[1]. Typical membrane displacement for the micro-actuator considered is about 50 μm[1]. p is the input power and τ is the response time of the device. Thus it can be viewed as the ratio of the mechanical work done by the system in one output cycle to the energy input required per cycle. While a principal drawback of the thermal approaches has been the required input power, as sizes are reduced and the quantity of material to be heated is diminished, the power requirements also fall. The optimization of the system is also conducted according to the parameters such as input power and response time. Substituting the numerical values gives $\Delta x^* = 0.0875$, which is resonable compared to other actuators[3].

Table 1. Physical and geometrical properties of the phase-change actuator considered.

conduction air gap	L_g	20 μm
cavity	L_c	300 μm
	a_c	600 μm
working fluid: R11	L_l	5 μm
	$T(t=0)$	298.15 K
	Δh_{lg}	1.802×10^5 J/kg
Silicon	L_{si}	10 μm
thermoelectric layer	J_e	15 mA
	l_{TE}	40 μm
	N_{TE}	8×16 junctions
	a_{TE}	20 μm
substrate: Cu	L_s	30 μm

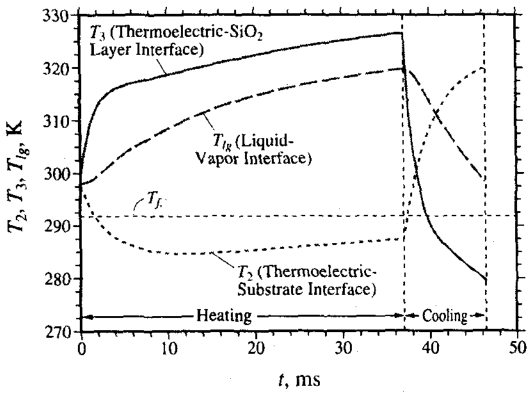

Fig. 2 Evolution of the liquid-gas interfacial temperature, Si layer temperature and thermoelectric-interfacial temperature.

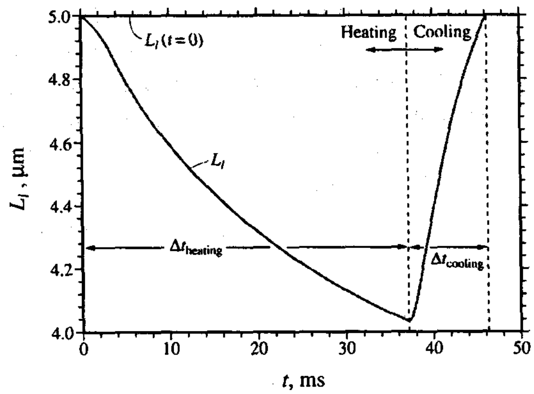

Fig. 3 Evolution of the liquid-film thickness.

3.2 Cyclic behavior of micro-actuator

Figure 2 shows the rise and fall of the various temperatures, T_2, T_{lg} and T_3 for the optimum performance of micro-actuator. Note that the response time (~46 ms) of the device is much smaller than that of the passive heating/cooling case[3]. The temperature at the thermoelectric-substrate interface drops (due to Peltier cooling) during the heating of the liquid layer. The reverse occurs during the cooling of the liquid layer. As was mentioned, only a small amount of liquid is needed for the evaporation and the rise to the desired pressure. This is shown in Fig. 3, where the initial thickness of the liquid $L_l = 5$ μm and only reduces to 4μm at the end of evaporation pressure.

4. CONCLUSIONS

This paper has discussed micro-actuators based on thermally-induced liquid-vapor phase-change in a partially-filled closed cavity. The type of micro-actuator has advantage in required relatively large forces and displacement by the large volume expansion of liquid-vapor phase change. Active (thermoelectric) heating and cooling results much shorter response time compared with that of passive heating, which improves the performance of device. The optimization of the system is conducted according to the parameters such as input power and response time. The obtained optimum value of COP in test condition is $\Delta x^* = 0.0875$, which is resonable compared to other actuators.

REFERENCES

(1) Zhang, Y. and Wise, K. D., Performance of non-planar silicon diaphragms under large deflections. Journal of Microelectromechanical Systems, 1994, 3, 59-68.

(2) Kabei, N., Kosuda, M., Kagamibuchi, H., Tashiro, R., Mizuno, H., Ueda, Y. and Tsuchiya, K., A thermal-expansion-type microactuator using paraffin as expansive material. JSME, 1996, 62, 200-205.

(3) Bergstrom, P. L., Ji, J., Liu, Y-N., Kaviany, M. and Wise, K. D., Thermally driven phase-change microactuation. Journal of Microelectromechanical Systems, 1995, 4, 10-17.

(4) Kaviany, M., Principles of heat transfer, Course Pack, University of Michigan, 1998.

(5) Ozisik, M, N, Heat conduction, 2nd edn., John Wiley & Sons, Inc., New York, 1993.

(6) Goodman, T. R., Trans. ASME, 1953, 80, 335-342.

(7) Sonntag, R. E. and Van Wylen, G. J., Introduction to thermodynamics, 3rd edn., John Wiley & Sons, Inc., New York, 1991.

(8) Yamanashi, M., A new approach to optimum design in thermoelectric cooling systems. J. Appl. Phys., 1996, 80, 5494-5502.

(9) Tabib-Azar, M., Direct optical control for a silicon microactuator. Dig. Int. Conf. Solid-State Sensors and Actuators, 1989, 229-235.