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Design of Valveless Micropump using Preliminary Characteristics from Fluid Flow

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Abstract: The need for cooling in advance thermal systems is ever in demand. The administration of such cooling will need miniaturization of the current pumping system for small-scale use. A valve less pump is one of the methods to create a small microscale flowrate pump. It has intake and outlet on the same side. Advances in fluid mechanics are able to capture the working principles of such pumps and give a close approximation of the pump characteristics. The fundamental aspect that a micropump will endure is analyzed from fluid mechanics analysis, is a key in the development of the model. The sizing and criteria of the pump is set based on fluid equations of mass, momentum and energy. A design is laid out by using computer-aided design (CAD) based on the voltage frequency that will be applied to the piezomaterial. The movement of the material due to current will cause the fluid to move, as the material will act as a diaphragm. The design is then analyzed using computational fluid dynamics (CFD) from the frequency inputs and a steady flow design is simulated. The reading of the small flowrate is analyzed and a proper method of designing the valve less pump is gathered.

Key words: CFD, fluid flow, micropump

INTRODUCTION

As microelectronics is expanding with wide demands of computing, the need to manage the thermal aspects of systems is playing a critical role in the packaging industries. With high power density levels, computer mainframes, telecommunication equipments, supercomputers and high powered systems will increasingly require improved cooling that is not possible that traditional air-cooling or direct immersion cooling technologies. As such a novel cooling method with improve pumping performance is crucial to in facing the growing need of the electronic markets.

Micropumps have been developed by using several actuation methods, such as electromagnetic (Bohm *et al*., 1999), piezoelectric (Stemme and Stemme, 1993; Olsson *et al*., 1995; Koch *et al*., 1998; Saggere *et al*., 2000; Suzuki and Yoneyama, 2003; Yang *et al*., 2004; Li *et al*., 2005), shape memory alloy (Benard *et al*., 1998), electrostatic (Francais *et al*., 1997; Teymoori and Abbaspour-Sani, 2005) and thermo-pneumatic (Takao *et al*., 2003) devices. Most of these micropump have complex structures and high power consumption. On the contrary, piezoelectric actuation has advantages due to its relatively simple structure and lower power consumption.

In this study, a new type of thin, compact, and light weighed diaphragm micropump will be developed to actuate liquid by the vibration of a diaphragm. The amplitude of vibration by a piezoelectric device produces an oscillating flow and alters the chamber volume by the curvature change of a diaphragm. This enables the pump to function to transfer fluids such as water or air.

A valve less pump consists of two fluid flow rectifying diffuser/nozzle elements, which are connected to the inlet and outlet of a pump chamber with a flexible diaphragm. Stemme and Stemme (1993) proposed the first prototype of valve less pump consisting of a circular cylindrical volume where the topside had a thin brass diaphragm to which a piezoelectric disc was fixed. Its flow rate was 15.6 mL min^{-1}. Olsson *et al*. (2000, 1995) investigated the flow-directing properties of several diffuser elements with different lengths and opening angles for valve less micropump. Using the Computational Fluid Dynamics program ANSYS/Flotran did numerical simulations. They found that a commercial micropump with a valve could be developed with central actuating as in Fig. 1. The drawback is the manufacture and installation of the valve.

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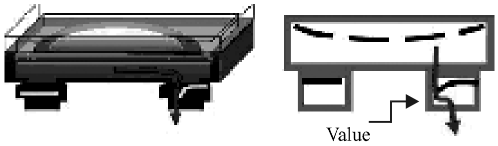

Fig. 1: View of SDMP305D micro-diaphragm pump

The aim of the study is to obtain a simple three-dimensional model of the micropump enhanced without a valve-using computer aided design (CAD). The model will be tested using CFD to observe the operation of the prototype.

THEORY AND METHODS

In Fig. 2, a new micro-diaphragm pump with piezoelectric effect has been designed to actuate the working fluid by the vibration of a diaphragm with one-side sector-shaped piezoelectric device. The vibration amplitude of the piezoelectric device produces an oscillating flow and alters the chamber volume by the curvature change of a diaphragm.

When the actuator moves downwards to decrease chamber volume shown in Fig. 2a, the outflow will be in one direction by moving from a inlet diffuser to an outlet diffuser. When the actuator moves upwards to increase chamber volume shown in Fig. 2b, the fluid flowing into the pump will be in the chamber through the diverged cone, while the fluid outlet will be from the converged cone of the pump as in Fig. 3.

In addition, the actuating force can be enforced by its harmonic resonance of the working fluid with the vibration of a rectangular piezoelectric device, diaphragm, and two cones in the pump chamber. The design of the cones is important in terms of fluid moving into the inlet and going out. The structure of nozzle/diffuser cone is shown in Fig. 4.

From fluid mechanics it is known that, the dynamic resistance is minimum at the range of θ = 5°, and the dynamic resistance is maximum when θ = 7°. To start the analysis the minimum angle is used. The flow equation of clearance and pressure distribution of nozzle is given by:

$$p = p_1 - \Delta p \frac{\left(\frac{D}{h}\right)^2 - 1}{\left(\frac{D}{d}\right)^2 - 1} \tag{1}$$

And pressure distribution of cone can be expressed as:

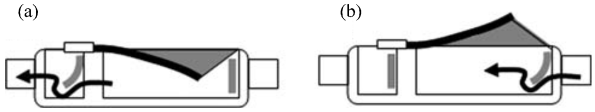

Fig. 2: Working principles of a single acting micropump

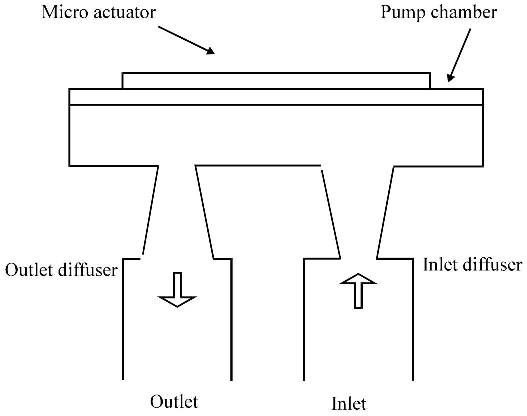

Fig. 3: Working principle of valve less micropump

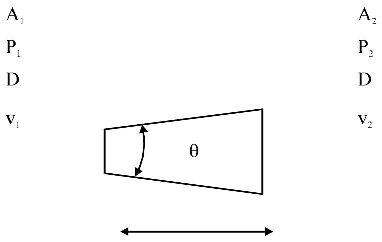

Fig. 4: Cone dimensions

$$p = p_1 - \Delta p \frac{1-\left(\frac{d}{h}\right)^2}{1-\left(\frac{d}{D}\right)^2} \tag{2}$$

where, h being the cross sectional diameter of the cone. The flow equation of the cone is given by the Bernoulli equation as:

$$\frac{p_1}{\rho g}+\frac{v_1^2}{2g}=\frac{v_2^2}{2g}+\sum\zeta\frac{v_2^2}{2g} \tag{3}$$

Where:

$$v_1 = v_2\left(\frac{d}{D}\right)^2$$

$$\Delta p = p_1 - p_2$$

$$P^2=0$$

and

$$v_2 = \frac{1}{\sqrt{1+\sum\zeta-\left(\frac{d}{D}\right)^4}}\sqrt{\frac{2p_1}{\rho}} \qquad (4)$$

With, $\theta = 5°$ and pipe losses estimated at, $\xi = 0.0045$, the flow rate Q can be expressed by:

$$Q = v_2 A_2 = \frac{\pi d^2}{4}\frac{1}{\sqrt{1+\sum\zeta-\left(\frac{d}{D}\right)^4}}\sqrt{\frac{2p_1}{\rho}} \qquad (5)$$

Modeling: Based on the boundary equation above and previous research of Ma *et al.* (2008) the opening of the converged cone is set at d = 0.6 mm, and flowrate targeted to 0.6 mL sec^{-1}. With the two boundaries predetermined a simulation was targeted by using a CFD tool. This is because the boundary condition is important to represent the flow in the mixer for CFD analysis to begin. The CFD software utilizes the Navier Stokes equations to solve the flow behavior:

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k)=0 \qquad (6)$$

$$\frac{\partial\rho u_i}{\partial y}+\frac{\partial}{\partial x_k}(\rho u_i u_k-\tau_{ik})+\frac{\partial P}{\partial x_i}=S_i \qquad (7)$$

$$\frac{\partial(\rho E)}{\partial y}+\frac{\partial}{\partial x_k}\left((\rho E+P)u_k+q_k-\tau_{ik}u_i\right)=S_k u_k+Q_H \qquad (8)$$

where, u is the fluid velocity, ρ is the fluid density, S_i is a mass-distributed external force per unit mass, E is the total energy per unit mass, Q_H is a heat source per unit volume, τ_{ik} is the viscous shear stress tensor and q_i is the diffusive heat flux.

The preliminary model is done as shown in Fig. 5 with both cones attached to form the micropump. A moving wall was targeted to oscillate as per the piezomaterial frequency and two outlets, one being an input and the other being an output is modeled in CFD.

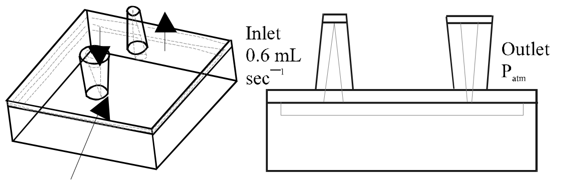

Fig. 5: Preliminary Design

RESULTS

From the software, a basic mesh is obtained showing the path that will be taken by the fluid into the micropump system. Fig. 6 shows the grid distribution in the small cavity. The spacing is done automatically by the software for the preliminary analysis to show the system functionality.

The results obtained for pressure and velocity show that the pump cavity can deliver the flow as per calculations. Figure 7 and 8 shows the respective simulation. There seem to be a small pressure buildup as the flow is moving from the inlet and exiting the outlet. The amount is small about 18 Pa. This creates very little pressure drop to the system and is seen as an advantage to the design. In the velocity plot the converged section shows an increase in velocity. This relates to Bernoulli equation where the higher-pressure region (inlet) creates a lower velocity and the lower pressure region (converged cone) create higher velocity.

Due to the velocity movement, the flow seems to accumulate more in the inlet cone, in the converging section. As seen in Fig. 9, the region may cause some fluids with particles to clog the inlet. Small foreign objects will also cause this inlet to be clogged if the flow is too fast. A fillet may help in the future design.

The other parameters that requires further investigation is on the wall, to ascertain the behavior when piezomaterial is used. The current CFD software

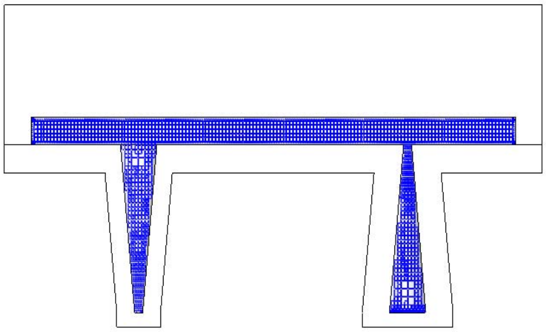

Fig. 6: Grid spacing

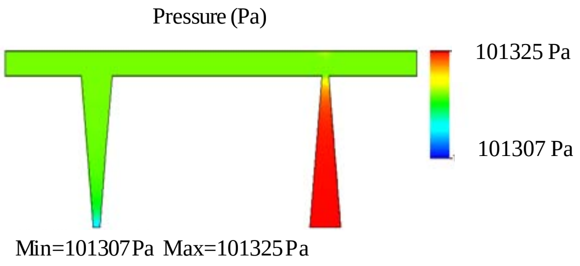

Fig. 7: Pressure readings

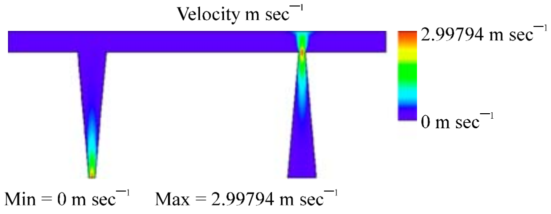

Fig. 8: Velocity readings

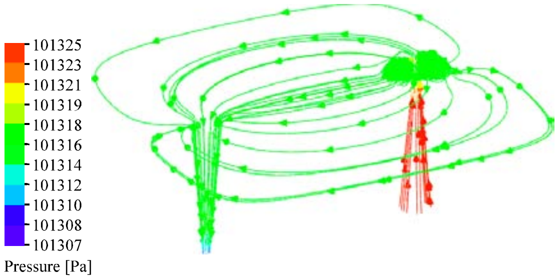

Fig. 9: Trajectories of the Flow Moving in the Pump

used can only enable pressure plots and fluid flow. Hence, more elaborate models will be required to represent the wall as moving per frequency of the model.

CONCLUSION

The model presented in this study is under the development stage and many unknowns still have to be finalized to obtain to the final model. The fluid flow equations from fundamental may help, but a CFD approach enables visualization with fluid properties at the micro flow level. The second challenge would be to develop the required methods find more accurate flow speed and an experimental design will be required to lead to a solution.

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