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Numerical analysis of mechanical micropump using membrane-based check-valves for microfluidic applications

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ABSTRACT: In this paper, we mentioned a numerical analysis method for simulation of a micropump for microfluidic applications. Each section of the micropump, including microvalves and pumping chamber, were studied using three-dimensional fluid-structure interaction analysis and their operational characteristic equations were extracted independently. These extracted equations were used to solve time-domain pressure equation and to obtain the flow rate of micropump. Afterwards, we were able to study different effects of actuation pressure and actuation frequency on micropump's flow rate with and without the presence of outlet backpressure. The results of microvalve show that it lets fluid pass through after passing threshold pressure of about 100 Pa. However, it blocks fluid flow in reverse mode with extremely negligible leakage rate. The results of micropump operation show that when actuation frequency is 1 Hz and actuation pressures are equal to 1000, 1500, 2000 Pa, pumping flow rate reaches 30, 48 and 65 mm^3/min, respectively. Also, this micropump can overcome maximum backpressure of approximately 950 Pa when it was actuated using pressure of 1000 Pa, regardless of its actuation frequency. These results show that the simulated micropump reasonably agrees to the microfluidic and lab-on-a-chip applications.

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1. Introduction

Since controlling and transporting small fluid (liquid or gas) flow is very essential in microfluidic and lab-on-a-chip applications, there have been many investigations on development of on-chip microvalves and micropumps [1-3]. Among different pumping methods, diaphragm mechanical micropumps have linear response to the actuation pressure, and are immune from backflows. Fig. 1 shows design of mechanical micropump which is consisted of two micro check-valves and one pumping chamber. This micropump has two operating phases, known as suction and pumping phases. Most of the previously reported works were concentrated on different fabrication and actuation methods while there are fewer works discussing simulation methodology of this type of micropump [4-6].

In this paper, we will design and simulate a mechanical micropump using the finite element method to obtain time-domain pumping flow rate. Then, effects of actuation amplitude and frequency on micropump flow rate will be studied. At last, we will check backpressure effect on micropump flow rate to see its capability beside other microfluidic elements and for on-chip applications.

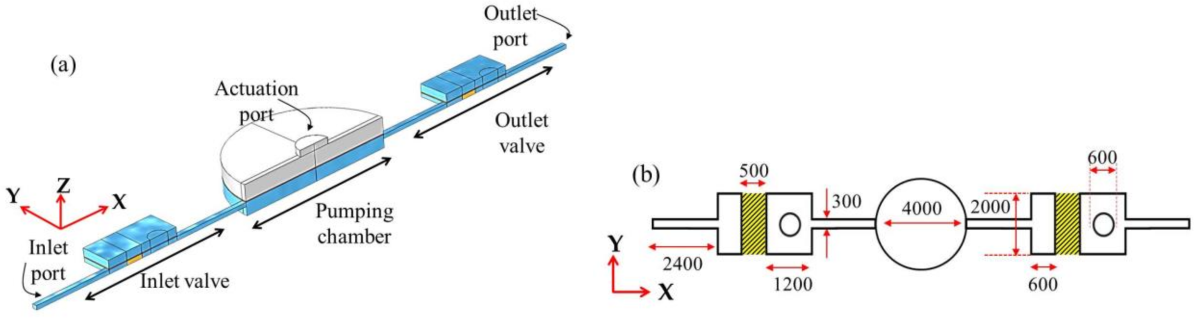

Fig. 1. (a) Three-dimensional design, and (b) Schematic design of micropump, dimensions are in microns.

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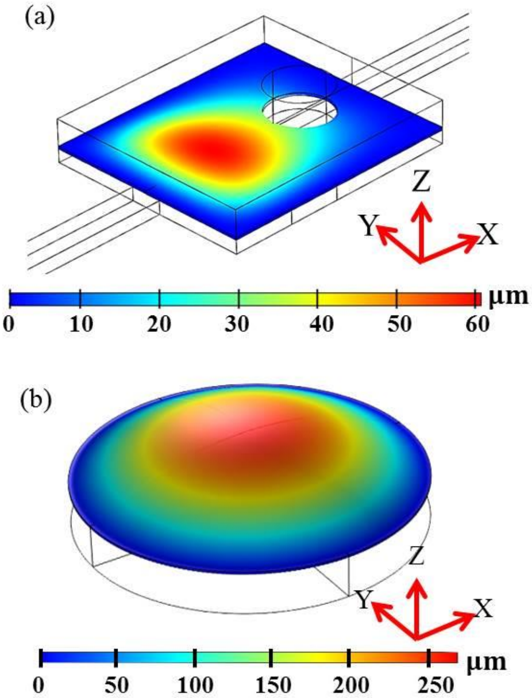

Fig. 2. (a) Microvalve and (b) Pumping chamber displacement vs actuation pressure of 3kPa.

2. Simulation Method

In this section by inspiring from [6], we tried to calculate the time-domain pressure of pumping chamber (P_{ch}) to reach the flow rate of micropump. To do so, we first simulated microvalve section of the micropump using three-dimensional fully-coupled fluid-structure interaction and extracted its Q-P characteristic curve and equation (Q_{iv} and Q_{ov}). In addition, volume displacement equation of the microvalve is extracted which is a function of actuation pressure ($\forall_{iv}$ and $\forall_{ov}$). Then, pumping chamber is simulated using fluid-structural analysis to extract volume displacement ($\forall_{ch}$) of pumping chamber versus actuation pressure. Afterwards, by substituting the extracted characteristic curves inside Eq. (1) and calculating this equation, pressure inside pumping chamber can be calculated which is a time-domain variable.

$$\frac{dP_{ch}}{dt}=\frac{Q_{iv}(p_{iv})-Q_{ov}(p_{ov})-\left.\frac{\partial\forall_{ch}}{\partial P_{ch}}\right|_{P_{ch}}\cdot\frac{dP_{act}}{dt}}{\left.\frac{\partial\forall_{ch}}{\partial P_{ch}}\right|_{P_{act}}-\frac{d\forall_{iv}}{dP_{ch}}+\frac{d\forall_{ov}}{dP_{ch}}} \qquad (1)$$

Now, we can use chamber pressure to evaluate flow rate and other important parameters of micropump. At last, we should mention that, differential equations that describe behavior of fluid domain of fluid-structure interaction are momentum, mass and energy equations (Navier-stocks equations). While solid side of fluid-structure interaction analysis can be solved using impulse equation.

3. Results and Discussion

According to the previous section, each part of micropump was analysis separately and finally all the results were coupled into each other by using Eq. (1).

Figs. 2a and 2b show displacement of microvalve and pumping chamber displacement versus actuation pressure, respectively, which were simulated using fluid-structural interaction analysis.

Fig. 3a shows the amount of liquid pumped by the designed pump with different actuation pressure (Pact) in a 10 second time-frame. In this figure, actuation frequency was 1 Hz while actuation pressure varies from 1, 1.5 to 2kPa which shows pumping flow rate reaches to 30, 48 and 65 mm3/min, respectively. These values quite fit to the lab-on-chip applications. Fig. 3b shows pumping flow rate linear increment versus increment of actuation pressure. Fig. 3c studies effect of actuation frequency on pumping flow rate. It is obvious with increment of frequency, flow rate reaches a maximum flow rate of about 40 mm^3/min and decreases after frequency of 3Hz. Finally, the effect of backpressure on micropump's operation was studies. Figure 3d demonstrates this effect in which the time-domain volume of pumped liquid decreases when the backpressure at outlet increases.

4. Conclusions

In this paper, we proposed a novel numerical analysis for a check-valve micropump. We first simulated check-valves and pumping chamber by employing three-dimensional fluid-structure interaction analyses. This is opposed to the prevailing trends where 2D simplified models are generally used due to hardware and software limitations. Next, we

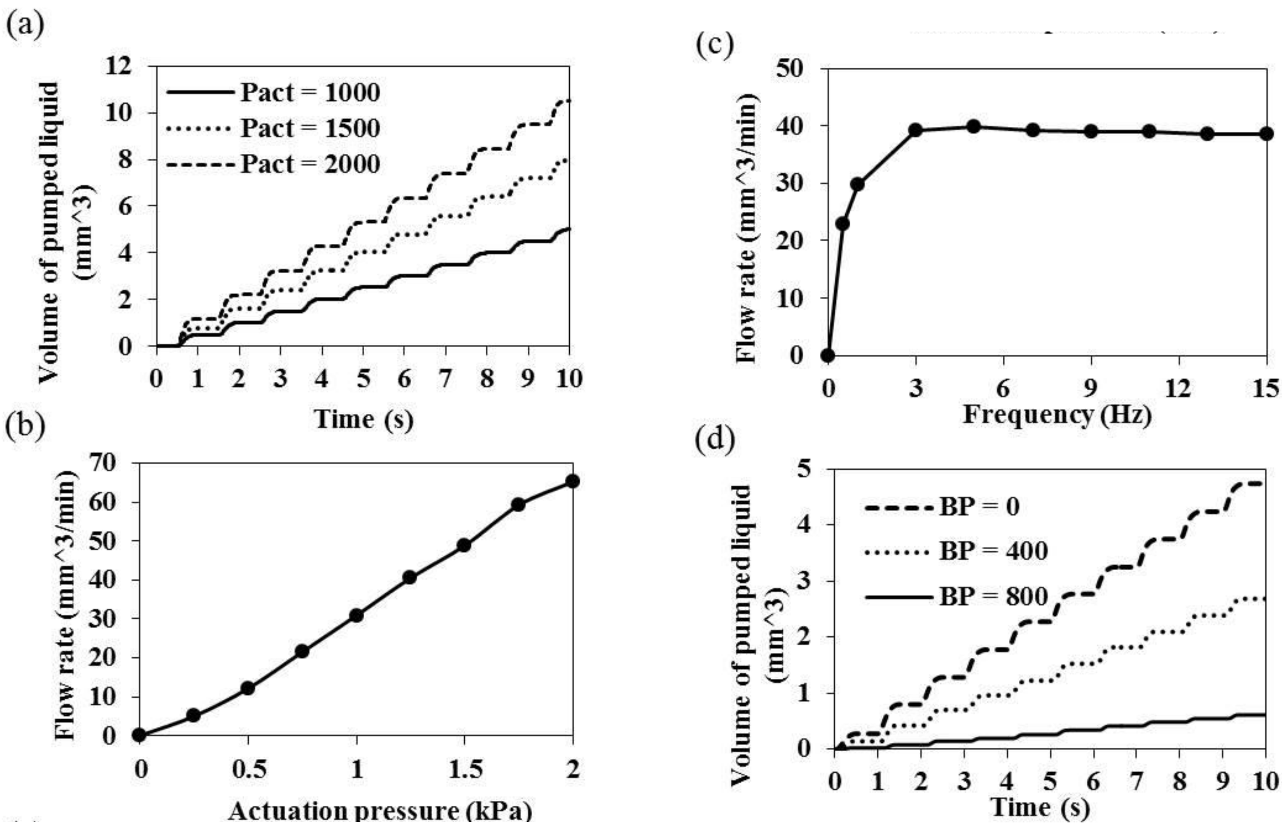

Fig. 3. (a) Time-domain pumped liquid volume, (b) Flow rate of micropump versus actuation pressure, (c) Flow rate of micropump versus actuation frequency, (d) Time-domain pumped liquid volume with different backpressure at micropump's outlet.

used characteristic curves of the check-valve and pumping chamber for solving the micropump's main equation. Finally, we evaluated the time-domain pressure of the pumping chamber and used this pressure to better understand the effects of actuation pressure and frequency on the micropump behavior.

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