Research on liquid flow behavior in deformed microfluidic channels made of PDMS material

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Abstract: In order to improve the application performances of current microfluidic systems, the liquid flow behavior in deformed microfluidic channels made of PDMS material is deeply researched in this study. During the flowing process, liquid pressure features in inelastic and elastic channels are tested and compared respectively, serious channel deformation in elastic PDMS channels is found, and the key influencing factors are summarized and provided, including channel aspect ratio $\alpha$, top membrane thickness $h$, and channel width $w$, etc. This study reveals the liquid flow behavior in microfluidic systems made of PDMS material, and provides theoretical and experimental basis for further structural optimization of the systems.

1. Introduction

Recently, various microfluidic devices have been developed for medical diagnosis[1,2], chemical detection[3-5] and biological analysis[6,7], due to the small volume, fast speed and low cost[8]. Nowadays, microfluidics have also made significant progress in the optical field[9-11]. For instance, Peris et al. developed an integrated optical microfluidic biosensor using a polycarbazole photodetector, which can provide point-of-care detection of hormonal compounds[12]. Zhao et al. reported a liquid-filled tunable lens with a membrane of variable thickness, a wider range of focus length and smaller diffraction effect[13] were shown in this lens. American Superfocus Company has also commercialized the liquid-filled tunable lens and has applied it for vision adjustment of astronauts at international space station.

The application of microfluidic systems for colour-changing has also aroused the attention of many researchers. Whiteside and co-workers at Harvard University developed a microfluidic network operated on a soft machine, which could easily realize display/camouflage and movement of the machine[14]. In recent studies, we have fabricated a microfluidic liquid colour-changing lens[15,16] based on the PDMS matrix. PDMS optical membranes with microfluidic channel structures were fabricated by soft lithography[17-19], which replaced conventional mechanical machining. Some basic applications of the microfluidic lens were realized, including vision protection, camouflage and optical filtering[20]. However, no in-depth analysis of the liquid flow behavior in these systems has been carried out so far, resulting in an insufficiently optimized structures and poor performances of the systems.

In this study, the liquid flow behavior in microfluidic systems made of PDMS material is researched.
The liquid pressure characteristics in PDMS channels are tested during liquid flowing, obvious non-linearity of the liquid pressure in elastic PDMS channels is shown compared with that in inelastic channels, and the key influencing factors are analyzed and summarized, including channel aspect ratio \((\alpha)\), top membrane thickness \((\bar{h})\), and channel width \((w)\), etc. This research provides theoretical and experimental basis for further structural optimization and performances improvement of the microfluidic systems.

2. Flow characteristics in deformed PDMS channels

2.1 Theoretical analysis

Due to the elasticity of the PDMS material, PDMS channels deform during the liquid circulation process, resulting in the liquid pressure changes in channels. In this study, the liquid pressure characteristics in elastic PDMS channels and common inelastic channels are analyzed and tested under different experimental conditions.

For common inelastic channels (e.g. glass, PMMA, PC, etc.) with rectangular cross-sections, the liquid pressure parallel to the flow direction can be expressed as:

\[
-\frac{\partial p(x)}{\partial x} = \frac{12\mu}{h^3w(1-0.630\frac{\bar{h}}{w})}Q
\]

(1)

where \(x\) is the distance from the measured point to the channel inlet parallel to the flow direction, \(p(x)\) is the liquid pressure at the measured point, \(h\) is the channel depth, \(w\) is the channel width, \(Q\) is the liquid flow and \(\mu\) is the dynamic viscosity of the liquid.

In this study, the cross-sections of the PDMS channels are all flat rectangular, which meets the condition of \(h < w\), as shown in figure 1(a). Therefore, the channel deformation along \(Y\) direction is much larger than that along \(Z\) direction, so only the former is investigated here. Figure 1(b) shows that the channel deformation along \(X\) direction gradually decreases with increasing \(x\) value.

From figure 1, the channel depth \(h(x)\) at the measured point in elastic PDMS channels can be expressed as:

\[
h(x) = h_0[1 + c_x p(x)]
\]

(2)

where \(c_x\) is the deformation coefficient related to the elastic modulus of the PDMS membrane and \(h_0\) is the initial channel depth before deformation.

Inserting Eq.(2) into Eq.(1) leads to

\[
-\frac{\partial p(x)}{\partial x} = \frac{12\mu}{h_0^3w(1-0.630\frac{\bar{h}}{w})}[1 + c_x p(x)]^{-3}Q
\]

(3)

Eq.(3) provides the liquid pressure characteristics in elastic PDMS channels parallel to the flow direction.

By comparing Eq.(1) and Eq.(3), an obvious non-linear relationship between the pressure change \(\frac{\partial p(x)}{\partial x}\) and the liquid flow \(Q\) is observed in elastic PDMS channels during liquid circulation, otherwise a linear relationship exists in the case of inelastic channels.
2.2 Experimental details and discussions

PDMS channel samples with different dimensions are designed and manufactured for liquid pressure tests, as shown in Table 1. Figure 2 shows the experimental diagram, which mainly consists of an air compressor, a pressure regulating valve, a switch valve, miniature pressure sensors and PDMS channels under test. The air compressor (Eluan Limited Company, China) is used to generate high pressure air, the pressure regulating valve IR1000 (SMC Corporation, Japan) is used to adjust and stabilize the channel inlet pressure, whereas the miniature pressure sensors 40PC015G2A (Honeywell Company, America) are employed for liquid pressure tests. In this study, the channel inlet is connected with the high pressure air, whereas the outlet pressure is exposed to the atmospheric pressure. The liquid pressure is tested at five different points for each channel sample, the total channel length of each sample is 42 cm, the distance between the first test point and the channel inlet, as well as between any adjacent test points, is 7.5 cm.

Table 1 PDMS channel samples with different dimensions for liquid pressure tests

| Sample number | Channel width $w$ (μm) | Channel depth $h$ (μm) | Aspect ratio $α$ | Channel gap $g$ (μm) | Top membrane thickness $th$ (mm) |
|---------------|------------------------|------------------------|------------------|-----------------------|-------------------------------|
| 1             | 500                    | 50                     | 10               | 200                   | 1.0                           |
| 2             | 500                    | 100                    | 5                | 200                   | 1.0                           |
| 3             | 500                    | 100                    | 5                | 200                   | 3.0                           |
Figure 2. Experimental system for liquid pressure tests: (a) experimental diagram and (b) experimental setup.

Figure 3 shows the liquid pressure results under different experimental conditions. The dotted lines represent the theoretical results for inelastic channels, whereas the solid lines are the experimental test results for elastic PDMS channels. When the pressure at channel inlet is 30 kPa, the liquid pressure at test points 1, 2 and 3 is 25.54 kPa, 15.72 kPa and 6.19 kPa respectively in inelastic channel. For PDMS channel sample 1, the experimental results are 15.24 kPa, 10.92 kPa and 2.92 kPa respectively (figure 3(a)). For PDMS channel sample 2, these values are 17.80 kPa, 12.32 kPa and 4.05 kPa respectively (figure 3(b)), and for sample 3, 20.55 kPa, 14.52 kPa and 5.01 kPa are obtained respectively (figure 3(c)). Therefore, compared with the inelastic channels, the liquid pressure in elastic PDMS channels shows obvious non-linearity, which is consistent with the finding from the theoretical analysis.

Comparing between sample 1 ($w = 50 \mu m, \alpha = 10$) and sample 2 ($w = 100 \mu m, \alpha = 5$), it can be seen that the channel deformation and the non-linearity of liquid pressure gradually decrease as reducing the channel aspect ratio $\alpha$. Comparison between sample 2 ($\alpha = 5, th = 1 mm$) and sample 3 ($\alpha = 5, th = 3 mm$) further indicates that the channel deformation and the non-linearity of liquid pressure gradually increase as reducing the PDMS top membrane thickness $th$. Therefore, proper channel dimensions should be selected to meet the system requirements. In this study, based on the extensive experimental research and comprehensive consideration of the production factors and elastic deformation, it is suggested that the appropriate value range of the channel aspect ratio $\alpha$ should be 3–6, and that of the top membrane thickness $th$ is about 1.5–2.5.
Figure 3. Experimental test results of the liquid pressure under different conditions: (a) sample 1, (b) sample 2, (c) sample 3 and (d) comparison when the channel inlet pressure is 30 kPa.

3. Conclusions
In this research, liquid pressure features in elastic and inelastic channels are analyzed and compared. Typical non-linearity of the liquid pressure is observed in elastic PDMS channels compared with that in inelastic channels, and the key influencing factors are summarized and the proper values are suggested. The liquid flow behavior revealed in this research can be adapted to various microfluidic systems made of PDMS material, and can provide foundation for further structural optimization and performance improvement of the systems. We have just focused on a few areas, further research is needed about the influence of PDMS materials on other aspects of liquid flow characteristics in microfluidic systems.

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