Deformation properties between fluid and periodic circular obstacles in polydimethylsiloxane microchannels: Experimental and numerical investigations under various conditions

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(Received 9 July 2013; accepted 20 August 2013; published online 6 September 2013)

Understanding the mechanical properties of optically transparent polydimethylsiloxane (PDMS) microchannels was essential to the design of polymer-based microdevices. In this experiment, PDMS microchannels were filled with a 100 μM solution of rhodamine 6G dye at very low Reynolds numbers ($\sim 10^{-3}$). The deformation of PDMS microchannels created by pressure-driven flow was investigated by fluorescence microscopy and quantified the deformation by the linear relationship between dye layer thickness and intensity. A line scan across the channel determined the microchannel deformation at several channel positions. Scaling analysis widely used to justify PDMS bulging approximation was allowed when the applied flow rate was as high as 2.0 $\mu\text{l}/\text{min}$. The three physical parameters (i.e., flow rate, PDMS wall thickness, and mixing ratio) and the design parameter (i.e., channel aspect ratio = channel height/channel width) were considered as critical parameters and provided the different features of pressure distributions within polymer-based microchannel devices. The investigations of the four parameters performed on flexible materials were carried out by comparison of experiment and finite element method (FEM) results. The measured Young's modulus from PDMS tensile test specimens at various circumstances provided reliable results for the finite element method. A thin channel wall, less cross-linker, high flow rate, and low aspect ratio microchannel were inclined to have a significant PDMS bulging. Among them, various mixing ratios related to material property and aspect ratios were one of the significant factors to determine PDMS bulging properties. The measured deformations were larger than the numerical simulation but were within corresponding values predicted by the finite element method in most cases. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4819918>]

I. INTRODUCTION

As microfluidic systems are being investigated in laboratories across the world for novel applications in biomedical assaying, chemical analysis, electronic technology, and drug discovery, polymer-based micro-devices have advanced with microfabrication technology.¹⁻³ Microchannels are essential parts of such systems and are exploited as micro-heat exchangers, microbioreactors, concentrators, mixers, and separators.⁴⁻⁷ As alternative materials from the

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classical glass and silicone, polymers, such as polydimethylsiloxane (PDMS), polymethylmethacrylate (PMMA), cyclic olefin copolymer (COC), and polystyrene (PS), have a wide range of successful applications due to their outstanding functionalities.^{8,9}

One of the most widely used elastomeric materials is PDMS, an advance of soft lithography process. PDMS has become the preferred material for biomedical electronics and microscale fluid devices due to the following advantages: (a) low production cost compared to traditional MEMS substrate materials such as silicon or glass; (b) optical transparency (transparent for a wavelength range of 400–700 nm); (c) biocompatibility; and (d) easy bonding to itself or other substrates.^{10–14} In addition to those advantages, the rubber elastic properties of PDMS have become versatile tools for microfluidic devices and have been used in micro-flow cytometry, peristaltic pumping and mixing, microvalves, and portable immunosensing systems.^{15–18} A highly flexible PDMS chip also was used to maintain chemostatic conditions for bacterial and yeast colony growth.¹⁹ The rubber elastic properties of PDMS have expanded their roles to a wide range of applications but there are a few arising drawbacks. The PDMS compatibility with some solvents generated the unwanted swelling of PDMS due to its porous nature.²⁰ The experiment was carried out by using a certain length of solid pieces and immersing them in various organic solvents. The degree of swelling by solvents was measured before and after being immersed. A more advanced approach found that the PDMS channel roof showed a parabolic shape with a maximum deformation of $7\text{ }\mu\text{m}$ under pressure-driven solvents.²¹ This unwanted swelling induced a change of droplet trajectories. In addition, the channel deformation with organic solvents had extraordinarily strong bulging compared to regular solutions. Microchannel deformations due to pressure-driven water-based liquids have received great interest. In general, the shallow microchannels have a strong tendency to deform and bulge under pressure-driven flow. These uncontrolled displacements hinder making appropriate modeling and accurate prediction for flow properties between the fluid and structure as well as cardiovascular fluid mechanics between the blood flow and arterial walls due to the cross-sectional area change. Thus, microchannel deformation gives rise to large deviations from predictions by classical fluid theory. PDMS microchannel deformation was investigated under various flow rates, and using 3D confocal microscopy with software analysis, it was found that microchannel bulging is greatest at the inlet (highest pressure) and least at the outlet (lowest pressure).²² The severe effects of channel deformation induced by the pressure drop did not increase linearly with the imposed flow rates, although the classical theory suggests that it should. It was found that when the flow rates were doubled the pressure drop increased by only 55%. Hardy *et al.*²³ introduced an alternative fluorescence microscopy method with Rhodamine 6G dye which was pumped through microfluidic channels and created the fluorescent intensity difference based on the deformation of the microchannels. They reported a 65% increase in the pressure drop when the flow rates were doubled. *In situ* pressure measurement within rectangular PDMS microfluidic channels was investigated with commercially available external pressure transducers to monitor real-time measurements.²⁴ The measured pressure drops were smaller than the rigid channel theory due to the deformable PDMS properties. In addition, the deviation from those predicted by the rigid channel theory increased with increasing the aspect ratio.

The bulk properties of PDMS have been acknowledged that a low Young's modulus E (varying experimental condition) and a high Poisson ratio ($\nu=0.5$) make a prototype of rubber elastic material.²¹ However, the mechanical properties of PDMS should be carefully controlled due to variously yielded elasticity, and strongly dependent on the amount of cross-linking agent and UV exposure time.^{22,25} For instance, a higher curing temperature and longer curing time accelerate the solid polymers. Consequently, there have been several studies made on the characterization of PDMS properties.^{26,27} PDMS mechanical properties were also dependent on three factors: the thinner concentration, temperature, and strain rate.²⁸ The lower the concentration of cross-linking agent, the less solid the viscous polymer becomes. High aspect ratio micropost arrays were fabricated using PDMS to investigate mechanical properties.²⁹ The micropost arrays cured at a high temperature were much stiffer than those cured at room temperature. They also found Young's modulus was dependent on the scale of PDMS microposts even if they were fabricated with the same PDMS mixture and identical fabrication methods.

In the present article, we present a study of the deformation of PDMS microchannels containing periodically spaced circular obstacles under various conditions. The investigated flow was operated at the laminar flow under the very low flow rates. PDMS wall thickness, flow rate, and mixing ratio were considered as significant parameters for PDMS microchannel deformations. In addition to these three parameters, the effect of microchannel aspect ratio was investigated by increasing channel heights. The experimentally measured pressure data and the tensile test of the Young's modulus were applied to two theoretical approaches: (a) scaling analysis and (b) finite element method (FEM) using ANSYS Workbench. Scaling analysis was compared with ANSYS Workbench to find discrepancies and whether this method can be applied to low flow rates. The analyses of the FEM were then compared to experimental measurements. Throughout this study, it is expected that this interdisciplinary study dealing with the complex interaction between elastic material structure and liquid improves understanding of the classical fluid dynamics as well as the mechanical property of PDMS. Also, this understanding of the mechanical properties of PDMS elastomer provides an essential tool to making an accurate modeling between the blood flow and arterial walls.

II. EXPERIMENTAL METHODS AND MATERIALS

A. PDMS sample preparation

Silicone RTV 615 (Momentive Performance Materials, NY, USA), consisting of part A and part B, was used in this study. Part A of RTV 615 is a siloxane oligomer, containing polydimethylsiloxane, while part B of RTV 615 is a cross-linking oligomer containing a cross-linker. The covalent bonding between the vinyl group of part A and the silicon hydride of part B can be formed during the mixing process.²⁷ To measure mechanical properties, PDMS specimens with three different mixing ratios (ratio of A:B = 5:1, 10:1, and 15:1) were prepared with two different PDMS wall thicknesses (3 mm and 6 mm). Part A and part B were well mixed with the suggested ratios and the solution was poured into the prepared cast (4 cm × 6 cm). The PDMS was then cured at 85 °C for 1 hr after degassing. The cured PDMS was peeled off the mold and cut into the samples. For mechanical properties, two samples with the same mixing ratio were prepared for different PDMS wall thicknesses. The thickness of PDMS was manipulated by the volume of pouring PDMS.

B. Analysis of mechanical property

The mechanical properties performed on various mixing ratios and different wall thicknesses of PDMS samples were characterized using a screw-driven Instron 4400R (Instron Inc., MA, USA) universal material testing machine in accordance with ASTM method, as shown in Figures 1(a) and 1(b). Prior to the actual test, each specimen was very carefully inspected for any visible defect (i.e., crack, bubble, etc.). The test sample was mounted on specially created double clamped grippers to prevent slippage of the specimen. A tensile force was applied to the control specimens. Mechanical properties, such as the elongation and the corresponding force, were automatically recorded on a computer and repeated several times to get reliable data.

C. Experimental design and microchannel fabrication

The experimental setup is schematically shown in Figure 2(a). Tygon tubing (0.06" OD × 0.02" ID, Saint-Gobain Corp., Akron, OH) connected a syringe pump (Harvard Apparatus, Holliston, MA) to the microfluidic chip through a needle (0.025" OD × 0.013" ID, New England Small Tube Corp., Litchfield, NH) at the microfluidic chip inlet. The flow rates investigated in this study were maintained constant by the syringe pump ($\pm 0.5\%$ accuracy) at either 1.0 $\mu\text{l}/\text{min}$ or 2.0 $\mu\text{l}/\text{min}$ depending upon the experimental protocol. The time-dependent applied pressure was directly measured throughout each entire experiment by a gauge pressure transducer (PX138, Omega Engineering, Inc., Stamford, Connecticut). The transducer voltage was digitized and recorded with a computerized data acquisition system (DI-148U, DATAQ Instrument, Akron, OH). Calibration of the pressure transducer voltage was performed using a

(a)

(b)

FIG. 1. (a) The experimental apparatus for the mechanical properties (before) and (b) the experimental apparatus for the mechanical properties (after).

water manometer prior to beginning experiments on microfluidic devices. The outlet channel in the microfluidic chip was open to the atmosphere and remained at atmospheric pressure for the entire experiment duration.

Microfluidic channel height of $50\text{ }\mu\text{m}$ was fabricated by reactive ion etching (RIE) techniques and the process is briefly described below. AutoCAD software (AutoDesk, Inc., San Rafael, CA) was used to produce a mask design which was then printed on a transparent film by CAD/Art Service, Inc. (Bandon, OR). A positive photoresist (AZ P4620) was applied to a 4-in.

FIG. 2. (a) Schematic of the experimental apparatus and (b) close-up image of the obstacles used in the present study.

silicon wafer by Silicon Quest International Inc. (Santa Clara, CA). A patterned silicon mold ranging in height from 6 to 7 μm was then etched with a Surface Technology system (Redwood, CA) using 30 s etch/3 s passivation cycles, producing an etch rate of around 2 $\mu\text{m}/\text{min}$. Each etch/passivation cycle was followed with an oxygen plasma for removal of residual volatile organic species in the chamber and C_4F_8 (Perfluorocyclobutane) deposition for reducing sidewall roughness of the silicon. For more effectively preserving silicon wafer structures after completion of the etch/passivation cycles, the silicon wafer was coated with (1,1,2,2 H perfluorooctyl)-trichlorosilane (PFTS). Surface coating with this chemical increases silicon surface hydrophobicity so that the silicon mold-PDMS replica is less likely to stick together.^{30,31} The achieved silicon surface uniformity was within 5% of original channel dimensions. Polydimethylsiloxane (PDMS, GE RTV 615; elastomer: cross-linker = 5:1, 10:1, and 15:1) was then poured onto the wafer inside the mold structure to produce the 3mm- and 6mm-thick chip with the characteristic fluidic structure. The microfluidic chip was cured at 85 $^{\circ}\text{C}$ for 1 hr for PDMS cross-linking effect. The microfluidic chip was then peeled off the wafer/photoresist and holes for inlet and outlet ports fabricated using a 19 gauge punch (Technical Innovations, Inc., Brazoria, TX). The microfluidic chip and glass slide (Fisher Scientific, Pittsburgh, PA) were exposed to oxygen plasma (Plasma cleaner PDC-326, Harrick Plasma Inc., USA) to make a hydrophilic surface, allowing for easier liquid filling and strong bonding.³²

The microfluidic chips produced by this procedure contained fabricated channels with a measured width of $243 \pm 1 \mu\text{m}$ and measured heights of $50 \pm 2 \mu\text{m}$ and $243 \pm 8 \mu\text{m}$, respectively. An aligned row of periodic obstacles were arranged along the centerline of each channel,

as shown in Figure 2(b). The microfabricated circular obstacles in this study exhibited characteristic lengths of $172\ \mu\text{m}$.

D. Flow and bulging measurements

The flow front along the microfluidic channel was followed by microscopic observation (Nikon Ti/U E20L80 Inverted Microscope, Japan) and recorded with an image intensifying CCD camera (Nikon Digital Sight DS-Q1MC). The recorded image movie files enabled direct determination of the position of the liquid front as a function of time and also calculation of the bulging of microchannels. The position of the liquid front was analyzed by Nikon viewer software. The pressure data recorded on computer 1 (see Figure 2(a)) by time stamping the pressure data file at the moment when the liquid front just touched the first obstacle were synchronized in time with the CCD image files recorded by computer 2 (see Figure 2(b)). The relationship between the imposed flows and the pressure drop developed along the microfluidic channels was investigated to determine whether uncontrolled PDMS bulging was created from pressure-driven flows. Each experiment was repeated a minimum of three times and new, unused microfluidic channels were used for each experimental measurement. This method was then cross-checked with the method using Imaris 4.2 image analysis software (Bitplane Inc., South Windsor, CT, USA) based on 3D confocal images (Nikon A1, Japan).²² The difference between the two methods was less than 8%, so this method provided a reliable measurement for PDMS bulging. Bulging displacement during pressure-driven flows was measured by fluorescence microscopy as a syringe pump delivered a $100\ \mu\text{M}$ solution of rhodamine 6G dye into the microchannels at two different flow rates. A line scan technique shown in Figure 3 was used to measure the intensity of the fluorescence dye as it moved in-between the obstacles. The baseline measurement was also measured at a zero flow rate when the initial channel height was at its original value.

FIG. 3. Images of channel section with different flow rates (left: no flow, right: $2\ \mu\text{l/min}$) and line scan (red line).

E. Finite element methods

Finite element simulations for the interaction between liquid flow and the flexible PDMS channel deformation were performed using commercial software (ANSYS Workbench, NH, USA). In order to compare simulated channel deformations and experimental results, the significant strategy of simulation was to reduce geometrical complexity from 3D to 2D. The generated geometry and mesh used in this study were shown in Figure 4, which investigated using the line scan area to make a simple modeling. The PDMS structure used for channel deformation measurements had two wall thickness (6 mm and 3 mm) and the width of a 30 mm rectangular structure. The microchannel structure inside the PDMS structure had two different heights (50 μm and 243 μm) and a width of 243 μm . The refinement of 2D mesh by means of increasing relevance for finite element simulation provided more reliable data in ANSYS Workbench.³³ The classical material properties of PDMS were initially used in this simulation. The Poisson ratio was 0.49, which was considered a perfectly incompressible material. The Young's modulus was assumed to be 750 kPa.³⁴ Both sidewalls were set as the free boundary condition and the bottom wall between the PDMS structure and glass slide was set as the fixed support because the PDMS channels were strongly sealed onto the glass slide. The ANSYS Workbench results were then compared with scaling analysis which assumed the shapes of PDMS displacement were parabolic due to applied high flow rates. Since the operated flow rates in this experiment were much lower than other studies, it is important work to determine whether scaling analysis is still available to use in this study. The experimental Young's modulus was applied to the ANSYS Workbench simulation and compared with experimental bulging. The differential pressure transducer was connected to the channel inlet, assuming the pressure decrease as the channel outlet approached ambient value.²² The estimated pressure was then applied to the finite element simulation and created the entire PDMS bulging. A mesh refinement study indicated that a mesh of 3277 nodes and 1032 elements would reliably simulate the current structure.

III. THEORETICAL BACKGROUND

The pressure drop across microchannel length L is represented by³⁵

$$\frac{\Delta p}{L} = Q \frac{12\mu}{h^3 w}, \quad (1)$$

where Δp is the pressure drop across channel length L , μ is the kinematic viscosity of the Newtonian flow, Q is the applied flow rate, and h is the channel depth. Note that if the imposed flow rate became double, the predicted values of $(\Delta p/\Delta x)_{QS}$ should become double based on the assumption that the microchannel has rigid walls. In order to understand the interaction between fluid and flexible PDMS structure, numerical simulations are used to predict the extent of the channel displacement along with pressure distribution inside flexible microchannels. Since an analytical approach is too complicated to solve the system of equations, a scaling approximation provides a proper estimation of the amount of channel deformation based on applied pressure. Also, scaling analysis has been widely used when the applied flow rates are relatively high. The relative equation for the maximum thickness variation of a microchannel at any given position can be described as^{22,23,35}

FIG. 4. Geometry and mesh used in ANSYS Workbench and PDMS bulging result.

FIG. 5. Experimentally determined relationship between pressure drop along with channel length and imposed flow rates in the microchannel with a 50 μm channel height.

$$\frac{\Delta h_{\max}}{h_0} = c_1 \frac{pw}{Eh_0}, \quad (2)$$

where $\Delta h_{\max}$ is the height increase at mid-width of the channel under deformation, h_0 is the initial channel depth, w is the channel width, c_1 is a fit parameter, and E is the Young's modulus of PDMS (750 KPa). The total microchannel height as a function of any position is dependent on the measured pressure as

$$h(z) = h_0 \left(1 + \alpha \frac{p(z)w}{Eh_0} \right), \quad (3)$$

where $\alpha = \frac{2}{3}c_1$. However, there are some restrictions to applying this method. One is if the applied flow rates are high enough with relative displacements. The other is if the shape of the deforming PDMS wall is parabolic.²²

FIG. 6. Comparison of fluorescence intensity by various flow rates.

IV. RESULTS AND DISCUSSION

A. PDMS bulging analysis

From the measured data, the experimentally determined relationship between pressure drop along with channel length and imposed flow rates did not show the linear relationship, while the theoretical rigid channel did showed the linear relationship. From Figure 5, it is indicated that uncontrolled PDMS bulging takes place in the elastic PDMS microchannels, since it is against Eq. (1). The predicted quasi-steady final $(\Delta p/\Delta x)_{QS}$ values are expressed in a dotted line. Non-linear behavior indicates that elastic PDMS microfluidic channels tend towards unwanted channel expansion as a result of the imposed flows. In addition, more on this non-linear behavior is presented, where the severely non-linear behavior is observed in the soft PDMS microfluidic channel by reducing component B (a cross-linker) or increasing component A. It is also observed that the measured pressure in the flexible channel is lower than that of the rigid channel because the flexible channel is able to increase cross-sectional areas.

(a)

(b)

FIG. 7. (a) The experimental measurements of the elongation and the corresponding force and (b) analysis of the Young's modulus with various mixing ratios and wall thicknesses of PDMS.

The fluorescence intensity measured at the baseline measurement is used to quantify the channel deformation using the relationship between dye layer thickness and fluorescence intensity in fluorescence microscopy with pressure driven flow, as shown in Figure 6. The principle of this measurement is based on rhodamine dye thickness, which is proportional to fluorescence.²³ PDMS microchannel displacements can then be estimated from dye intensity changes. Increasing flow rates provide great intensity because of their great channel deformation as shown in Figure 6. However, it indicates that the shape of the deforming wall is analogous to a flat wall rather than parabolic wall if the applied flow rate is low.

B. Numerical simulations

The relationship between the stress and the corresponding strain curves was discovered according to the experimental measurements of the elongation and the corresponding force in Figure 7(a). The stress-strain relationship of PDMS specimens is represented in the elastic nature of the PDMS. The actual Young's modulus in PDMS microchannels was applied to the finite element method, as shown in Figure 4. The Young's modulus was analyzed by a slope of the stress-strain curve. The measured data with different mixing ratios and wall thicknesses of PDMS are shown in Figure 7(b). It is clear that the Young's modulus of elastic PDMS is proportional with the wall thickness of PDMS. It is also indicated that the Young's modulus of

FIG. 8. Analysis of finite element method and scaling analysis for circular 50 μm channel height at both flow rates: (a) 1.0 μl/min (C1:1.815) and (b) 2.0 μl/min (C1:2.121).

PDMS wall thickness decreased with decreasing wall thickness. However, the wall thickness does not provide an enormous difference. Instead of wall thickness, various mixing ratios of PDMS solutions provide a more dominant effect to Young's modulus. The analyzed data show that the Young's modulus decreases as the ratio of A:B increases. The soft material properties are observed in the case of the high portion of A and the low portion of B in the PDMS. This property is attributed to the polymerization of the PDMS.

Two different numerical methods, finite element method and scaling analysis, were compared and analyzed the characteristic feature discrepancies at low flow rates. The comparison of the finite element method and scaling analysis is shown in Figure 8. Since the shape of the deformed PDMS wall is not fully parabolic (Figure 6) with applied low flow rates, the comparison of the two methods provides information on whether scaling analysis is available in the case of low flow rates and non-parabolic shapes of PDMS bulging. Figure 8 clearly shows that the discrepancies become smaller as the flow rates increase. This means that the shape of the deforming wall is not fully parabolic when the applied flow rate is $1 \mu\text{l}/\text{min}$. The differences between the two methods ranged from 5% to 8% at $2 \mu\text{l}/\text{min}$. However, when the applied flow rate is $2 \mu\text{l}/\text{min}$, the deforming wall begins to resemble a parabolic

FIG. 9. Analysis of PDMS microfluidic channel ($50 \mu\text{m}$ height) bulging using two different wall thicknesses under the same mixing ratio (10:1): (a) Experimental and (b) ANSYS workbench analysis.

shape, but is not a perfect match. As a result, scaling analysis is able to estimate the proper amount of deformation when the applied flow rates are larger than at least $2\ \mu\text{l}/\text{min}$. From Figures 8(a) and 8(b), the predicted microfluidic channel deformation is strongly a function of applied flow rates. This means that the flow of $2\ \mu\text{l}/\text{min}$ experienced larger deformation than the flow of $1\ \mu\text{l}/\text{min}$.

C. Experimental and FEM PDMS displacement

The experimental PDMS bulging is compared with simulation data from ANSYS Workbench software, as shown in Figures 9 to 11. The new data set from the present investigation provides a significant contribution to increasing a fundamental understanding about PDMS material property and microchannel design strategy, as the microfluidic channel itself has complicated structures and operates at very low flow rates. There are four important factors to be considered in this study, the first of which is PDMS wall thickness. PDMS bulging property at two different wall thicknesses (3 mm and 6 mm) is characterized with experimental and

FIG. 10. Analysis of PDMS microfluidic channel ($50\ \mu\text{m}$ height) bulging with various mixing ratios and 6 mm the wall thickness: (a) Experimental and (b) ANSYS workbench analysis.

ANSYS Workbench analysis, as shown in Figure 9. It exhibits that the thinner wall of PDMS tends toward strong bulging at the same flow rates. For example, large discrepancies shown in Figure 9 are observed throughout portions of the inlet where the maximum pressure achieved. In addition, the applied flow rates, a significant physical factor for channel deformation approved by several studies, also provide different aspects for channel deformation in this study. However, the most important finding in this study is the mixing ratio, which contributes to changes in PDMS material properties. For instance, PDMS microfluidic channels using 6 mm wall thickness, shown in Figure 10, demonstrate the importance of PDMS mixing ratio. The flexible (mixing ratio = 15:1) channels shows a significant deformation rather than rigid (mixing ratio = 5:1) channels. The findings of the present study demonstrate that the channel flexibility (mixing ratio = 15:1) is one of the most important material properties with respect to channel deformation, rather than the applied flow rates and wall thickness. This means that material property control in this study is responsible for channel deformation along with physical conditions. In addition to material property effect on PDMS bulging, Figure 11 provides important

FIG. 11. Analysis of PDMS microfluidic channel bulging with two different aspect ratios (50 μm height:0.21, 243 μm height:1) under the wall thickness (6 mm) and mixing ratio (10:1): (a) Experimental and (b) ANSYS workbench analysis.

chip design strategies to avoid PDMS bulging. When the aspect ratio (channel height/channel width) of the microchannels becomes 1, serious bulging phenomena shown in a 50 μm channel height (aspect ratio = 0.21) is significantly reduced. It indicates that fundamental understanding of the importance of microchannel design plays a pivotal role in avoiding serious bulging in microdevices. From Figures 9(b)–11(b), data analyses with the finite element method indicate that the difference between the experiment and finite element method is not significant.

V. CONCLUSION

This paper has described the elastic property of PDMS with two different flow rates, various mixing ratios, different wall thicknesses, and different aspect ratios of rectangular PDMS microfluidic channels. The very low Reynolds number liquid-flows under the low flow rates moved through homogeneously embedded circular obstacles and simultaneously measured the pressure distribution. The deformation of the flexible channel using fluorescence microscopy provided a cost effective alternative method compared to confocal microscopy. The classical PDMS properties were used to predict microchannel displacements with two different simulations such as FEM and scaling analysis. Even though scaling analysis is one of the outstanding methods to assume PDMS bulging, this method does not satisfy with a prerequisite, parabolic shape of the deforming wall at low flow rates. The discrepancies were found to be at low flow rates and became smaller as flow rates increased. As a result, scaling analysis is able to estimate the proper amount of deformation when the applied flow rates are larger than at least 2 $\mu\text{l}/\text{min}$. The experimentally determined Young's modulus was used to produce more reliable data due to its impact on PDMS bulging. In addition, the achieved pressure indicated that the measured pressure in the flexible channel was lower than that of the rigid channel because the flexible channel was able to increase cross-sectional areas. Increasing cross-sectional areas due to microchannel displacements corresponds with deceleration of the pressure distribution and the fluid velocity along the axis. It was observed that liquid flowing through a lower mixing ratio (5:1) and thicker-walled PDMS (6 mm) channels were inclined to achieve strong pressure with small displacement. It was demonstrated that the deformation of PDMS microfluidic channels was strongly dependent on three important physical factors related to material rigidity, such as wall thickness, mixing ratio, and applied flow rates. Among them, a various mixing ratio was one of the strongest factors to determining PDMS properties, while PDMS wall thickness and applied low flow rate showed relatively minimal influence. In addition to material rigidity, design of the microchannel played a key role to controlling PDMS bulging. The serious PDMS bulging was also significantly attenuated by increasing the aspect ratio of the microchannels. The aspect ratio of 1 significantly reduced PDMS bulging compared to the low aspect ratio microchannels. Therefore, design of the microchannel, along with the various mixing ratios, can control PDMS bulging. Experimentally measured channel deformation was larger than the numerical simulation even though the predicted values were located in the experimental range.

ACKNOWLEDGMENTS

This project was funded by the U.S. Federal Aviation Administration (FAA) Office of Aerospace Medicine through the National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE), Cooperative Agreement 07-C-RITE-AU. Although the FAA has sponsored this project, it neither endorses nor rejects the findings of this research.

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