Ferrofluid-based microchip pump and valve

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Abstract

Fluid control is a key element in the performance of microfluidic "lab-on-a-chip" devices. The development of integrated multi-function micro-chemical reactors and analysis platforms depends upon on-chip valving and pumping. In this work, microfluidic valves and pumps were fabricated from etched glass substrates each bonded to a second glass substrate lid that had ultrasonically drilled access holes. The devices contained ferrofluid plugs of approximately 10 mm in length that were actuated by external magnets. The ferrofluid used in the devices was a colloidal suspension of ferromagnetic particles in a hydrophobic fluorocarbon carrier and was immiscible in water. With air in the channels, ferrofluid devices could withstand pressures of 12 kPa and could be opened and closed against pressures of 8.5 and 5.0 kPa, respectively, under a magnetic field of 2.8 kG. A ferrofluid pump comprising a ferrofluid piston and two ferrofluid valves was able to generate air pressures in excess of 5 kPa. In untreated glass channels, leakage of water around ferrofluid seals was significant. However, when the portions of the channel network that contained the ferrofluid were coated with a hydrophobic organo-silane, leakage was not detectable.

Keywords: Ferrofluid; Valve; Pump; Microfluidic; Lab-on-a-chip

1. Introduction

Fluid control, namely pumping and valving, is critical for microchip-based chemical processing. For many microchip applications, electrokinetic (EK) effects alone are sufficient to provide all necessary fluid control. Electrokinetic pumping, i.e., electroosmosis, has been very effective in microfluidics through the application of high voltage to the fluid access points and reservoirs on the chip [1–4]. The same EK application of voltages can be used for valving [1,3,5]. EK pumping is sensitive to channel surface conditions, buffer composition, meniscus effects at reservoirs [6] and is subject to breakdown. Since EK valves are not physical barriers they can leak as result of diffusion or small electrical current flows at the channel junctions. Evidently, other pumping and valving techniques would be useful for integrated microchip processing.

A variety of microfluidic control elements have been reported, many of which are peristaltic or diaphragm devices based on piezo-electric [7,8], magneto hydrodynamic [9–11] pneumatic [12–14], electrostatic [15] and magnetic [16–19] actuation. Such devices generally require extensive fabrication such as deep reactive ion etching or multi-masking steps on the substrate material. Many approaches use diverse bonded polymers in membrane microfluidic devices [12,16,17]. The reported pressures accommodated by these devices range from millimeters to a few meters of water (ca. 0.03–30 kPa). Although rarely measured, leakage is mentioned as a common problem likely due to the difficulties of preparing smooth valves and valve seats.

The purpose of this work was to investigate the use of magnetically actuated ferrofluid plugs in microchannels. Ferrofluids are magnetic fluids created by suspending ferromagnetic particles in a carrier fluid. The particle size is typically 10 nm. Carrier fluids can be water, diesters, hydrocarbons or fluorocarbons and have a range of physical properties to serve many different applications. Ferrofluids conform to the channel shape, potentially providing very good seals and respond to external localized magnetic forces, providing easy actuation. These features offer advantages over other methods of fluid control. Previously, we reported the use of ferrofluids as valves in microchannels [20]. Hatch et al. [21] described the use of ferrofluids based on piezo-electric [7,8], magneto hydrodynamic [9–11] pneumatic [12–14], electrostatic [15] and magnetic [16–19] actuation. Such devices generally require extensive fabrication such as deep reactive ion etching or multi-masking steps on the substrate material. Many approaches use diverse bonded polymers in membrane microfluidic devices [12,16,17]. The reported pressures accommodated by these devices range from millimeters to a few meters of water (ca. 0.03–30 kPa). Although rarely measured, leakage is mentioned as a common problem likely due to the difficulties of preparing smooth valves and valve seats.

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were used to produce the magnetic fields. Alnico magnets were purchased from ALL Magnetics (Anaheim, CA). Samarium-cobalt and neodymium-iron-boron magnets were from Johnmaster Magnets (Mississauga, ON, Canada).

2.1. Materials and reagents

The water-immiscible fluorocarbon-based ferrofluid NF-554A was generously provided by Ferrofluidic Inc. (Nashua, NH). It had a viscosity of 600 cP and a maximum magnetization of 300 G. H1H1H2H2H perfluorodecyltrichlorosilane (FDTS) was obtained from Lancaster Synthesis (Georgetown, ON, Canada). Magnets ranging in size from 0.125 to 0.250 in. diameter, and from 0.06 to 0.125 in. thick were used to produce the magnetic fields. Alnico magnets were used to produce the magnetic fields. Alnico magnets were purchased from ALL Magnetics (Anaheim, CA). Samarium-cobalt and neodymium-iron-boron magnets were from Johnmaster Magnets (Mississauga, ON, Canada).

2.2. Device fabrication

Devices were fabricated in 4 in. × 4 in. Corning 0211 glass, 0.5-mm thick, using single-mask micro lithographic patterning and an HF/HNO3 etchant [22,23]. Devices consisted of two pieces of bonded glass. The masked patterns used to produce the channel networks were isotropically etched from an initial width of 10 μm to a depth of 20 μm. After etching the channels had a roughly semicircular (or D-shaped) channel cross-section with a top width of 50 μm, a bottom width of 10 μm and curved sides of radius 20 μm. Some devices contained larger features, etched to the same 20-μm depth, that were used in valve experiments. Dimensions for these are given in the figure captions. Access holes, 1.6 mm in diameter, were drilled ultrasonically in the top plate. The plates were cleaned and then bonded at elevated temperature, as previously described [1].

In some of the devices the channels were modified using a self-assembled monolayer (SAM) of FDTS by either flow-through or masked methods. In each method the surface was treated with aqueous potassium hydroxide (45%, w/w), rinsed with de-ionized water, dried with nitrogen gas, then treated sequentially with neat isooctane (HPLC grade, Fisher Scientific), 1 mmol FDTS in isooctane, then neat isooctane for 5 min each. In the flow-through method the modification took place after the cover plate was thermally bonded to the etched plate. The chemicals required for the monolayer assembly were driven through the device in the above order by syringe via the access holes. The potassium hydroxide solution was diluted 1:1 (v/v) with de-ionized water to reduce the viscosity, and was pumped through the device for 1 h. Rinse water then was pumped through the device for 10 min. In the masked method the SAM/FDTS modification was carried out prior to bonding. To do so a thin layer of chromium was sputter deposited on both the etched plate and the cover plate. Standard photolithographic procedures [22] were used to remove the chromium to reveal the alignment marks and the locations where the SAM/FDTS layer would be formed. The remaining photoresist was stripped from the plates. The formation of the SAM/FDTS was achieved by immersion of the plates in baths of the chemicals in the above order. The photoresist was spotted onto the alignment marks with a syringe, then soft-baked. The remaining chromium and the spotted photoresist were sequentially stripped from the plate, leaving only the FTDS and the chromium alignment marks. The top and bottom plates were aligned using the alignment marks and bonded following the procedures of [22]. The bonding temperature was maintained below 150 °C (ca. 145 °C) to protect the FTDS monolayer. In separate experiments the hydrophobic properties of FTDS monolayer were observed to withstand heating for 2 h at 150 °C. The lower bonding temperature resulted in a weaker bond than is
creased slowly on the constrained plug at about 0.5 kPa/min (Upchurch cat# F-290 and F-294). The air pressure was in-
Harbor, WA) and PEEK flat-bottomed ferrule-nut fittings
connected to a small electric air pump (KNF Neuberger Inc.,
the access holes remained open to the air; the other was con-
sured 0.5 mm (the plate thickness) from the magnet. One of
ferrofluid plug between 2.4 and 5.8 kG. The field was mea-
varied using permanent magnets having field strengths at the
constrained by a permanent magnet. The magnetic field was
of ferrofluid was drawn into the channel, positioned, and
Fig. 2). For sustainable pressure experiments, a 10-mm plug
m deep) with an access hole at each end (see
the lower sketch. The lower sketch depicts the cross section of microfluidic chip
contain the etched glass channel plate and the bonded cover plate. The
bottom width of the channel was 10 μm. The upper sketch depicts the
layout for the compression experiment to determine static leakage. The
chip and channel geometry for the compression experiment was that of
the lower sketch.

Fig. 2. Sketches of microchip channels, ferrofluid plugs and magnets (not
to scale). The lower sketch depicts the cross section of microfluidic chip
containing the etched glass channel plate and the bonded cover plate. The
bottom width of the channel was 10 μm. The upper sketch depicts the
layout for the compression experiment to determine static leakage. The
chip and channel geometry for the compression experiment was that of
the lower sketch.
standard for such devices, but adequate for the experiments
described here.

2.3. Methods

The performances of several ferrofluidic device configu-
ations were evaluated, including: (1) a plug in a straight
channel; (2) a Y-valve; (3) a well valve; and (4) a pump com-
prising two well valves and a plug-piston. Ferrofluid was
introduced into the chips through one of the access holes
and positioned in the microchannel by a combination of cap-
illary action and an external permanent magnet. Ferrofluid
plugs of approximately 10 mm were easily formed in the
microfluidic channel network.

Sustainable pressure and static leakage experiments in
ferrofluid devices were carried out on a chip containing a
70-mm straight channel (50-μm wide top, 10-μm wide bot-
tom, 20-μm deep) with an access hole at each end (see
Fig. 2). For sustainable pressure experiments, a 10-mm plug
of ferrofluid was drawn into the channel, positioned, and
constrained by a permanent magnet. The magnetic field was
varied using permanent magnets having field strengths at the
ferrofluid plug between 2.4 and 5.8 kG. The field was mea-
sured 0.5 mm (the plate thickness) from the magnet. One of
the access holes remained open to the air, the other was con-
ected to a small electric air pump (KNF Neuberger Inc.,
Trenton, NJ, model UNMP02) and a pressure sensor (Hon-
eywell, North York, ON, model 18SPC125DT) using PEEK
tubing (1/16 in. o.d., 0.030 in. i.d., Upchurch Scientific, Oak
Harbor, WA) and PEEK flat-bottomed ferrule-nut fittings
(Upchurch cat# F-290 and F-294). The air pressure was in-
creased slowly on the constrained plug at about 0.5 kPa/min
and the position of the plug was monitored visually. As the
pressure increased the plug shifted toward the low-pressure
end of the channel. This shift continued until the magnet
was no longer able to hold the plug in place. The pressure
just prior to the plug being expelled from the magnetic field
was recorded as the sustainable pressure. After the plug was
expelled the air pump was shut off. The blowout process
ejected a portion of the plug out the low-pressure access hole
and shattered the portion that remained in the channel. The
remain of the ferrofluid plug were removed by a hand-held
magnet.

For static leakage experiments two 10-mm plugs were
created in the microchannel between the access holes. A
plug of air approximately 35 mm long separated the fer-
rofluid plugs. The chip was placed in a holding frame
and the distance between the plugs was measured using a
stereomicroscope equipped with a reticle. Prior to the ex-
periment, reference marks were scored onto the cover plate
using a fine scribe; the positions of the plugs were measured
using a ruler and the reticle with respect to the reference
marks. The accuracy of the measurements was ±30 μm. Af-


and the closing pressure was the highest pressure measured stati-

cally when the valve was closed and there was no pressure

drop due to fluid flow, for which this process could be

completed. Closing pressures were measured by applying

a pressure to the channel while the valve was closed. The

valve was opened by drawing the ferrofluid into the well.

The opening pressure reported was the highest pressure,
3. Results and discussion

3.1. Sealing action and sustainable pressure of ferrofluids

The first step in the development of ferrofluidic devices was to demonstrate the ability to control the movement of a ferrofluidic plug and to compress air in microfabricated glass channels 50 μm wide at top, 10 μm at bottom and 20 μm deep. Plugs of ferrofluid, typically 10 mm in length, could be repeatedly shunted back and forth using a permanent magnet. When the plug was shuttled into a dead end channel, the air could be readily compressed to a pressure greater than 10 kPa above ambient, as calculated by the ideal gas law. A plug velocity of 1.3 mm/s (1.0 nl/s) in air-filled capillaries under magnetic control was readily achieved. In channels where the ferrofluid plug was used to push a 10-mm plug of water, the maximum plug velocity was about 0.5 mm/s (0.4 nl/s).

The ability of a ferrofluid to function as a seal for an air-filled channel was examined by determining the upper limit of static sealing of a 10-mm ferrofluid plug in a known magnetic field. One side of the plug was at atmospheric pressure and the other side was connected to an air pump and pressure sensor. As the pressure was slowly increased measured statically while the valve was closed, for which the valve would open successfully without having the ferrofluid pushed past the valve and into the outlet channel. Measurement of Y-valve opening and closing pressures was done in a similar manner with one arm of the Y being held at pressure and the other arm and the stem, which contained the bulk of the ferrofluid, being open to the atmosphere. The valve was closed by drawing ferrofluid from the stem into the junction of the stem and the two arms (see Fig. 1).

The microchip that was used as the ferrofluidic pump contained two well valves, a piston consisting of a 10-mm ferrofluid plug in a 40-mm long, 0.50-mm wide straight channel, and access holes. This device was etched to a depth of 30 μm. A laboratory-built mounting frame equipped with computer-controlled stepper motors was constructed to operate the pump device. The pumping action was monitored by an off-chip pressure sensor (Honeywell 185PC15DT) connected to one of the access holes via PEEK tubing and PEEK ferrules (Upchurch). The dead volume between the high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl. The stepper motor apparatus contained three magnets each of high-pressure valve and the sensor was about 40 μl.

Fig. 3. Sustainable and operating pressures of ferrofluidic devices in a magnetic field. The plot shows the maximum sustainable pressure for 10-mm ferrofluid plugs in an open-ended straight (air- or water-filled) channel device, indicated by the legend as “channel.” Also shown are the maximum closing pressures of a well valve in an air-filled device. The solid line represents the calculated values (from Eq. (2)) of the maximum sustainable pressure for a 10-mm ferrofluid plug in an air-filled channel.

The pressure difference between the ends of a ferrofluid plug in a narrow straight channel can be expressed to first order as

$$\Delta P = \mu (M_1 H_1 - M_2 H_2) \quad (1)$$

where $\mu$ is magnetic permeability and $M$ and $H$ are the magnetization and magnetic field strength, respectively, of the ferrofluid at the ends of the plug [24]. The high and low-pressure ends are denoted by 1 and 2, respectively. $H$ is a property of the configuration of the magnet and channel and was measured using a Gauss meter. $M$ is a property of the ferrofluid in a magnetic field. Magnetization curves were supplied by the ferrofluid manufacturer so that $M(H)$ could be determined. In the absence of external pressure the plug centered itself above the magnet in the channel; the force at each end was equal and the net pressure was zero. When an external pressure was applied to one end of the plug, the position shifted so that the magnetic pressure was equal to the applied pressure. As the applied pressure was increased the plug shifted to a position of increased magnetic pressure. The maximum pressure occurred when the applied (high) pressure end of the plug was at the center of the magnet. The ferrofluid plug was sufficiently long that at the position of maximum sustainable pressure, the low-pressure end of the plug extended to a region of low magnetic field, thus...
The maximum pressures were calculated using Eq. (2) and are shown in Fig. 3. The calculated and measured values are in good agreement, although at the high range of the magnetic field (5.8 kG) the calculated pressure exceeds the experimental by about 11% suggesting that the $M_1H_1$ term in Eq. (1) was not negligible. These findings on the behavior of ferrofluid plugs in microchannels, namely the relative ease of movement of ferrofluids in microfabricated channels and the ability of plugs constrained by external magnets to withstand pressure, indicated the potential use for ferrofluids in microchip fluid control devices.

3.2. Static leakage of air in a ferrofluidic device

The effectiveness of a ferrofluid seal is dependent upon the leakage at the ferrofluid-glass interface. Two types of leakage are possible: dynamic leakage that occurs while the plug is moving and static leakage that occurs while the plug is stationary. In order to determine the extent of static leakage, air was compressed by a pair of magnetically actuated ferrofluid plugs and maintained in the compressed state for an extended period of time (as depicted by Fig. 2). The plugs were then restored to the original positions to prevent or minimize dynamic leakage and the magnets were removed. The experiment was designed so that static leakage of air while under compression would be observed as a decrease in the distance between the plugs (correcting for ambient temperature and barometric pressure) after removal of the magnets at the end of the experiment. The magnets were quasi-statically (slowly) moved toward each other, over a period of 18 h, so that the air within was compressed to about 15 kPa above ambient pressure, calculated by the ideal gas law. The system was left unperturbed for 6 days to give the seals ample time to leak after which the magnets were removed.

3.3. Ferrofluidic valves

The experiments above demonstrated the use of ferrofluid plugs as passive components, i.e., seals, in microfluidic devices. Valves require active components to control fluids in channels. Thus for valve operation a ferrofluidic device would be required to open and close, often against a pressure differential. The first valve design implemented was the Y-structure shown in Fig. 1 wherein a magnet was used to draw the ferrofluid out of the branches of the “Y” and into the side channel to open the valve and allow the air to flow. Under a magnetic field of 2.8 kG, valve action in the Y-structure, both opening and closing, could be accomplished provided the pressure during the transition was low, below 1.5 kPa. However, when opening against a pressure greater than about 2 kPa, we observed the loss of small portions of the trailing end(s) of the ferrofluid plug that were subsequently carried downstream with the fluid flow. Similarly when closing against an air flow there were losses at the edge leading into the arms of the Y-channel. Although the Y-valves could be operated at higher pressures using stronger magnets, some ferrofluid was always lost.

The well valve (Fig. 1) was an alternate design. The external magnet was used to close the valve by drawing the ferrofluid from the well region into the narrow neck that leads to the channel. Under a magnetic field of 2.8 kG the valve could be opened against an air pressure differential of 8.5 kPa without any noticeable loss of ferrofluid at the valve exit. Under the same field it could be closed effectively against a pressure of 5.0 kPa. At higher magnetic fields the operating pressures were higher. The closing pressures of a well valve at various magnetic fields are given in Fig. 3 and are similar to the sustainable pressures of ferrofluid plugs in a straight channel. The well design proved more reliable than the Y-design since it was less susceptible to loss of ferrofluid through self-recovery of the detached fragments back into the well. Fig. 4 shows a photograph of the valve in operation. Typical transition times for valve opening or closing were 15–30 s.

3.4. Pumping action of a ferrofluidic device

A microchannel ferrofluid device capable of executing pumping action in air-filled channels was constructed. A schematic diagram is given in Fig. 5. The device contained three active components, a ferrofluidic piston and two ferrofluidic well valves (of the type described above). In order to monitor the pressure continuously during the experiments an external pressure sensor was employed. The dead volume associated with the off-chip sensor was 40 μl, which was large compared to volume elements on the chip and those normally used in microfluidic devices; hence the piston stroke in the device needed to be large, ca. 2 cm. This length of the stroke plus the high viscosity of the ferrofluid produced a cycle time of about 30 min. The action of the device was to pump air from the atmosphere to the off-chip...
dead volume and pressure sensor. The volume of the piston channel was 520 nl when fully drawn and 210 nl when fully compressed. Each stroke displaced 310 nl of air. During the draw stroke the output valve was closed and the intake valve was open to the atmosphere so that the piston could draw air into the piston channel. After the draw stroke was completed, the intake valve was closed, the output valve was opened, and the compression stroke was initiated. The piston pushed air from the piston channel into the dead volume. The event sequence and timing for the pump is shown in Table 1.

Fig. 6a shows the results of an experiment with the pump device over 30 cycles; each cycle was 30–31 min. The maximum pressure attained in the experiment shown was 5.7 kPa. Several cycles of pumping action were required before the internal pressure started to increase. Fig. 6b (inset) is an expanded time scale over five cycles of pumping. At the beginning of Fig. 6b the sensor reported an initial pressure of 1.85 kPa. Over the next five cycles the pressure increased to 5.63 kPa. The pressurization curve exhibited a saw-tooth pattern with local maximum and minimum for each cycle. The maximum occurred at the end of the compression stroke; the minimum about a minute after the end of the draw stroke (prior to the beginning of the next compression stroke) when the intake valve was closed and the output valve was opened.

For the data shown in Fig. 6b the mean pressure increase per cycle was 0.78 (S.D. = 0.16) kPa. The decrease in pressure associated with the local minima was about 0.15 kPa.

After the drive mechanism of the pump was stopped and the magnets kept in place, the maximum pressure remained constant. The data in Fig. 6a shows that there was

Table 1: Timing sequence for components of ferrofluidic pump

<table>
<thead>
<tr>
<th>Sequence no.</th>
<th>Magnet action</th>
<th>Function</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>V-in</td>
<td>Closed</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>V-out</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td>Compressed</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>V-out</td>
<td>Open → closed</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>V-in</td>
<td>Closed → open</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>Piston</td>
<td>Draw stroke</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>V-in</td>
<td>Open → closed</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>V-out</td>
<td>Closed → open</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>Piston</td>
<td>Compression stroke</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>Repeat sequence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The behavior of a ferrofluid plug under pressure in a water-filled channel is given in Fig. 3. The maximum sustainable pressure as a function of magnetic field was similar to air. However, unlike air, water in the channels of the ferrofluid device produced static leakage effects that were apparent even over short periods of 15–30 s. Although the position of the ferrofluid plug against the pressurized water could be maintained, water would leak around the plug, eventually equalizing any pressure differential. The build-up of water on the low-pressure side of the ferrofluid plug was readily observed using dyed water. However, the mechanism of the leakage itself was not apparent under a microscope. We hypothesize that the leak was a sheath layer in contact with the channel wall. This hypothesis is supported by the observation that water would spontaneously replace the ferrofluid at the surface of a clean glass slide. During this work we experimented with hydrophobic organo-silane surface coatings to alleviate leakage of water past the ferrofluid–glass interface. We found that channels treated with a self-assembled monolayer of perfluorodecyltri-chlorosilane provided a good seal to the fluorocarbon-based ferrofluid. In channels so treated, water no longer spontaneously replaced the ferrofluid, nor did the ferrofluid spontaneously replace the water. Leakage of water past such a seal was reduced dramatically compared to an untreated channel. The leakage was less than the detectable limit of 70 nl per day at 10 kPa. For untreated channels we observed leakage of 200 nl per day at 0.5 kPa. In well structures (Figs. 1 and 4), valve action of water-filled channels was similar to air-filled. The valves could be closed or opened against about 5–10 kPa, although the measured pressures were dependent on the field strength of the magnet, the amount of ferrofluid in the valve, and the actuation timing.

3.6. Device footprint

The ferrofluidic devices described herein had relatively large footprints. Valves required an area of 1 cm × 1.5 cm and the pumps (including the inlet and outlet valves) required an area of 3 cm × 4 cm. The magnets were up to 0.25-in. diameter and the magnet field spread rapidly through the 0.5-mm thick substrates. The full-width half-maximum of the magnetic field seen by the ferrofluid was about 1.25 times the magnet diameter. To produce significant magnetic pressure, the ferrofluid must span a distance between high and low fields, thus the plug lengths were in the range of 10 mm. Separation of neighboring components was necessary to prevent cross talk that occurred from the overlap of the magnetic fields. The devices were slow due to the high viscosity of the ferrofluids (600 cP) and the channel dimensions (50 μm × 20 μm) that produced a high resistance to flow. Thus the speed of the magnets was limited to the response time of the ferrofluid in the channel. Since narrower channels generate greater resistance to flow, it follows that lower volume devices operate more slowly.

3.7. Pump speed

The operating speed of ferrofluid piston in the pump device was about 30–50 μm/s. When the pump was operated at higher piston speeds we readily observed deformation whereby the ferrofluid moved faster at the walls than in the bulk. The leading ends of ferrofluid along the walls would eventually merge in the channel 0.5–1 mm from the bulk of the piston, thereby forming a bubble of pumped fluid (i.e., air or water) inside the body of ferrofluid plug. We investigated this phenomenon and found that the onset was dependant on the type of pumped fluid (i.e., air or water), the speed of the ferrofluid plug in the
channel, and the cross section of the piston channel. The appearance of bubbles in response to these experimental variables was suggestive of the Saffman-Taylor instability, also referred to as viscous fingering, seen in two-dimensional Hele-Shaw flow cells [25,26]. Extensive investigation and discussion of viscous fingering were beyond the scope of this study. The problem was remedied by keeping the pumping speeds low.

4. Conclusions

The work presents a demonstration of the ability of ferrofluid plugs to function as seals, valves and pumps in standard microfabricated glass structures. To date most of our work on ferrofluidic devices has used air as the fluid in the channels. Potential microfluidic applications for a ferrofluidic pump could use the pressurizer generated on the chip itself to do work. Such devices could be used in gas phase micro-reactors or as pressure sources for driving liquids downstream in a microchannel network. A technical problem that we encountered early on was the leakage of water past the ferrofluid plugs in untreated channels. During the course of the work we addressed this problem using hydrophobic patch coatings of organo-silane liquids downstream in a microchannel network. A technically oriented paper that we encountered early on was the leakage of water past the ferrofluid plugs in untreated channels.

Acknowledgements

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