A Novel Passive Ferrofluid One-way (Check) Valve

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Small pumps and valves enable flow management in microfluidic systems. This paper presents a novel passive ferrofluid check valve, without utilizing mechanical or electrical input, implemented through only a unique channel-and-chamber geometry, ferrofluid, and a stationary magnetic field. The proposed design, open to improvements through various parameters, can be used for microfluid handling and lab-on-a-chip applications. The prototype valve and experimental setup are explained and performance of the valves cracking and collapse pressure reported.

1 INTRODUCTION

Ferrofluid can be manipulated by electronically controlled magnetic fields to exert force on fluids[1, 2, 3]. This makes it possible to build pneumatic or hydraulic devices, perhaps on very small scales such as a single chip[4, 5], to miniaturize fluid handling, often for biomedical purposes[6], although this paper reports only on experiments done with air. This could be used to make a "lab on a chip" (LOC) or even to heat or cool different areas. A fundamental component of such devices is the check or one-way valve. A perfect check-valve opens or *cracks* with minimal pressure on the inlet side and sustains maximal pressure on the outlet side before *collapse*, allowing fluid to flow in only one direction. Following[7] we call the maximum pressure differential the valve can resist in the direction it is intended to check (from outlet to inlet) the *sustainable* or *collapse* pressure. Two check valves on either side of a chamber whose volume can vary creates a positive displacement pump. This paper presents an initial, preliminary design of a functioning passive ferrofluid check valve (PFCV) that has no moving parts except for the ferrofluid bolus itself, which is stationary in normal operation. By passive, the authors mean a check valve that functions without changes to the magnetic field affecting the bolus, whether that field is induced by a permanent magnet or an electromagnet. That is, the flow is determined purely by the difference between the inlet port pressure and the outlet port pressure. (This terminology is not completely standardized, for example [7] uses the term *active* to simply mean a valve that is not a permanent seal.) To our knowledge, no passive ferrofluid check valve has been reported before, despite being an active area of research, and despite such a valve having significant advantages for fabrication over valves with moving parts.

2 RELATED RESEARCH

A number of papers report on ferrofluid pumps, focusing in particular on micropump and lab-on-a-chip applications[3, 8]. Many of these papers use a version of mechanical valve not based on passive ferrofluid. For example, a corrugated silicone micro valve[4, 9] has been reported. Other researchers use active valves, which require syncronization with the ferrofluid plug to form a pump, such as [10], which describes an active T-Valve with a moving ferrofluid plug, and [11] describes a complete fluid pump with valves that use active control of a ferrofluid bolus, which is possible because the action of the plunger may be synchronized with the opening and closing of the valves. Nonetheless a passive valve would be simpler and less expensive, and would not require knowledge of the timing of the plunger. [7] similarly describe two kinds of active valves, a *well valve* and Y valve. A passive ferrofluid two-way valve with tunable opening and closing pressure based on magnetic field strength[12] has been tested, but could not be passively used to make a pump.

This paper has not studied the closing pressure of the PFCV, but reports on the opening (or cracking) pressure

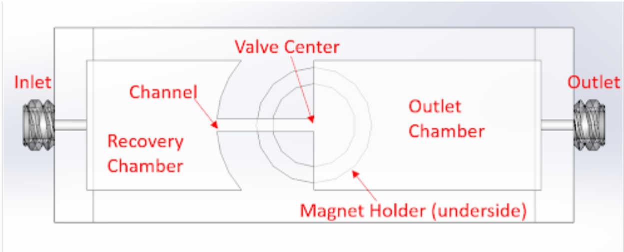

Fig. 1. The passive ferrofluid check valve components

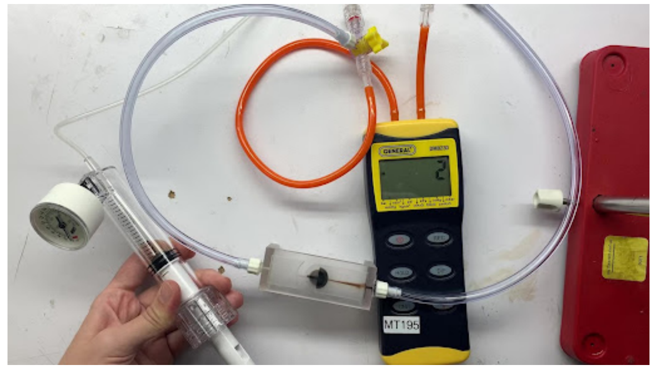

Fig. 2. Equipment set up

(for flow from inlet to outlet) and sustainable (or collapse) pressure when the outlet pressure is higher than the inlet side. An interesting functional micropump in which the moving ferrofluid bolus merges with a fixed ferrofluid valve and then separates on each pumping cycle has been described[5], but is not a one-way valve.

3 PASIVE FERROFLUID CHECK VALVE (PFCV) DESIGN

The PFCV depicted in Figure 1 is a simple asymmetric volume centered in a magnetic field which holds a ferrofluid bolus in place. In the center of a radially symmetric magnetic field a narrow channel meets are large open chamber. The ferrofulid bolus is large enough that at rest in the field it forms a semi-circle in the open chamber. The narrow channel is longer than the radius of the bolus at rest. The broad chamber is the outlet side of the valve. The narrow chamber opens onto a recovery chamber on the inlet side of the valve. This design allows the bolus to be recovered from the recovery chamber when the pressure is equalized if the outlet pressure is raised above the collapse pressure, driving the bolus away from the magnetic field. The PFCV does not perform as well in absolute terms as a large valve made out of moving, solid parts. That is, the sustainable pressure it can resist on the outlet side before failing is relatively low, and pressure required to crack it open and allow flow is relatively high. However, it may operate reliably within a range of known pressures, and thus be sufficient to build a pump-on-a-chip. Furthermore, the PFCV reported here is a preliminary design which can probably be significantly improved. The authors found the existence of the PFCV exciting enough to report on it immediately.

4 METHOD

The valve depicted Figure 1 was designed using Solidworks 2016. The model consists of a 15mm long, 2mm wide and 2mm high channel, two female luers, a magnet holder ring and two legs to provide room for the magnet. Viewed from the top, one end opens up to a recovery chamber of circular profile 30mm in diameter and the other an outlet chamber with a flat wall. A magnet holder ring half an inch in diameter was created centered on the channel-chamber junction, where the bolus is placed, to hold a permanent magnet in place at the center of the valve. When two magnets are used, the magent on top naturally stays in the same position due to attraction to the magent below. On the inlet side the channel opens into a recovery chamber shaped to allow the ferrofluid to be passively drawn back into the channel by the magnetic field after a collapse of the bolus. The model was printed on a Projet MJP 2500 (3D Systems, Rock Hill, SC), using Visijet M2G-CL and VisiJet M2 SUP as material and support respectively (3D Systems, Rock Hill, SC). Support material was removed by using an EasyClean system (3D Systems, Rock Hill, SC) and Dawn dish soap (Procter & Gamble, Cincinnati, OH) to remove residuals.

As shown in Figure 2, a basixCOMPAK 30atm pressurizing syringe (Merit Medical, South Jordan, UT) is connected to the model via a two-way stopcock (Qosina, Ronkonkoma, NY), tubing (Natvar, City of Industry, CA), and male (Injectech, Fort Collins, CO) and female luer (Qosina, Ronkonkoma, NY), allowing integration of a manometer (General Tools, Secaucus, NJ) to measure pressure. A 1/2" x 1" cylindrical neodymium magnet (Apex Magnets, Petersburg, WV) was placed inside the magnet channel by means of a tight fit and 0.4 mL of ferrofluid (Apex Magnets, Petersburg, WV) was injected into the model using a 3mL syringe (BH Supplies, Jackson, NJ).

To obtain values, pressure was applied through the pressurizing syringe. Pressure applied from the outlet side of the model, in which fluid flowed through the channel, will be referred to as the sustainable pressure. Pressure applied from the inlet needed to initiate flow will be referred to as the cracking pressure.

Table 1. Result pressures

Magnet configuration	Cracking Pressure kPa (mmHg)	Collapse Pressure kPa (mmHg)	Pressure Difference kPa (mmHg)	Approx. Ratio: Cracking to Collapse Pressure
Single	1.1 (8)	5.5 (41)	4.4 (33)	1:5
Dual	8.5 (64)	17.5 (131)	8.9 (67)	1:2

The cracking pressure was first measured by increasing the pressure difference on the inlet side until flow is initiated (at which point pushing the syringe plunger faster simply increases flow.) Then the sustainable pressure was measured by increasing the pressure difference on the outlet side. At pressures below the sustainable pressure, the valve holds pressure well with no observable leaks of air in the short time (a few minutes) of our experiment. When the sustainable pressure is exceeded, the bolus explodes violently into the recovery chamber. When the pressure difference is equalized, the bolus may passively recover into the central position, or it may need to be actively "combed" with a magnet back into the central position.

The procedure was performed first with one magnet, named the "Single Magnet" configuration, placed below the channel-chamber connection. The "Dual Magnet" configuration was performed with the magnet in the same position as the Single Magnet case in the same position, but with a second magnet of equal one placed vertically on top of the model, arranged to be strongly attracted to the lower magnet.

5 RESULTS

The final pressures obtained demonstrate a clear difference between the inlet cracking pressure and outlet sustainable pressure, creating an effective passive check valve.

The ferrofluid had observable differences in behavior between the two configurations. With two magnets, when recollecting the ferrofluid to the center of the model (following a collapse of the bolus due to exceeding the sustainable pressure), fluid further from the bolus remained stationary while the fluid closer was pulled back to the center. Following the removal of the top magnet, the stationary fluid then began to return to the bolus. This is consistent with the localization of the magnetic field between two magnets, and the weakening of the magnetic field further from the channel-chamber juncture.

Thus, although the trial with two magnets demonstrated a larger pressure difference due to magnet strength, the single magnet trial granted a larger ratio via expanded field lines.

6 CONCLUSIONS

This paper demonstrates an apparently novel passive ferrofluid one-way valve or check valve (PFCV). This valve is completely passive in that it depends entirely on the pressure at the inlet port and the outlet port. The valve has no moving parts (except for the ferrofluid, which is almost stationary), and a remarkably simple design, consisting of nothing but a channel, a chamber, and a bolus of ferrofluid in a static magnetic field.

Although no effort has been made to optimize the design, the pressure difference between the cracking pressure and the sustainable back pressure appear great enough to make an effective micropump. The performance of this one-way valve may improve with additional design effort; the authors sought to publish this result as soon as it was observed. Obvious future research possibilities are:

1. To improve the performance by varying the geometry of the passive design or shape and strength of the magnets.
2. Utilizing this design to make a micro-pump similar to earlier micro-pumps but with this simpler check valve design.
3. To provide an explanatory and predictive theory of operation, for example based on magnetic field strength as per [11].
4. Studying the ability of the valve to recover after a collapse when high outlet pressure is reduced.

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