A Novel Passive Ferrofluid One-way (Check) Valve Based on Energy Minimization

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ABSTRACT

Small pumps and valves enable flow management in microfluidic systems. A novel passive ferrofluid check valve is presented. The valve consists of only a unique channel-and-chamber geometry, ferrofluid, and a stationary magnetic field. The flow is determined only by the inlet and output pressure, and the magnetic field is completely static. The prototype valve and experimental setup are explained and performance of the valves cracking and collapse pressure reported. This initial design can be used for microfluid handling and lab-on-a-chip applications.

Additionaly we present a theory of operation based on energy minimization and compare predicted performance to actual performance.

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. This has been proposed for biomedical purposes[6] that would use water or body fluids, although this paper reports only on experiments done with air. Miniature pumps and valves could be used to make a "lab on a chip" (LOC) or even to heat or cool different chip areas.

A fundamental component of such devices is the *check* or one-way valve. Two check valves on either side of a chamber whose volume can vary creates a positive displacement pump. 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 or block (from outlet to inlet) the *sustainable* or *collapse* pressure.

This article is a brief report on an initial but functioning design of a 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. To our knowledge, no passive ferrofluid check valve has been previously reported, despite being an active area of research and despite such a valve having significant advantages for operation and especially fabrication over valves with moving parts.

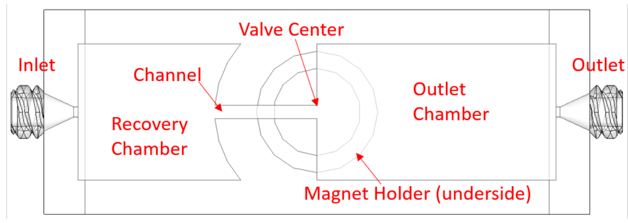

Fig. 1. The passive ferrofluid check valve components

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, even though they move a ferrofluid bolus with a magnetic field. For example, a corrugated silicone micro valve[4, 9] has been reported. Other researchers use active valves, which require synchronization 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. At least two additional kinds of active valves, a *well valve* and *Y-valve*, have been described[7]. Active control is possible because the action of the plunger or bolus 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.

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.

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 (for flow from inlet to outlet) and sustainable (or collapse) pressure when the outlet pressure is higher than the inlet side.

3 PASSIVE FERROFLUID CHECK VALVE (PFCV) DESIGN

The PFCV depicted in Fig. 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 a larger open chamber at a right angle. The ferrofluid 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 resist pressure as well as a valve of the same size 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 worth sharing immediately.

4 METHOD

The valve depicted Fig. 1 was designed using Solidworks 2016. It is freely licensed via the CERN OHL Strong Reciprocal License[13, 14]. The model consists of a 15mm long, 2mm wide channel, a large outlet chamber, a recovery chamber, two female luers, a magnet holder ring and two legs to provide room for the magnet. All volumes are 2mm high. The 3D shape of the chambers can be thought as a 2mm high extrusion of a 2D shape. 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 12.7mm inner diameter (1/2”) was created centered on the channel-chamber junction, below where the bolus is placed, to hold a permanent magnet in place at the center of the valve. When two magnets are used, the magnet on top naturally stays in the same position due to attraction to the magnet below. On the inlet

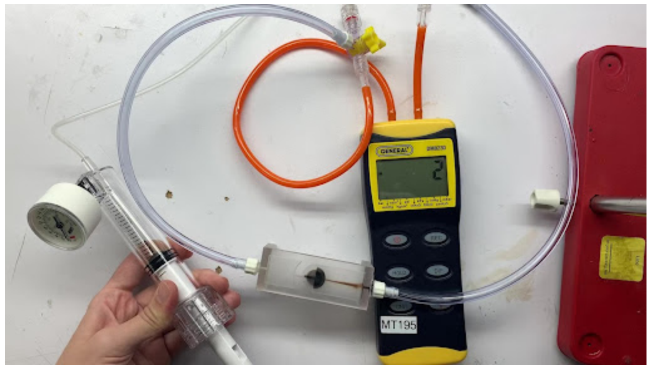

Fig. 2. Equipment set up

side of 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 Fig. 2 and in our demonstration video[15], 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 12.7mm x 25.4mm (1/2" x 1") cylindrical neodymium magnet (Apex Magnets, Petersburg, WV) with a pull force of 14.6 kg (32.24 pounds) was placed inside the magnet channel by means of a tight fit and 0.2 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, as demonstrated in a video [15]. Pressure was first applied from the outlet side of the model. The maximum pressure difference from the outlet side that the valve can withstand before collapsing, will be referred to as the sustainable pressure or *collapse* pressure. Pressure applied from the inlet needed to initiate flow will be referred to as the *cracking* pressure.

The cracking pressure was first measured by increasing the pressure difference on the inlet side until flow is initiated (at which point the valve is "open" and pushing the syringe plunger faster simply increases flow without increasing the pressure.) Then the collapse 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 the same kind 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. After the pressure equalized following a collapse of the bolus due to exceeding the sustainable pressure, the single magnet configuration often repaired itself by drawing the fluid back into a centered bolus passively. After a collapse with two magnets, 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

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 magnetic field between two magnets, and the weakening of the magnetic field further from the channel-chamber juncture in the dual magnet configuration.

Although the dual magnet configuration demonstrated a larger absolute pressure difference due to magnetic field strength between the cracking and the collapse pressure, the single magnet configuration granted a larger ratio of collapse pressure to cracking pressure due to the much lower cracking pressure. The authors conjecture that the low cracking pressure may have been not only to the weaker magnetic field, but the weakening at the top of the 2mm high channel, which was further away from the magnet in the single magnet configuration.

6 THEORY OF OPERATION (BEST AS OF APR. 25)

Let us consider an ideal blob of ferrfoluid.

Assume that a blob in this section means an ideal 2-dimensional blob, approximated by a blob constrained into a very thin plane.
Assume that the B-field is purely perpendicalur to this plane, and that it completely dominates the magnetism induced in the ferrofluid itself.
Assume that all forces of viscosity and surface tension may be ignored.
Although we will not model the forces that make it so, we will assume that blob of ferrofluid is self-connected and will not split into more than one blob.
The blob is perfectly incompressible, and so has an absolutely unchanging area.
The magnetic particles are evenly distributed in the fluid no matter what the magnetic field, so that the potential energy in the fluid by being in the field depends only on the strength of the field.
We need not treat the motion, velocity, or inertia of our fluid in any way.

Under suitable assumptions, we can state two drastically simplifying assumptions.

Conjecture 1 (Magnetostatic Blob Minimization). *The magnetostaic force on an ideal 2-dimensional blob tends to minimize the potential energy in the blob and this occurs when its surfaces are in equal strength fields. Equivalently, every surface of a blob at rest with no outside forces is a line of equal field strength and all surfaces are equal.*

Theorem 1 (Surface Force Computation). *The force exerted on an ideal blob by the magnetic field is the sum over each surface of the integral of magnetic field along that surface, either pushing the surface into the blob or pulling the surface away from the blob.*

Proof. Force is work times distance. Within an infinitessimal distance, force is the change in potential energy. Because or fluid is uniform, the potential energy of a blob one position and a blob displaced from that position by an infinitessimal changes only by the change in the thin areas along the surfaces. The change in potential energy in these infintessimal areas is purely a function of the their path through the B-field and the intensity of the field at that point.

If the area is expanding the blob, it always decreases potential energy. If the area is contracting the blob, it always increasing potential energy. However, since the B-field at the two (or more) surfaces may be different, there may be a force exerted on the blob. In particular, we are interested in the force exerted on the blob counterbalancing the force exerted on by fluid pressure of non-ferrofluid at the surfaces.

Now imagine that a we have a monotone decreasing field centered on the origin which which is not necessarily circular, with the A region containg a thin tube, and the B region containing a wide open region. Imagine that the field in B is radially symmettric, but monotonically decreasing with distrance from the origin (but not necessarily the same in the region A.) A force resisting flow from the outlet to the inlet (from B to A) is equal to the field strength at a point multiplied by the surface length. In this scenario, the air pressure on the blob is a function of the length of the surface, but the magnetostatic force is also a function of length, so the length cancels out and becomes irrelevant. The collapse pressure is therefore the maximum force at any point between the rest position and the origin (this field is by construction equal on a semi-circular arc.) The collapse pressure also depends on the field strength at the point of the surface in A, but this surface has small length, and therefore contributes little to the sum of the force.

Conversely, the cracking pressure will be minimized by making the field strength in the region B as low as possible at the point when the ferrfofuid has been entirely driven into region A by air pressure from the inlet.

Understanding this, we can deign a profile of the ideal magnetic field to maximize the ratio of collapse pressure to cracking pressure as shown in the figure below.

6.1 Warmup: A Bolus in A Channel

A relatively simple problem is to consider a bolus of ferrofluid in thin channel. By making assumptions, we can analyze this to obtain closed form solutions which match our experience and inform more complicated cases. This is depicted in Figure 3.

Consider a thin channel that we will treat as one-dimensional. Imagine that it has an external magnet that produces a field centered on the origin with a strength:

$$B(x) = \frac{1}{1+x^2} \tag{1}$$

$$\tag{2}$$

This field might be hard to produce with actual magnets but is good enough for our analysis; a more complex field can be substituted without changing the approach or the qualitative result.

Now imagine that bolus has a length of 2, and let x be the midpoint of the bolus. The force on the ferrfoluid is purely a function of the position of the two surfaces, which are by construction at $x-1$ and $x+1$. Ignore constants based on units for the time being. For a surface at y,

$$F(y) = \begin{cases} dB(y), & \text{if y} < 0 \\ -dB(y), & \text{if y} \geq 0 \end{cases}$$

The total force on the bolus is by pure algebra:

$$F(x) = F_A(x-1) + F_B(x+1) \tag{3}$$

$$F(x) = dB(x-1) + -dB(x+1) \tag{4}$$

$$F(x) = d(1/(1+(x-1)^2) + -1/(1+(x+1)^2)) \tag{5}$$

$$F(x) = \frac{4dx}{x^4+4} \tag{6}$$

Plotting this function of x, we immediately find it matches our experience. If you put a bolus in a thing straw subject to a magnetic field and blow on it, it will be displaced a bit, increasing the force it exerts on your breath. At some point of increasing pressure, the bolus is displaced to a point that the magnetic force on it goes down, and the bolus explodes violently away from your breath, generally spattering and making a mess.

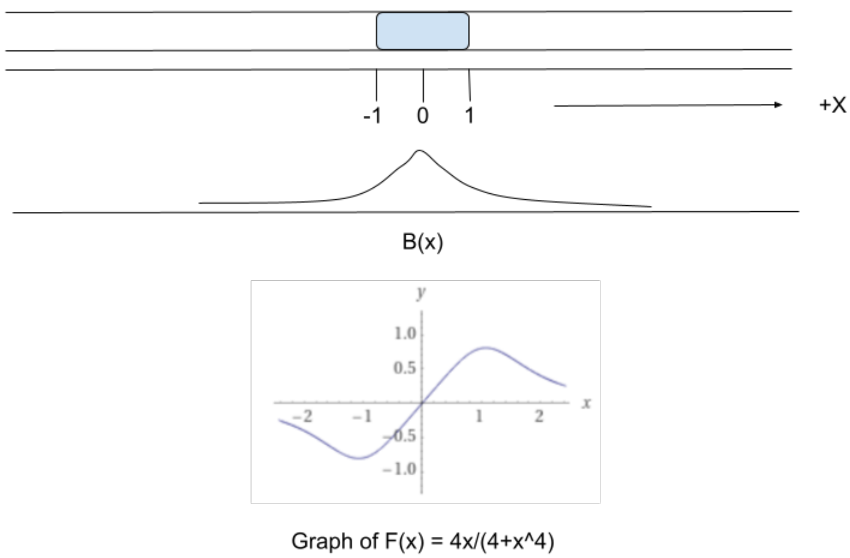

Fig. 3. One Dimensional Bolus Math

It is interesting to note that we obatin the same result by a different method. We can consider the potential energy of the bolus. Reling on the fact that the bolus always has a length of 2, the potential energy is the integral of the field strength times the area:

$$PE(0) = \int_{-1}^{1} dB(x)dx \tag{7}$$

$$PE(y) = \int_{-1+y}^{1+y} dB(x)dx \tag{8}$$

$$\int \frac{1}{1+x^2} dx = \arctan x \tag{9}$$

$$PE(y) = d(arctan{-1} + y - arctan 1 + y) \tag{10}$$

But change in potential energy is work, which is force times distance, to force is the change in potential energy divied by the distance:

$$F(y) = \frac{\Delta PE(y)}{\Delta y} \tag{11}$$

$$\tag{12}$$

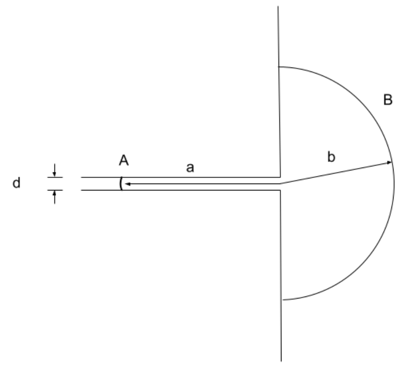

Fig. 4. Channel To Chamber Geometry

The limit of this as Δy goes to zero is just the derivate of $PE(y)$:

$$F(y) = PE'(y) \tag{13}$$

$$F(y) = \frac{4dy}{y^4 + 4} \tag{14}$$

The extrema of this force $F(x)$ occur at $(-\frac{\sqrt{2}}{\sqrt[4]{3}}, \frac{\sqrt{2}}{\sqrt[4]{3}})$, or $(-1.0746, 1.0746)$, which again accords with physical experience of how much a bolus can be displaced before it explodes. It must be remembered, however, that these calculations will change if the intensity of the magnetic field is modeled differently. Nonetheless, having a closed-form solution to this problem is valuable both for the intuition it provides and to allow direct design of bolus ferrofluid system.

6.2 The Channel-to-a-Chamber

Our goal, however, is to analyze a somewhat more complicated geometry. In particular, we are interested in a channel-leading-to-a-chamber, as depicted in Fig. 4.

We would ideally like to treat this as a one-dimensional problem as well. Let us assume once again that a magnetic field is placed at the center at our diagram (where the channel meets the chamber.) Call the region to the left A and the region to the right B, and assume the orgin is at the center of the diagram.

The most important geometric feature of the channel-and-chamber valve design is the radius of the cylindrical magnet or magnets in it. It will be most convenient to take the radius of this magnet to be unity (1.0) and express all other spatial measures relative to that. The origin of our plane of operation will be the center of the top face of the cylindrical magnet, which is assumed to be beneath the plane, with its North face in contact with the plane.

Note: I believe using a magnetic force that falls off with the square of distance may not allow for a stable solution. I am not sure how to model this in a way which is realistic and convenient. Using the fourth power will probably work and may be realistic given of action is perpendicular to the magnet. I think I will try it.

Let us assume once again a magnetic field centered on the origin of strength

$$B(x) = \frac{1}{1 + x^2}$$

where x is the distance from the orgin.

If we assume as previously argued the principle that a bolus can be treated as a single object (The One Dimensional Bolus Theorem), at least until it collapses, then we can can relate a and b via the total area of the bolus S by:

$$S = d \cdot a + \frac{1}{2}\pi b^2$$

when $a > 0$ and $b > 0$, so that the areas of A and B are both positive. It is most convenient to measure our position of the bolus, which is changing shape in this case, as the coordinat b, so we we express a in terms of b. This can be solved for a:

$$a = -\frac{\pi b^2 - 2S}{2d} \tag{15}$$

Note that when $a = 0$, the dependence on d vanishes and:

$$b = \sqrt{\frac{2S}{\pi}} \tag{16}$$

$$b^2 = \frac{2S}{\pi} \tag{17}$$

Since at rest the bolus surface A will be in the same field strenght as surface B, we can set:

$$B(a) = B(b) \tag{18}$$

$$B(-\frac{\pi b^2 - 2S}{2d}) = B(b) \tag{19}$$

This can be solved by WolframAlpha (results not incuded here.) As expected, $b = -a$, that is, both surfaces are equidistant from the center of our radially symmetric magnetic field.

6.3 A strategy for computing force

Our fundamental goal is to compute the collapse and cracking pressure. This is determined by the maximum force needed to reduce b and the force needed to drive the region A to the orgin respectively.

If the bolus at rest is displaced, the potential energy increases, moving off a minimum. At a given point, the infinitessimal change in energy divided by the infinitessimal change in distance is equal to the force.

If we had a formula for the potential energy as a function of b, we would have a chance of computing this analytically.

Considering only the surfaces and using Eq. 15:

$$F_B(b) = \pi b B(b) \tag{20}$$

$$F_A(b) = dB(a) \tag{21}$$

$$F_A(b) = dB(-\frac{\pi b^2 - 2S}{2d}) \tag{22}$$

$$F(b) = F_A(b) + F_B(b) \tag{23}$$

$$F(b) = \frac{d}{1 + (-\frac{\pi b^2 - 2S}{2d})^2} + \frac{\pi b}{1 + b^2} \tag{24}$$

Of course, $F(b)$ is a function of S (the bolus area) and d, the channel width. For a physically realizable geometry, we might have d be about one-tenth the diameter of the bolus, and it might be convenient to have the diametor of the bolus be close to 1.

The cracking pressure will me the maximum force the magent can exert on the blob in the range $a < 0$, because when $a >= 0$, the air or water being valved will "bubble" out of the valve.

The collapse pressure will be the maximum force time half-circumference in the range $b >= 0$. By the time b decreases to $b = 0$ (and probably before), the valve will explosively collapse.

It is clear that we want the bolus to be somewhat large then the semi-circle of maximum magnetic force, so that as the outlet pressure is increased it will find this maximum point of force and hold itself against the highest outlet pressure possible without collapsing. (Nontheless we must have a field monotonically increasing with b in order to sure inlet fluids "bubble away" from the blob to the outlet side.)

To find the collapse pressure, we want to find the b that maximizes of $F(b)$.

$$F(b) = \frac{d}{1 + (-\frac{\pi b^2 - 2S}{2d})^2} + \frac{\pi b}{1 + b^2} \tag{25}$$

Recall however, the this derivation uses a suspect formula for $B(x)$. Possible we can design the magnetic field, for example using conical magnets, to make this valve more performant.

Important note: This math strongly suggest that the valve can be made twice as performant by opening the chamber completely, so that the valve is merely a chamber in the center of the bolus. Likewise thickening of the chamber (in the z-dimesion, violating our current 2-dimensional assuption) at the point of the strongest magent force would mean that more ferrofluid would have to be driven away at that point, increasing the potentially energy and therefore requiring more force.

6.4 Idea

We can protect the valve from explosive collapse by using a separate valve that cracks before the collapse pressure, acting as a "pop-off" valve.

6.5 Other Thoughts

The valve can be explained by relatively simple magnetostatics. In a magnetic field, ferrofluid tends to minimize the potential energy.

Let us first perform a thought experiment. Consider a two-dimensional magnetic field in the shape of a disc formed by two sheets of glass or plastic in, for example, a circular air gap in a magnetic circuit. Assume for a moment that the magnetic field is perfectly uniform within the disc and perfectly zero outside of the disc. Although there is no gradient in such a scenario, if a connected blob of ferrofluid enters the disc, it will be pulled entirely within the disc, since it is magnetically connected to itself and this minimizes the potential energy, even though there is no magnetic gradient at any point. In such a scenario, if the blob is smaller than the disc, it will not matter where it is inside the blob resides, since the field is uniform, any is as good as any other. If however, the blob is larger than the disc, it will tend to form a circle centered on the disc center. If the blob is smaller than the disc, it will still self-attract itself into a circle, but the center of the blob circle might not coincide with the center of the magnetic disc.

Now let us consider a complex two-dimesional field of arbitrary shape varying in intensity at every point–for example, it could be in the shape of a star or a bunny rabbit. Setting aside for a minute the fact that the ferrofluid will interact with itself a small amount to vary the shape of this field as it enters it, we now what the magnetic potential energy at every point of the boundary of this blob will be the same. If it is not, it will not be in a minimum energy configuration, and it will flow until it reaches a minimum configuration. The blob, however or small, will effectively define an "isopotential line" of the magnetic field.

If we assume the field is radially symmetric, it is clear the blob will be circular. (Let us ignore a field which had several local minima energy conditions.)

Now, let use return to a uniform magnetic field of radius R wish is of strength B_R within this disc and zero outside it. Now, what is the potential energy of a ferrfluid blob at any arbitrary position (before it has sought a minimum)? For a given patch of ferrfofluid A and the magnetization of the ferrofluid is M_A the potential energy is:

$$U = -B_R A M_A, \text{if } A \text{ is with disc } R, \tag{26}$$
$$U = 0, \text{if } A \text{ is outside the disc} \tag{27}$$

Representing this a Kronecker Delta δA,

$$\delta_A = \begin{cases} 1, & \text{if } A \text{ is with disc } R, \\ 0, & \text{if } A \text{ is outside the disc} \end{cases}$$

we can integrate over the entire area, we have:

$$U = \int_A -B_R M_A \delta_A \, dA$$

, but since B_R does not depend on A, we have:

$$U = -B_R \int_A M_A \delta_A \, dA$$

,

If we approximate our magnetic field as "strong" within a small finite boundary and zero elsewhere, and assume that the within the strong field the ferrofluid reaches its saturation magnetization M_s, we can simplify this further:

$$U = -B_R M_s \int_A dA$$

In other words, the potential energy is minimized by keeping as much of the ferrorfluid in the disc R as possible.

It is clear from this that if a bubble of air was magically placed inside the blob of ferrofluid in inside R, it would quickly be pushed out by energy minimization.

But how can we smuggle a bubble of air into the blob? Well, we can make a thin "staw" and pace the end of it inside the blob. Now, it take no work to displace the blob until it is pushed outside the disc. Now the ferrofluid will form the shape of a circle naturally, whether a straw is pushed into it or not.

If we blow into the straw (in other words, if we raise the pressure there), the ferrofluid will easily move out of the straw, making the remainder circular blob bigger—until it starts to push the ferrofluid outside of the disc. At that point, the ferrofluid would resist being further displaced. If, however, there was enough room in the disc for all of the ferrofluid, even when that inside the valve was displaced, the air would enter the bolus and then be elimnated to the other, non-straw boundary of the bolus. In other word, the valve would have "cracked" and allowed the air to pass out.

Now suppose that you push from the other side. The circle would shrink, and to the extent that the circcle shrinks, that much ferrofluid would have to be pushed out the straw. However, if the other end of the straw were at the disc boundary and a wall prevented the ferrofluid from returning, it would be removed from the disc. But this requires work, because we are increasing the energy, by moving away from a minimum energy configuration.

Unfortunately, we cannot analyze this further without introducing gradients.

7 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, an inlet chamber, and outlet 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 magnetic field.
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 automatically when high outlet pressure is removed, which would increase robustness in some applications.

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