Working principle of a multiple drop ferrofluid pump

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***Abstract*— Pumps utilizing the displacement of a ferrofluid drop are relatively new. Pumps utilizing the displacement of multiple ferrofluid drops have not been designed yet and the question that arises is what traits do they have and what are the possibilities for these pumps? An advantage would be the absence of shear stress and rough wall contact, making it suitable for biological fluids since these fluids are extremely vulnerable to these properties. In this paper the working principle of a multiple drop ferrofluid pump is tested, this is done with physical experiments. By measuring the pressure differences over multiple drops the following conclusions were drawn: the total pressure difference over a channel is equal to fixed pressure difference over a drop times the amount of drops, the influence of magnets on each other has a large impact on the maximum pressure differences over drops and there are three distinct drop behaviours. The eventual goal is to gain knowledge to design an initial multiple drop ferrofluid pump.**

I. Introduction

A ferrofluid is a fluid that can be manipulated by magnetic fields, which leads to various applications, one of them is to pump other fluids. Pumps using a *single* ferrofluid drop actuated by an external magnetic field are found in [1], [2], [3] and a typical single drop pump is depicted in figure 1. Ferrofluids are dielectric (non conducting) and the resulting magnetic behaviour is (super)paramagnetic.[4]

A ferrofluid pump could be useful for pumping biological fluids. These biological fluids are vulnerable to shear stresses and rough wall contact [5], [6], [7], [8], two properties that decrease with a pump which uses ferrofluid drops to push the biological fluid [2], [3].

Using a single ferrofluid drop, the maximum pressure that can be achieved is the pressure difference that one drop can withstand. Thus, when using multiple drops, a higher maximum pressure should be reachable. This theory has not yet been tested in literature and will be the topic of this paper.

The hypothesis is the maximum pressure difference $\Delta P_{d,max}$ over a single drop will lead to a maximum total pressure difference over a channel of $\Delta P_{tot} = \Delta P_{d,max} N$ over N drops. For this to be true, the drops should open up when $\Delta P_d > \Delta P_{d,max}$ and let some fluid pass, thus the drop can recover as ΔP_d lowers again. This working principle is visualized in figure 3. The hypothesis is the main principle for a multiple drop ferrofluid pump.

Two other principles must be tested to sufficiently design a pump, namely:

- $\Delta P_{d,max}$ increases if the maximum distance between drop and magnet decreases.
- The width of the test channel has no influence on $\Delta P_{d,max}$ if the magnet is much wider then the channel.

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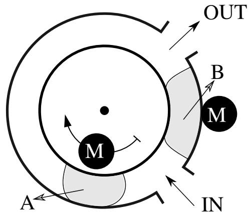

Fig. 1. A typical single drop pump modeled after [2]. A stationary magnet keeps a drop plug in place (B). A moving magnet displaces a ferrofluid which in turn actuates another fluid(A). The moving drop can pass the seal, the pumped fluid cannot.

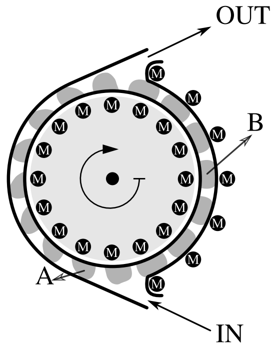

Fig. 2. A multiple drop pump, with magnets attached to a rotating disk which holds the ferrofluid drops (A). The rotating disk moves the drops and by this build up the pressure. The stationary drops (B), which create a plug, make sure the pressure difference is contained, because the ferrofluid drops can pass this plug but the air cannot.

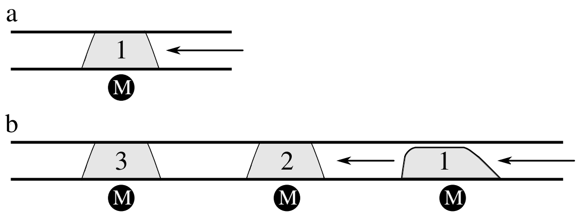

Fig. 3. Single drop pumping principle (a): When pressure is build, the air flow has to be hold by the single drop (1). Multiple drop pumping principle (b): If the pressure gets to high, drop 1 slightly opens and thus allowing air to flow to drop 2. This causes the pressure difference over drop 1 to be limited and drop 1 will form back sealing the channel again. This process repeats itself until the pressure between drop 1 and 2 is to high for drop 2 to hold. Then air starts to flow to drop 3.

In the theoretical section a physical model is developed showing the effect of magnetic fields on the pressure differences over drops. Test setups are made to validate this model. In the section for the results the data of these test setups is presented. With the test setup the two essential components of a pump can be tested, the plug with stationary drops, depicted as (B) in figure 2 and the rotating disk with moving drops, depicted as (A) in figure 2.

The tests will be conducted in a *stationary situation*, due to the eventual pump moving slow enough to consider it as stationary. The method section describes the test setup consisting of a closed channel with several drops, a pressure regulator and a manometer. Multiple measurements with different number of drops and varying channel heights are conducted. Using linear least squares regression the data is analysed.

II. Theoretical model of ferrofluid drop

For a better understanding of the test setup design - and the physics behind the working principle - it is useful to consider a simple model of a single ferrofluid drop. To this end, a part of the Rosensweig model shall be applied [4] in the form formulated by Nochetto et al [9]. For a full formulation of the model and its assumptions the reader is referred to the book and the paper. This paper only considers the most important assumptions, part of the conservation of linear momentum, and the solution to this partial differential equation. With the model, critical assumptions and conditions are defined, which give insight into proper construction of a stationary test setup and provide an inital step towards a useful pump design.

To start consider a mass of homogeneous, imcompressible colloidal ferrofluid contained in a bounded simply connected domain $\Omega \subset \mathbb{R}^3$. Now initially assume that: the ferro- or ferrimagnetic particles are spherical; have same size and mass; are distributed homegeneous; have no interaction among each other; linear- and angular velocity of the drop is 0; the magnetic field is homogeneous and fluid effects like surface tension and viscosity etc. are limited. Now define the magnetic field properties using the *maxwell equations* and applying magnetostatic conditions to obtain:

$$\operatorname{div}\mathbf{B} = 0,\ \operatorname{curl}\mathbf{H} = \mathbf{0}\,\text{in}\,\mathbb{R}^3 \tag{1}$$

Here the induced magnetic field is:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{2}$$

With units of T; the permeability of free space is $\mu_0 = 4\pi \times 10^{-7} \cdot Hm^{-1}$ and $\mathbf{M}$ is the magnetization field of the ferrofluid, its units are Am^{-1}. The maximum magnetization of the fluid is called the magnetic saturation $||\mathbf{M}|| = M_s$ and it is a scalar. The magnetic field $\mathbf{H} = \mathbf{H}_{ext} + \mathbf{H}_d$ is composed of the externally applied magnetic field $\mathbf{H}_{ext}$ and the demagnetization field $\mathbf{H}_d$. Here $\mathbf{H}_d = -D\mathbf{M}$, D is the demagnetization factor which is less then unity.

An important assumption is made to simplify the complicated magnetic field. In this experiment and for practical applications, $||\mathbf{H}||$ dominates over M_s and thus also over $\mathbf{H}_d$. To put it precisely consider -the from now on called *critical assumption*-:

- $M_s << min||\mathbf{H}||_\Omega$, this leads to $\mathbf{H} \approx \mathbf{H}_{ext}$ and the fluid having no influence on the externally applied field.

The assumption will be validated in the methods section. There are no analytic solutions for strongly magnetized fluid with a resulting effect of $\mathbf{H_d}$ [10] and only Nochetto et al. (2016) [9] created a stable numerical scheme incorporating these effects.

With this exact description of the magnetic field a stationary version of the conservation of linear momentum as given in [4] is introduced, this version uses gradients of magnitude of the vector fields. The equation is introduced and immediately simplified with the assumptions to:

$$\begin{aligned} \nabla P &= \mu_0 M \nabla H \\ &= \mu_0 M_s \nabla H_{ext} \end{aligned} \tag{3}$$

∇P is the pressure gradient, ∇H_{ext} the gradient of the external magnetic field magnitude, M is the magnitude of the magnetization, here a constant M_s. To explore this partial differential equation the domain Ω is now put in a test setup channel which has a rectangular cross-section as depicted in figure 4. An Cartesian coordinate system is introduced. Equation 3 is now expanded to:

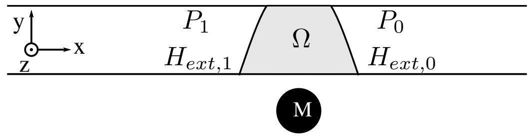

Fig. 4. Schematic view of the drop Ω in a channel with rectangular cross-section in the xy-plane. As demonstrated in equation 6 the drop surface will follow the contours of isomagnetic strength. Here P_1 is equal to P_0.

$$\begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \\ \frac{\partial P}{\partial z} \end{pmatrix} = \mu_0 M_s \begin{pmatrix} \frac{\partial H_{ext}}{\partial x} \\ \frac{\partial H_{ext}}{\partial y} \\ \frac{\partial H_{ext}}{\partial z} \end{pmatrix} \tag{4}$$

The largest pressure gradient inside the Ω is along the channel, in the direction of the x-axis, so the magnetic field should be optimized such that the $\frac{\partial H_{ext}}{\partial x}$ dominates. This condition will from now on be called the *anisotropy condition*. A well functioning test setup or pumping device should adhere to this principle.

A second critical condition to adhere to follows from solving equation 3. Start by substituting equation 2 into 1 and use the critical assumption to obtain:

$$\operatorname{div}\mathbf{H}_{ext} = 0,\ \operatorname{curl}\mathbf{H}_{ext} = \mathbf{0}\,\text{in}\,\mathbb{R}^3 \tag{5}$$

Thus $\mathbf{H}_{ext}$ satisfies the *Laplace equation*. The solution of Laplace equations are harmonic functions, they have the property of being twice continuously differentiable. A gradient of the magnitude, H_{ext}, is also continuously differentiable. Now the fundamental theorem of line integrals can be applied to equation 3, integrating to the boundaries of the drop giving:

$$\begin{aligned} \int_C \nabla P \cdot \mathrm{d}\mathbf{r} &= \mu_0 M_s \int_C \nabla H_{ext} \cdot \mathrm{d}\mathbf{r} \\ P_1 - P_0 &= \mu_0 M_s (H_{ext,1} - H_{ext,0}) \\ \Delta P_d &= \mu_0 M_s \Delta H_{ext} \end{aligned} \tag{6}$$

Equation 6 will be called the *isomagnetic* condition. Boundaries of the drop tend to line out on curves of equal magnetic field magnitude. This has two important implementations. First, when depositing a drop in a channel, $\Delta P_{d,max}$ is obtainable when a drop has a volume that maximizes ΔH_{ext}. Secondly, the orientation and location of the magnet relative to the drop should be so that $H_{ext,1}$ can be maximized, to augment the upper limit of $\Delta P_{d,max}$.

III. Method

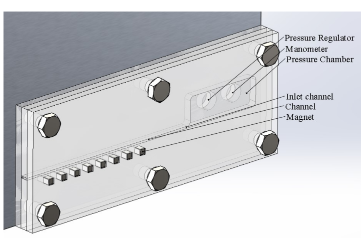

Fig. 5. 3D view of the test setup

Fig. 6. 4 ferrofluid drops above 4 magnets

The test setup is shown in figure 5. PMMA sheets were laser cut into samples with different geometries -with a precision of 0.1 mm - and glued together with acetone. These were

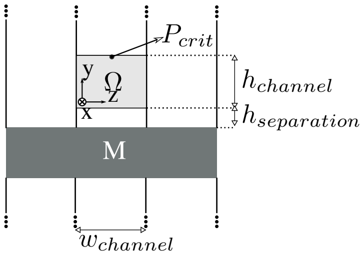

Fig. 7. Schematic cut-out of the test setup, looking into the channel. Ω represents the ferrofluid drop. The maximum pressure difference a drop can withstand, depicted as P_{crit}, is determined by the maximum distance from magnet to drop, $h_{seperation} + h_{channel}$.

attached to an aluminum plate, which was used to connect a manometer and a pressure regulator to these PMMA samples. Between the PMMA samples and the aluminum plate a layer of plastic foil was applied to prevent leakages. A test setup cut-out is depicted in figure 7.

The samples have 3 to 8 cut-outs for bar magnets, a pressure chamber for the pneumatics and a channel from the pressure chamber to the atmosphere, which is to be sealed by ferrofluid drops. A Wika Econosto Feinmeß manometer was used to measure the pressure in the chamber and a Festo LR-1/4-S-B pressure regulator was used to control the pressure. The magnets are HKCM Magnet-Cuboid Q12x03x03Ni-N52 type ($B = 1.43\ T$). A needle was used to inject the Ferrotec EFH1 ferrofluid into the channel.

A $h_{separation} = 0.4\ mm$ was found sufficient enough to prevent leakage between the channel and the magnets. The width of the channels is 3 or 4 mm and the magnets are 12 mm long to ensure a homogeneous field across the channel, thus ensuring $\frac{\partial H_{ext}}{\partial z} \approx 0$. The magnets are oriented with their poles parallel to the channel, because the direction of the strongest magnetic field is orthogonal to the surface of the poles. Also important is the orientation of the magnets. The magnets will be oriented differently during the tests. N-N-N means that poles that are alike are next to each other, so N-S-N means that opposite poles are next to each other.

The different sample geometries are summarized in table I.

TABLE I
NAMES AND GEOMETRIC PROPERTIES OF THE DIFFERENT TEST SETUP CHANNELS

test setup	1	2	3	4	5	7
$h_{channel}\ [mm]$	1	0.5	1	1	1.25	0.5
$h_{separation}\ [mm]$	0.5	0.5	1	0.4	0.4	0.5
$w_{channel}\ [mm]$	3	3	3	4	4	4
Max. amount of drops	3	3	3	4	4	8

The *critical assumption* is found to be satisfied. The greatest distance between ferrofluid and magnet is 2 mm with test setup 3. This results in $min||\mathbf{H_{ext}}||_\Omega = 1.20 \cdot 10^5\ Am^{-1}$. The used ferrofluid has a $M_s = 3.5 \cdot 10^4\ Am^{-1}$, thus ferrofluid behaviour is dominated by the magnet.

Measurements were conducted by recording ΔP over 1, 2, 3 and 4 drops, up until 8 drops for test setup 7. Filling the entire channel with fluid and then applying pressure resulted in air pocket formation, which positioned between the drops obtaining their optimal volumes. When drops that almost interact with each other are injected the same phenomenon occurs. If a certain ΔP is exceeded, all the drops were blown out of the channel. This pressure difference is ΔP_{tot} and this scenario is called $overfilled$. There is a critical volume, V_{crit} for a drop and when drops are below or near this V_{crit}, ΔP_{tot} cannot be exceeded. Here, close to ΔP_{tot} the drops slightly deform (see figure 3), let through some air, and form back to their optimal shape. This process repeats itself over and over, and almost no ferrofluid is lost during this process. Only after an considerable amount of time, ΔP_{tot} slightly lowers. A different ΔP_{tot} was found for slightly different volumes around V_{crit}, this scenario is called $filled$. The geometry of the channel determined the value of V_{crit}.

Calculating the value of $\Delta\overline{P}_{tot}$ was done with the arithmetic mean $\Delta\overline{P}_{tot} = \frac{1}{k}\sum_{k=1}^{n}\Delta P_k$. Where ΔP_k is a measured ΔP_{tot} over N drops. The data for all setups was put on a N versus ΔP_{tot} graph. A least squares regression analysis was made to check for a $\Delta P_{tot} = \Delta P_{d,max} N$ type relation. A $\Delta P_{d,max}$ is found if with every extra drop, the same ΔP is added to ΔP_{tot}. Error bars where added to the graph by means of the experimental standard deviation: $s(\Delta P_{tot}) = \sqrt{\frac{1}{k-1}\sum_{k=1}^{n}(\Delta P_k - \Delta\overline{P}_{tot})^2}$. Propagation of uncertainty methods were of no use and due to this $s(\Delta P_{tot})$ was used. The error introduced by injecting the drops was inestimable, the distribution of uncertainty of the manometer is unknown nor are user related errors.

IV. Results

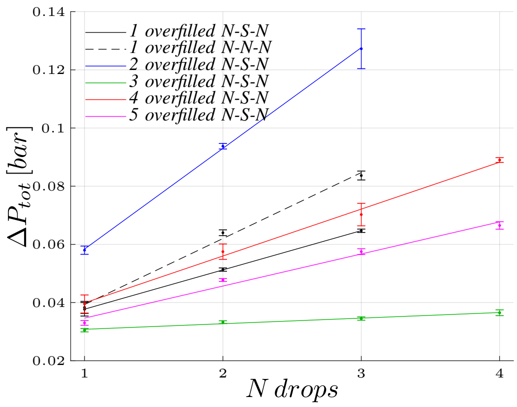

Fig. 8. The test results for setup 1, 2, 3, 4 and 5, specifications can be found in table I. Linear behaviour is shown by all setups with very small deviations confirming the hypothesis of linearity.

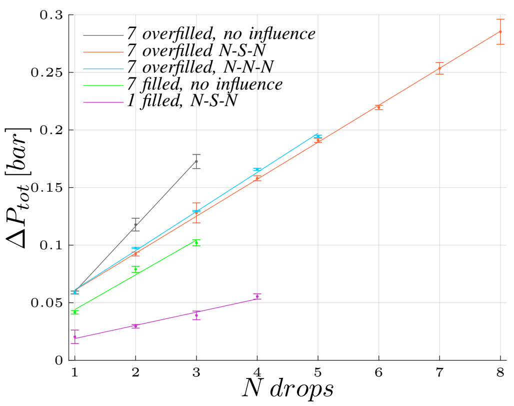

Fig. 9. The test results for setup 7 and 1, specifications can be found in table I. Linear behaviour is shown by very small deviations in all scenarios confirming the hypothesis of linearity.

The results of the tests are shown above. All magnets influence each other due to the small distance between them unless stated otherwise, thus no influence means that the magnets do not influence each other. A linear regression analysis with the data of test setups 1, 2, 3, 4 and 5 are shown with the linear fit through the points in figure 8. The coefficient of determination for four of the five lines is above 0.98 and is 0.91 for setup 3. Comparing 1 to 2 and 5 to 4, the only difference between these setups is the height of the channel.

In figure 9 the data for test setup 7 are shown but also data of the filled scenario from setup 1 is plotted, so the differences between the different filled scenarios can be seen. A linear regression analysis is also shown. The coefficient of determination for the fits with data from test setup 7 are above 0.97 and for the fit with the filled scenario of setup 1 it is 0.91.

V. Discussion

The results that have been found confirm the hypothesis, ΔP_{tot}= $\Delta P_{d,max}N$. Every setup shows this linear relation between $\Delta P_{d,max}$ and N. Moreover, decreasing channel height leads to an increasing $\Delta P_{d,max}$ and variation of the channel width has negligible effects on $\Delta P_{d,max}$, because setup 2 and 7, both overfilled and magnets placed N-S-N, only differ in width and lead to the same $\Delta P_{d,max}$. If the volume of the ferrofluid drop increases, the pressure difference increases, just as expected from Equation 6. With an $overfilled$ scenario, the magnet cannot hold the drop in position when ΔP_{tot} is exceeded, presumably because the working principle in figure 3 slightly differs in this scenario. In the $filled$ scenario ΔP_{tot} can never be exceeded, due to deformation of the drops. In figure 8 and figure 9, except for '7 overfilled, no influence' and '7 filled, no influence', a bias can be seen due to the lines not starting exactly at $\Delta P_{tot} = 0$ if the lines are extrapolated to $N = 0$. This phenomenon occurs when the magnetic fields influence each other, lowering $\Delta P_{d,max}$, this conclusion has been verified with setup 7. If the magnets are placed in such a way that they can not influence each other, no bias is found and a higher $\Delta P_{d,max}$ is reached. For this to be true a gap between the magnets of approximately 3 cm was needed. Furthermore, the orientation of the poles of the magnets affects $\Delta P_{d,max}$ if the magnets influence each other. If two opposite poles are next to each other, a lower $\Delta P_{d,max}$ is reached than with two poles that are the same. This effect gets smaller when $h_{channel}$ decreases as can be seen by comparing the figures.

The achieved results are very useful and give a good impression of how a pump can be designed. These results show the impact of different variables such as the height of the channel, the number of drops, the orientation of the magnets and size of the ferrofluid drops when designing a pump.

The measured results have on average a small variation, however these could be explained due to the various errors. The accuracy of the manometer and reduction valve can play a role due to human errors, the amount of ferrofluid drastically changes the pressure that can be build up, production errors can also be found and play a role.

VI. Conclusions and recommendations

The hypothesis is the maximum pressure difference $\Delta P_{d,max}$ over a single drop will lead to a maximum total pressure drop over a channel of $\Delta P_{tot} = \Delta P_{d,max}N$ over N drops. This hypothesis has been confirmed with physical experiments. The results can be incorporated in future pump design, for example when implementing more magnets ΔP_{tot} will increase linearly. Furthermore, a tolerance for $h_{channel}$ and $h_{separation}$ has been found. $h_{separation}$ should be as small as possible but 0.5 mm was already sufficient enough to build pressure. $h_{channel}$ can vary depending on the specifications of the pump, a smaller $h_{channel}$ will allow a higher ΔP_{tot}, however a larger channel will allow a higher volume displacement although a maximum $h_{channel}$ of 1.5 mm would be adviced. The plug of the pump, the stationary drops (B) in figure 2 which prevents the pressure from escaping the reservoir, must be able to hold a higher pressure than the rotating drops (A) of the pump can build up, otherwise the pump will not work sufficient. To achieve this, more of the same drops must be used in the plug than in the rotating disk, alternatively stronger magnets or different magnet orientations can be used to increase the magnetic field. Orienting the magnets in the N-N-N orientation offered on average a higher ΔP_{tot}, compared to N-S-N, but this effect becomes smaller when $h_{channel}$ decreases. In the final pump the magnets in the plug should all be orientated in a N-N-N direction towards the disk and the magnets in the disk should be orientated in the S-S-S towards the plug. With magnetic fields that do not influence each other, orientation of the magnets is irrelevant. Overfilling the plug compared to the channel will also lead to a higher ΔP_{tot} in the plug, however this has its limits due to the dangers of completely being blown away. Future research can be done into the impact of different magnets and ferrofluid on the results, scalability and dynamical effects are also concepts that can be tested. However with the results of this paper an initial pump design with optimum proportions can be constructed and tested.

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