Analysis Of A Magnetocaloric Pump

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***Abstract*—Magnetocaloric pumps have not found their way into the commercial world yet, but with their lack of moving parts these pumps can be a solution to fight wear in mechanical pumps. This can be useful in many application fields such as the cooling of a CPU (central processing unit) of a computer. A conclusion is drawn from analyzing a magnetocaloric pump using three types of ferrofluids. The objective is to analyze the flow and the build up in pressure established by a magnetic field and a temperature gradient. Results are estimated in a numerical model and determined analytically while experimental tests are used for measuring practicable data to validate the theory. Using a manganese zinc ferrofluid, the study verifies that the magnetocaloric pump is capable of establishing a fluid flow and pressure build up.**

***Keywords*—COMSOL, Ferrofluid, magnetocaloric effect, permanent magnet, pyromagnetic coefficient**

I. Introduction

Ferrofluids are a suspension of magnetic nanoparticles in a fluid (usually oil or water based). A surfactant is added to prevent agglomeration of the nanoparticles.

Several studies have contributed to new insights into possible applications for ferrofluidic pumps [1]. In conventional pumps moving parts contribute to wear and mechanical failure. Hence, many pumps must be replaced over time in complex systems or difficult to reach locations. Using magnetocaloric pumps, no wear or mechanical failure can occur due to mechanical friction since no moving parts are used. In complex systems, the use of magnetocaloric pumps will increase the lifespan. In present day only a few studies have been done concerning magnetocaloric pumps. Pal [2] and Love [3] succeeded in creating a fluid flow or pressure gradient using a ferrofluid in their pump (maximum of 0.025 ml/s and 345 Pa respectively). Both studies created a magnetocaloric pump using a coil to create an adjustable magnetic field. Research with such a pump using a permanent magnet has never been done before.

This paper analyses the flow of a ferrofluidic pump consisting of a heat source and permanent magnet. It is hypothesized that a fluid flow and pressure build up can be established with a temperature gradient from 20 °C to 70 °C in combination with a magnetic field. This is done to examine the possibilities for application of magnetocaloric pumps in CPU cooling. Most desktop CPU's should not reach temperatures above 50 °C to 70 °C for long term use.

An analytic, numerical and experimental analysis is performed. The methods and results to derive a conclusion are described whereafter the results are discussed. Lastly a conclusion is given to bind the research.

II. Method

Increase in the temperature of a ferrofluid causes decrease of its magnetization until it reaches zero at its Curie temperature (Fig. 1). The M-T curve starts dropping more steeply at higher temperatures (Fig. 2) [4]. Heating a ferrofluid and generating a temperature gradient will therefore cause an opposing gradient in magnetization.

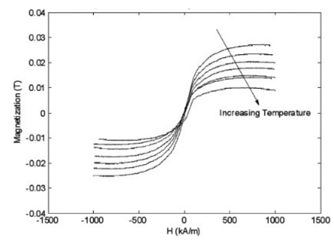


Fig. 1: Magnetization of a MnZn-ferrofluid, [3].

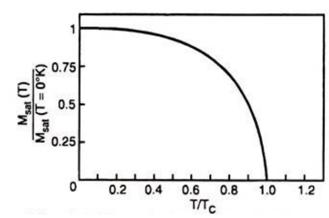


Fig. 2: Relative saturated magnetization plotted against relative temperature, [4].

To calculate a magnetic body force the equivalent magnetic charge method is used. In this method a coulombian representation of the magnetic field assumes that the magnetic field created by a body is equivalent to its virtual magnetic charges densities throughout the body. Using electrostatic equivalents of virtual magnetic charges, a formula for volume density force can be formulated (Eq. 1) [1] .

$$\boldsymbol{f} = -\mu_0 \nabla \boldsymbol{M} H \tag{1}$$

Assuming temperature has a gradient solely in the z-direction and operating in the field strength region of saturated magnetization, ∇M can be written as

$$\nabla \boldsymbol{M} = \frac{\delta M}{\delta T}\frac{\delta T}{\delta z} \tag{2}$$

substituted in Eq. 1 gives:

$$f_z = -\mu_0 \frac{\delta M}{\delta T}\frac{\delta T}{\delta z} H \tag{3}$$

where $\frac{\delta M}{\delta T}$ can be referred to as the pyromagnetic coefficient (PC). Eq. 3 does not take any surface forces into account, as these do not have a significant influence on the outcome [1]. When imposed to a magnetic field the body force on the ferrofluid will be unbalanced and a pressure gradient is generated, leading to a flow. To obtain the strongest effect, a ferrofluid should be used with a Curie temperature as close as possible (but slightly larger) to a CPU's Maximum Operating Temperature (MOT).

An analytic approach, a numerical model and a practical experiment for determination of the fluid flow created by a magnetocaloric pump are described below. A comparison between three different types of ferrofluid is made, a ferrofluid prepared with manganese zinc particles suspended in standard isoparaffin oils (F2378, Liquids Research Ltd), a suspension of magnetite particles in water (EMG300, Umincorp) and a suspension of magnetite particles in kerosene (EFH1, Ferrotec). In table I some properties of the fluids are shown.

TABLE I: Pyromagnetic coefficient, Curie temperature and viscosity of different types of ferrofluids

Ferrofluid	Material	PC ($\frac{A}{mK}$)	T_c(°C)	$\mu(mPa.s)$
F2378	MnZn	36	80-100*	6.1
EFH1	Magnetite	18*	580*	6.0
EMG300	Magnetite	20*	N/A	5.0*

$^*Derived\,from\,similar\,ferrofluids$ [5][6]

A. Analytic analysis

For analytic validation of the hypothesis, Eq. 3 is integrated over z to obtain the pressure difference (ΔP). For simplification it is assumed that the PC is linear over the temperature range from 20°C to 70°C (it has been shown that this is true for $T > 26.85$°C [7]), the ferrofluid enters the pump at 20 °C and exits at the desired temperature. The magnetic field strength (H) is adopted from the bulk field strength generated in the numerical environment.

ΔP is substituted in the Hagen-Poiseuille equation to obtain the flow rate (Q) Eq. 4. This equation is valid when the fluid is Newtonian, laminar and incompressible.

$$Q = \frac{\Delta P \pi R^4}{8 \mu l} \tag{4}$$

B. Numerical model

The first step in obtaining results is to simulate the different setups in the numerical modeling software package COMSOL Multiphysics.

In the general 2D-axis geometry model a vertical silicone tube ($ø3mm; Ø4mm; L = 250mm$) is placed in an airbox with the fluid ($1.25x250mm$) placed against the vertical axis. Halfway of the ferrofluid channel the tube is replaced with a small brass part ($ø3mm; Ø4mm; L = 80mm$). The outer surface of the brass part is set as a heat source with a constant temperature of 70 °C. Five attached magnets ($ø5mm; Ø9mm; L = 12mm$) are placed so that they partially overlap the heat source.

To obtain a symmetric magnetic field ring magnets are used with a flux density of 1.02 Tesla in the z-direction. A flow in a tube with an inlet and outlet is simulated. An extra parameter (β) is added, representing the PC of the fluid. A volume body force is added to include the magnetocaloric effect of the ferrofluid in the model in order to create a pressure gradient. Finally, a line integration of the velocity field in the negative z-direction at the outlet of the tube is computed to obtain the volumetric flow rate. Also the temperature distribution and flow of the ferrofluid in the model are achieved.

C. Setup Experiment

A pump is designed utilizing permanent magnets and an electrical heat source (Fig. 3). Permanent magnets are used, rather than coil magnets, to prevent local heat transmission and to create a higher field strength. Five permanent ring magnets ($ø5mm; Ø9mm; L = 12mm$) generate a symmetric magnetic field. The heat source consists of a brass tube heated by coiled constantan wire. A current through the constantan wire causes it to heat up to a temperature of 70 °C. The temperature is kept constant through a PI feedback loop, utilizing the thermocouple that is winded between the brass tube and the coil. The coil is winded in dual direction to prevent a magnetic field from arising.

On each side, the magnetocaloric pump is attached to flexible pneumatic pipes. One pipe is connected to a reservoir filled with ferrofluid (Fig. 3. Reservoir 1) and the other is connected to an empty reservoir (Reservoir 2). Each of these reservoirs are positioned on a load cell. The load on the load-cells is recorded using "LabVIEW". The exit of the pipe is positioned so that it is below the initial surface height of the ferrofluid in reservoir 1. The surface height of the ferrofluid will level with the height of the exit of the tube, ensuring an initial head of zero. After settling of the ferrofluid, the pump will be powered up (t_0).

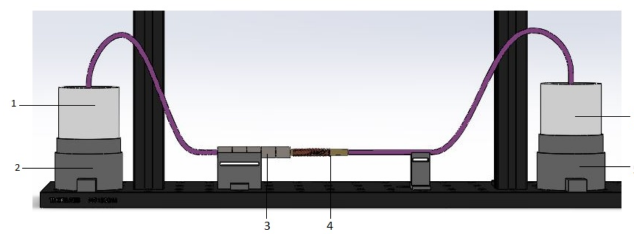


Fig. 3: Experimental setup of the ferrofluidic pump. 1. Fluid reservoir 1; 2. Loadcell; 3. Magnets; 4. Heatsource; 5. Loadcell; 6. Fluid reservoir 2

The head will increase when a flow is present and causes the ferrofluid surface to drop. The head can be calculated using:

$$\Delta p = \frac{g|m_0 - m|}{\pi R^2} \tag{5}$$

For all three ferrofluids four runs are performed. One extra run is performed with EMG300 at 90°C for better insight.

III. Results

The fluid flow of the three different types of ferrofluid is tabulated in table II as is the maximum pressure buildup. Graphs are shown to further illustrate the course. The analytic results for maximum pressure buildup and fluid flow are derived from Eq. 3 and Eq. 4, respectively.

For further understanding of the numerical results, the heat transfer in the ferrofluid is shown in Fig. 5a. It is observed that the heat is not equally distributed over the entire fluid. A graph with the pressure along the tube length is displayed in Fig. 4. The pressure builds up alongside the magnets and reaches its maximum at the end of the pump. An overshoot is observed after the fluid exits the magnetic field. In Fig. 5b the pressure field of the ferrofluid along the tube length is shown. The brass part is heated up to 70 °C. In Fig. 5c it is observed that the flow over the tube is not equally distributed.

TABLE II: Analytic, numerical and experimental results for the maximum fluid flow and pressure build up in different types of ferrofluid.

Ferrofluid	An.		Num.		Exp.	
	Q $\frac{ml}{min}$	ΔP Pa	Q $\frac{ml}{min}$	ΔP Pa	Q $\frac{ml}{min}$	ΔP Pa
F2378	78	$7.9 \cdot 10^2$	1.53	1.4	0.54	3.4
EMG300	59	$4.0 \cdot 10^2$	1.05	0.79	0.013	0.68
EFH1	46	$4.4 \cdot 10^2$	0.97	0.71	0.0012	0.32

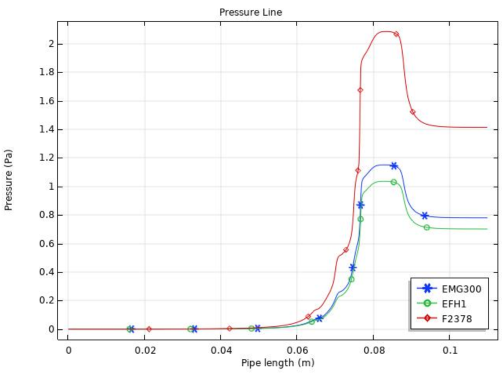
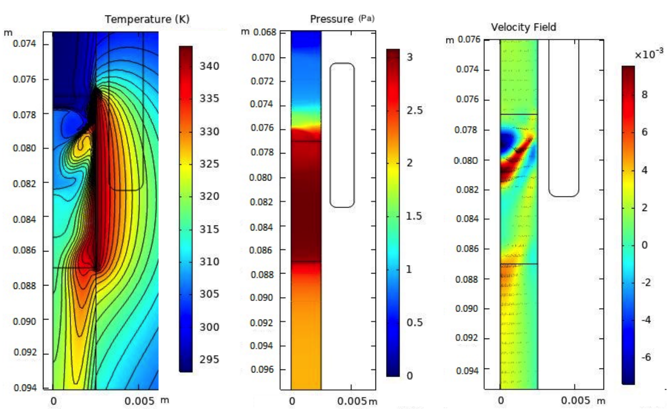


Fig. 4: Numerical pressure buildup of three types of ferrofluid



(a) Temp. distribution (b) Pressure buildup (c) Velocity field

Fig. 5: Numerical results of F2378

In Fig. 6 the volume of the ferrofluids is given as a polynomial. To derive the maximum fluid flow (table II) the derivative of the function at time point zero is calculated. In Fig. 7 the pressure build up as a function of time is displayed. In both figures one graph is given of EMG300 at 90 °C representing a higher fluid flow and higher pressure. All three test methods show that a fluid flow as well as a pressure buildup can be established with the temperature of the heat source at 70 °C in combination with a magnetic field, confirming the hypothesis.

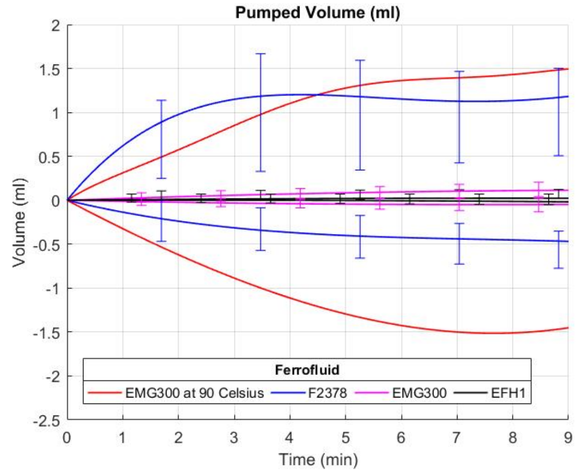


Fig. 6: Experimental results of pumped volume

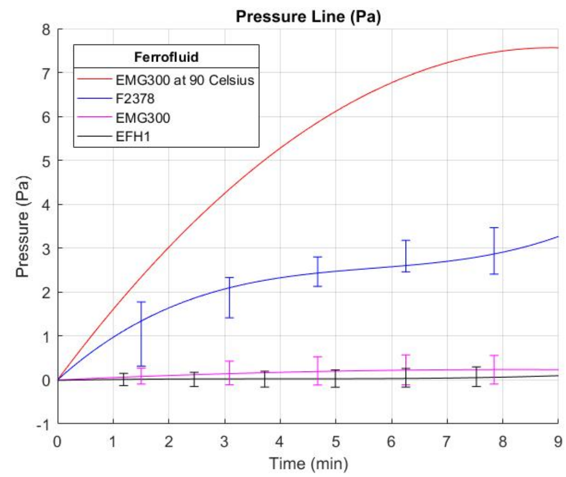


Fig. 7: Experimental results of pressure buildup

IV. Discussion

The PC of F2378 has the highest value compared to the estimated values of EFH1 and EMG300 (36, 18, 20 $\frac{A}{mK}$ respectively). Utilizing F2378 results in a larger fluid flow compared to the other fluids which correlates with the PC's. Another contributor to the variation in flow is the viscosity of the fluid. EMG300 and EFH1 have similar PC's, but their viscosity differs. A higher viscosity will result in a lower flow. This, however, does not explain the difference in total pumped volume (viscosity doesn't affect its pressure generation). One explanation for the difference in total pumped volume may be that the lower velocity of EFH1 offers more time for the fluid to heat up, meaning the temperature gradient is less over the area affected by the magnet. Leading to a lower pressure generation (Eq. 5).

There is a significant difference in analytic results and numerical and experimental results. Assumptions for analytic results must therefore be questioned. The analytic calculations are made in 1D rather than 3D, leading to an inadequate temperature gradient. A 3D temperate gradient might cause rotational flow within the pump's channel. Rotational flow also occurs in the numerical model (Fig. 5c). Moreover, the assumption that the ferrofluid has a 70 °C exit temperature is unlikely with the analytically calculated velocity. The assumptions made that the ferrofluid is at saturation magnetization and that the flow is laminar are valid assumptions [8].

It is discussed that the asymmetry of the fluid in/out flow in Fig. 6 is due to expansion of the heated ferrofluid. Expanding ferrofluid in the pump will cause ferrofluid to dissipate from the pump in both directions, lowering the outflow from reservoir 2 and increasing the inflow in reservoir 1. The expansion coefficient of F2378 (isoparaffin oil suspended) is higher than EMG300 (water suspended), hence the described effect is higher in F2378. However, to completely assign the asymmetry to an expansion of the fluid, 12.5 ml of F2378 has to be heated from 20 °C to 70 °C, which is unlikely in this setup.

The nanoparticles in the ferrofluid are aligned by the magnetic field lines. Energy is needed to push particles out of the alignment. This alignment causes the particles to act as a solid under a certain force. During testing it has been encountered that orthogonal field lines possibly cause an enhancement of this effect. This could be an explanation for low pressure and flow rate values. The mentioned phenomenon might explain the higher ΔP results shown by the EMG300 fluid at 90 °C. Also, the higher temperature might lower the energy needed for misalignment of the nanoparticles.

Comparing the results of current research with [2], an approximately 2.2 times higher experimental maximum fluid flow (0.02 ml/s) and an approximately 45 times larger pressure (7.6 Pa of EMG300 at 90 °C and 345 Pa of EFH3) are obtained. This can be due to the use of another type of ferrofluid (namely EFH3 with a higher magnetic saturation). In addition temperature was set at 100 °C allowing a larger demagnetization. Furthermore a coil is used instead of a permanent magnet, however it is not likely that this would directly affect the fluid flow.

V. Conclusion

An analysis of a magnetocaloric pump utilizing a permanent magnet and heat source is performed. This study shows that a magnetocaloric pump is capable of establishing a fluid flow of 0.54 ml/min and a build up pressure of 3.4 Pa using the F2378 ferrofluid, which confirms the hypothesis. It is shown that the choice of ferrofluid is of great importance to the performance of the magnetocaloric pump. A large contributor to the magnitude of the fluid flow is the pyromagnetic coefficient. The results of this study contribute to the development of a pump without moving parts.

Suggestion for further research is to use a more suitable ferrofluid containing a higher pyromagnetic coefficient and obtaining more data for understanding magnetocaloric flow. If suitable ferrofluids provide confident results, prospective research should focus on the heat dissipation by the ferrofluid so implementation in integrated cooling systems would become more feasible.

Acknowledgment

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VI. List of variables

Variable	Unit	Description
$\boldsymbol{f}$	N/m^3	Volume density force
H	A/m	Field strength
Δh	m	Height
l	m	Length
$\boldsymbol{M}$	A/m	Magnetization
m	kg	Mass
$\dot{m}$	kg/s	Mass flow
μ	$Pa.s$	Viscosity
μ_0	N/A^2	Vacuum permeability
ΔP	Pa	Pressure difference
Q	m^3/s	Flow rate
R	m	Radius
ρ	kg/m^3	Density
T	°C	Temperature
T_c	°C	Curie temperature
t_0	min	Begin time