# Impact of Magnets on Ferrofluid Cooling Process: Experimental and Numerical Approaches

Sleimane Nasser El Dine, Xavier Mininger, Caroline Nore, Frédéric Bouillault

Sleimane Nasser El Dine, Xavier Mininger, Caroline Nore, Frédéric Bouillault. Impact of Magnets on Ferrofluid Cooling Process: Experimental and Numerical Approaches. Compumag 2019, 2019, Paris, France. 10.1109/TMAG.2019.2949362 . hal-03324122

# Impact of Magnets on Ferrofluid Cooling Process: Experimental and Numerical Approaches

Sleimane Nasser El Dine[1], Xavier Mininger[1], Caroline Nore[2], Frédéric Bouillault[1]
[1]GeePs, UMR 8507 CNRS / CentraleSupelec - Sorbonne Université et UPSud, 91192 Gif sur Yvette cedex, France
Sleimane.Nassereldine@geeps.centralesupelec.fr, Xavier.Mininger@geeps.centralesupelec.fr,
Frederic.Bouillault@geeps.centralesupelec.fr
[2]LIMSI, CNRS, Univ. Paris-Sud, Université Paris-Saclay, F-91405 Orsay, France
Caroline.Nore@limsi.fr

**The cooling performance of a prototype immersed coil with magnetic fluid is evaluated in this paper, in order to estimate the heating process in a power transformer. For this purpose, thermocouples are inserted at several positions in the experimental setup. A magnetic fluid (Midel vegetable oil - $\mathbf{FeCo_2O_4}$ Cobalt ferrite magnetic fluid) with nanoparticles volume fraction of 7% is used to improve cooling efficiency. The impact of a radial ring magnet located close to the ferrofluid tank is studied. The magnetic suspension proposed for solenoid cooling is influenced, in addition of the heat source magnetic field, by the magnet location around the tank. The temperature reduction in the coil, due to thermomagnetic convection, has been already assessed in a previous study. Experimental results match with numerical ones performed with a 2D axisymmetric model of the setup, using the finite element method. It is shown hence that the magnet reinforces the temperature decrement.**

***Index Terms*—Cooling, Ferrofluid, Finite Element Method, Magnet, Power Transformer, Thermomagnetic Convection.**

## I. INTRODUCTION

POWER TRANSFORMER excessive heating is one of the commun severity problems that may risk sustainability of these devices. In order to enhance the heat transfer rate within the transformer, a new cooling fluid is proposed: Ferrofluid. A ferrofluid is a colloidal stable suspension of ferromagnetic nanoparticles dispersed in a non magnetic carrier liquid. In our study, cobalt ferrite nanoparticles have been seeded in Midel vegetable oil to form the ferrofluid.

Naturally, at constant magnetic field, a hot ferrofluid is less permeable than a cold one [1]. The dependence ferrofluid magnetization-magnetic field is taken into account by using the assumption of linear magnetic material for ferrofluids [2]:

$$\mathbf{M} = \chi(T)\mathbf{H}, \tag{1}$$

where $\mathbf{M}$ is the ferrofluid magnetization, $T$ the temperature, $\mathbf{H}$ the magnetic field and $\chi$ the magnetic susceptibility of the ferrofluid defined by:

$$\chi(T) = \frac{\phi\mu_0\pi d^3 M_{s,p}(T)^2}{18K_B T},\ M_{s,p}(T) = M_0(1-(\frac{T}{T_c})^{1.5}) \tag{2}$$

where $\phi$ is the volume fraction of magnetic material, $\mu_0$ the vacuum magnetic permeability, $d$ the particle average diameter, $M_{s,p}(T)$ the particle magnetization depending on the temperature, $K_B$ the Boltzmann constant, $M_0$ the particle magnetization at saturation, and $T_c$ the Curie temperature. Hence, the heated ferrofluid loses its magnetization at the windings, and is pushed up by the magnetic relatively cooler fluid from the surrounding. So, heat is transferred, through the warmer fluid, to the tank border then to the ambience [3]. Thus, a magnetic force is added to the buoyancy force, and changes the convection flow pattern into the tank. After losing its heat, the magnetic fluid regains its magnetization. The fluid convection related to the magnetic field is called the magnetoconvection. Therefore, the need to an external mechanical pumping system is avoided. This magnetic force can be modelled by the Helmholtz one (N/m$^3$) given by:

$$\mathbf{F} = -\mu_0\frac{\mathbf{H}^2}{2}\nabla\chi(T) \tag{3}$$

This force connects the magnetization variation with the thermal gradient. We first present a numerical simulation using the finite element method, to solve the fluidic thermal magnetic coupling. In particular, we study the impact of a radial ring magnet on the cooling process. Secondly, we perform an experimental test to validate the numerical results and make some comparisons.

## II. EXPERIMENTAL SETUP AND GOVERNING EQUATIONS

The experimental setup studied is based on a Copper coil immersed in ferrofluid, the total is set into an Aluminium tank, tighty closed at the top by a PVC cap as shown in Fig. 1. A radial ring magnet is located close to the tank border, to study its impact on the cooling process.

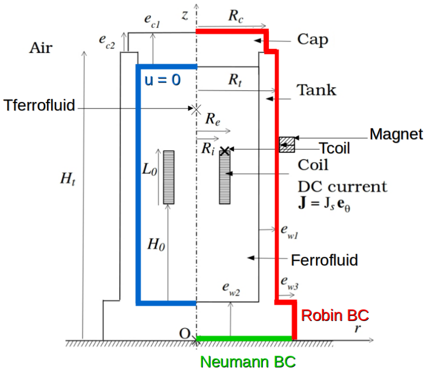

Fig. 1: Experimental setup using ferrofluid cooling

The magnetic fluid is considered as an homogeneous continuous medium, with incompressible Newtonian fluid behavior. The study of the thermal exchange through our cooling device requires the knowledge of the fluidic computation, governed by the laws of Navier-Stokes:

$$\left\{ \begin{array}{l} \nabla \cdot \mathbf{u} = 0, \\ \rho_l \frac{D\mathbf{u}}{Dt} + \nabla p - \rho_l \nu \nabla^2 \mathbf{u} = \rho_l \beta g (T - T_0) \mathbf{\dot{e}z} + \mathbf{F}, \end{array} \right. \tag{4}$$

with $\frac{D\mathbf{u}}{Dt}$ the material derivative, $\mathbf{u}$ the velocity vector, $p$ the pressure, $\nu$ the kinematic viscosity, $\rho_l$ the density of the magnetic fluid, $g$ the acceleration of gravity, $\beta$ the thermal expansion coefficient, $T_0$ the reference temperature. The two last terms at the right side of the Navier-Stokes equation are respectively the buoyancy thermal force and the magnetic force.

The heat transfer process that occurs in the ferrofluid is described by the following heat equation:

$$\rho_l C_p (\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T) = \nabla \cdot (\lambda \nabla T) + Q, \tag{5}$$

where $C_p$ is the specific heat capacity at constant pressure, $\lambda$ the thermal conductivity and $Q$ the volumic heat source dissipated by the Joule effect at the coil and given by $\frac{1}{\sigma} J_s^2$ (where $\sigma$ is the copper electrical conductivity, and $J_s$ the current density in the coil).

The computed electromagnetic field is assumed to be quasi-steady harmonic, and the ferrofluid magnetization is considered as instantaneously aligned with the magnetic field (see [4, p. 22-23]). The pyromagnetic coefficient is neglected. The magnetostatic equations are given by:

$$\left\{ \begin{array}{l} \nabla \times \mathbf{H} = \mathbf{J}, \\ \nabla \cdot (\mu \mathbf{H}) = 0, \;\; \mu = \mu_0 (1 + \chi(T)) \end{array} \right. \tag{6}$$

with $\mathbf{J} = J_s \mathbf{e_\theta}$, $\mu$ the magnetic permeability of the ferrofluid, and $\mathbf{B}$ the magnetic induction. The applied boundary conditions are : $q_0 \mathbf{n} = h(T_{ex} - T)\mathbf{n}$ at the tank top and lateral wall, $q_0 \mathbf{n} = \mathbf{0}$ at the bottom, $\mathbf{u} = \mathbf{0}$ at the fluid domain borders, $\mathbf{A} \times \mathbf{n} = \mathbf{0}$ at the tank exterior borders. Initially, we assume that $\mathbf{U_0} = \mathbf{0}$, $T = T_0$, $\mathbf{A_0} = \mathbf{0}$ with null reference pressure $P_0 = 0$, where $\mathbf{n}$ is the unit normal vector, $\mathbf{A}$ the magnetic potential vector, and $h$ the global heat exchange coefficient (tank-air).

The parameters are $\phi = 7\ \%$, $d = 10\ nm$, $\rho_l \nu = 0.1\ Pa.s$ as ferrofluid characteristics, where $\rho_l \nu$ is the dynamic viscosity. The electrical current in the coil is $I = 4\ A$ with a density $J_s = 3,35.10^6\ A.m^{-2}$, $B_r = 0.3\ T$ (magnet residual induction), $T_0 = 293\ K$ and $h = 8\ W/m^2.K$(for natural convection).

The setup dimensions are given in TABLE 1.

| Parameter | $H_t$ | $R_t$ | $e_{w1}$ | $e_{w2}$ | $e_{w3}$ | $H_0$ |
|---|---|---|---|---|---|---|
| Value (cm) | 12.5 | 3.1 | 1 | 2 | 1 | 3.9 |
| Parameter | $L_0$ | $R_i$ | $R_e$ | $R_c$ | $e_{c1}$ | $e_{c2}$ |
| Value (cm) | 2.1 | 0.8 | 1.175 | 2.6 | 2 | 1 |

TABLE 1: Experimental setup dimensions

## III. RESULTS AND COMPARISONS

We study the fluid behavior when hanging a magnet to the tank wall. For this first test, the magnetic field of the coil is canceled (see [4, p. 129-130]), and we have only the magnet effect in the model. After 250 minutes of applying the magnet, it is removed. We record temperature at 2 locations, on the coil and in the fluid (see Fig. 2). We note that without the coil magnetic field, the solenoid temperature increases when the magnet is removed, by a variation of about 1 K. At the same moment, the fluid temperature decreases.

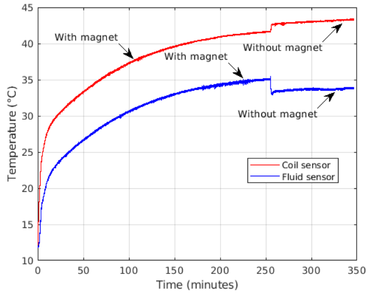

Fig. 2: Experimental temperature measurements when applying/removing magnet

The same process is numerically tested: the magnet impact is deactivated at t = 250 min, to see the crenelation reproduced numerically. As shown in Fig. 3, the numerical results are qualitatively and quantitatively in good agreement with experimental ones. The numerical results (data not shown) show that when the magnet is applied, the distribution of the magnetic force within the ferrofluid is changed. As a result, the fluid flow around the coil is modified, such that new recirculations arise and enhance the coil cooling.

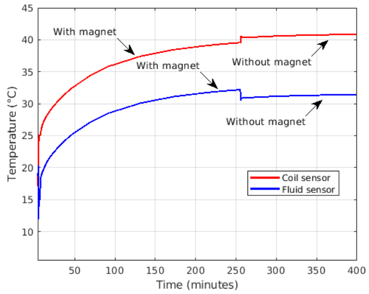

Fig. 3: Numerical results of temperature when activating/deactivating magnet effect

## REFERENCES

[1] M. Petit, A. K-Lebouc, Y. Avenas, W. Cherief, E. Rullière, "Etude expérimentale d'un système statique de génération de pression magnétothermique," Symposium de Génie Électrique 2014, Jul. 2014.

[2] R. Zanella, C. Nore, F. Bouillault, X. Mininger, J. -L. Guermond "Natural convection of a ferrofluid in a cylindrical container heated by a solenoid inside," Journal of Magnetism and Magnetic Materials, Jan. 2018.

[3] J. Patel, K. Parekh, R. V. Upadhyay "Prevention of hot spot temperature in a distribution transformer using magnetic fluid as a coolant," International Journal of Thermal Sciences, May. 2016.

[4] R. Zanella, "Thermomagnetic convection in ferrofluids: finite element approximation and application to transformer cooling," Thèse de doctorat de l'Université Paris-Saclay, Déc. 2018.