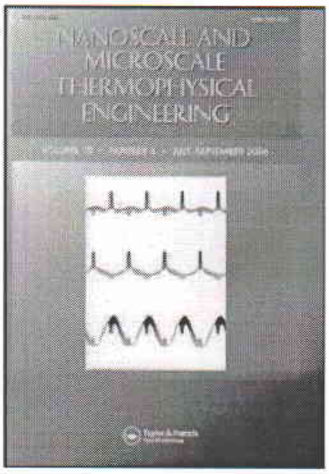
# ANNEX I:
# List of 10 relevant scientific publications

1. **Stoian, F.D**., Morimoto, H., Sato, T., and Maekawa, T. (2002). Cluster growth and structures of Lennard-Jones molecules near the critical point. MICROSCALE THERMOPHYSICAL ENGINEERING (in 2006 was changed to Nanoscale and Microscale Thermophysical Engineering). Vol 6(1), pp. 15-30, ISSN: 1556-7265, DOI:10.1080/108939502753428211 (ISI Article, FI 2015: 2.39)
2. **Stoian F.D.**, Pop G, Bica D, Stoica V, Marinica O, Vekas L. (2003). A fundamental study regarding the control of nucleate boiling in a complex magnetizable fluid by an applied magnetic field, in microgravity conditions, SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM - STAIF 2003 - AIP Conference Proceedings, ISSN 0094-243X, 2003, Vol.654, pp. 149-156, DOI: 10.1063/1.1541289 (ISI Conference Paper)
3. **Stoian F.D.**, Holotescu, S., Vekas, L., (2010). Bubbles generation mechanism in magnetic fluid and its control by an applied magnetic field, 12th International Conference on Magnetic Fluids (ICMF12), Japan, August 1-5, 2010, Book Series: Physics Procedia, 2010, Vol.9, pp. 216-220 (ISI Conference Paper).
4. Bica, D., Vékás, L., Avdeev, M.V., Bălăşoiu, M., Marinică, O., **Stoian, F.D**., Susan-Resiga, D., Török, G., Rosta, L. (2004). Magnetizable colloids on strongly polar carriers – preparation and manifold characterization, Progr. Colloid Polym. Sci., Vol. 125, pp. 1–9, (ISI Conference Paper).
5. **Stoian F.D.**, Holotescu, S., Stoica, V., Bica, D., Vekas, L. (2008). Comparative study of convective heat transfer in water and water based magnetizable nanofluid for thermal applications, 5th International Conference on New Research Trends in Materials Science, September, 2007, Romania, published in *Journal of Optoelectronics and Advanced Materials*, 2008, Vol.10(4), pp.773-776 (ISI Article/Conference Paper, FI 2015: 0.383)
6. **Stoian F.D.**, Holotescu, S. (2012). Experimental Study of Natural Convection Enhancement Using a Fe3O4-Water Based Magnetic Nanofluid, *J. Nanoscience Nanotechnology*, Vol.12, Nr.10, pp. 8211-8214 (ISI Article, IF 2015:1.338)
7. Morega, A.M., Morega, M., Pislaru-Danescu, L., Stoica, V., Nouras, F., **Stoian, F.D**. (2010). A Novel, Ferrofluid-Cooled Transformer. Electromagnetic Field and Heat Transfer by Numerical Simulation. 12th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2010, 20-22 May 2010, Brasov, Romania, Publisher IEEE, Print ISBN: 978-1-4244-7019-8, , 10.1109/OPTIM.2010.5510425, (ISI Conference Paper).
8. Holotescu, S., **Stoian F.D.**, Marinica, O., Kubicar, L., (2011). Utilization of the magnetogranulometric analysis to estimate the thermal conductivity of magnetic fluids, *Journal of Magnetism and Magnetic Materials*, 2011, Vol.323 (10), pp.1343-1347 (ISI Article/Conference Paper, IF 2015: 2.357)
9. **Stoian F.D.**, Holotescu, S., Taculescu, A., Marinica, O., Resiga, D., Timko, M., Kopcanski, P., Rajnak, M. (2013). Characteristic Properties of a Magnetic Nanofluid Used as Cooling and Insulating Medium in a Power Transformer, the 8th International Symposium on Advanced Topics in Electrical Engineering (IEEE Conference), Bucharest, May 23-25, 2013, ISBN: 978-1-4673-5980-1; 978-1-4673-5979-5, (ISI Conference Paper)
10. **Stoian F.D.**, Holotescu, S. (2014). Experimental study of cooling enhancement using a Fe3O4 magnetic nanofluid, in an applied magnetic field, 32nd Italian Union of Thermo-Fluid-Dynamics (UIT) Heat Transfer Conference Location: Pisa, ITALY Date: JUN 23-25, 2014, Book Series: Journal of Physics Conference Series, Volume: 547, Paper no. 012044 (ISI Conference Paper).

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# CLUSTER GROWTH AND STRUCTURES OF LENNARD-JONES MOLECULES NEAR THE CRITICAL POINT

Floriana D. Stoian; Hisao Morimoto; Takeshi Sato; Toru Maekawa

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# CLUSTER GROWTH AND STRUCTURES OF LENNARD-JONES MOLECULES NEAR THE CRITICAL POINT

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***We considered a two-dimensional system consisting of 529 molecules, interacting with each other via the full Lennard-Jones potential.***

***Using a constant NVT molecular dynamics simulation method, we studied the behavior of this system and analyzed the cluster growth process near the critical point. We considered several data sets near the critical point. By analyzing the cluster formation, we obtained a power law-like behavior for $N_S(t)$, the number of clusters, and $S(t)$, the average number of molecules in a cluster with respect to time.***

***We also carried out a steady-state analysis. Starting the molecular dynamics simulation in the canonical ensemble, after about 150 ps we changed the ensemble to microcanonical for another approximately 300 ps. We calculated the following static properties: isometric heat capacity, isothermal and adiabatic compressibilities.***

Beginning with the experimental discovery of the liquid–vapor critical point by Andrews in 1869, considerable efforts have been made to describe theoretically the phenomena at the critical point, of which we shall mention those of van der Waals (just four years after Andrews), Landau, Ising, Onsager, Widom, Kadanoff, and Wilson [1].

It is well known nowadays, both theoretically and experimentally, that the isometric heat capacity, $c_v$, shows a divergence and a jump at $T = T_c$ [2]. Also, the experiments carried out by Michels, for $CO_2$ [3], and recently by Pittman for He-3 [4], proved that the thermal conductivity, $k$, has a sharp increase at the critical point. While $k$ increases when approaching the critical point, the thermal diffusivity, $D_T$, decreases due to the strong effect of increasing the isobaric heat capacity, $c_p$.

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# A fundamental study regarding the control of nucleate boiling in a complex magnetizable fluid by an applied magnetic field, in microgravity conditions

**By:** Stoian, FD (Stoian, FD); Pop, G (Pop, G); Bica, D (Bica, D); Stoica, V (Stoica, V); Marinica, O (Marinica, O); Vekas, L (Vekas, L)

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## Abstract

A new type of working fluid to be used for boiling or multiphase heat transfer in microgravity conditions is proposed. The advantages of using a complex magnetisable fluid for boiling or multiphase heat transfer in microgravity are presented, based on the theoretical analysis of the body forces exerted by an applied magnetic field in such a fluid, in comparison with the similar phenomena determined by the body forces exerted by an applied electric field in a dielectric fluid. The experimental set-up designed to study the effect-of the applied magnetic field on the bubble dynamics, to be proposed for a microgravity experiment, and currently in preparation for experimentation under terrestrial conditions, are presented.

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# Bubbles generation mechanism in magnetic fluid and its control by an applied magnetic field

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**Abstract**

A comparison of the effect of an applied magnetic field on the bubble departure diameter in a magnetic nanofluid, for different orientations of the magnetic field gradient with respect to gravity, is presented. Using the instantaneous relative pressure during the bubble growth and departure and the instantaneous gas flow rate measured for a certain range of magnetic field intensity, the dependence between the average bubbles injection frequency, average bubble volume and the applied magnetic field were studied. An effect of the injection hole size on the bubble frequency was observed.



*Keywords*: bubble departure diameter; magnetic nanofluid; nucleate boiling; magnetic field.

## 1. Introduction

Heat dissipated in various types of devices and equipments that nowadays are getting more and more compact, surpasses the heat transfer performances of conventional cooling fluids. If we consider of combining the most promising passive method, that is the use of nanofluids as cooling fluid, with an active method – application of external fields, which can give the possibility of controlling the enhancement rate, than a solution could be offered by the magnetic nanofluids and an external magnetic field.

Boiling heat transfer is characterized by the highest heat transfer coefficients. Among the characteristic parameters of boiling, the average equivalent bubble diameter (assuming the bubble as a sphere, of an average size) is of major importance for the theoretical study of the nucleate boiling heat transfer but due to the parameters that influence the bubble formation and departure it is difficult to determine it theoretically [1]. Boiling of magnetic nanofluids was studied experimentally and theoretically, both from the point of view of enhancement rate and mechanisms [e.g. 2,3].

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The results of an experimental study regarding the bubble generation frequency and the bubble equivalent average diameter, as a function of the applied magnetic field, are presented in this work.

## 2. Theoretical background

The condition of bubble departure from the surface can be determined from the force balance on the vapor bubble during the process of growing. The simplest equation for the bubble departure diameter, $D_r$, includes the buoyancy and surface tension forces:

$$D_r = f(\beta)[\sigma/g(\rho_L - \rho_G)]^{1/2} \qquad (1)$$

where $f(\beta)$ is the liquid to surface contact angle, $\sigma$ – the surface tension, $\rho_L$ – the liquid density, $\rho_G$ – the vapor density, $g$ – gravitational acceleration. This equation does not include the effects of inertia and drag forces, like more recent and complex ones [1]. In the case of boiling of a magnetic nanofluid in the presence of an external magnetic field, the magnetic body force that acts on the growing bubble must be added in the force balance:

$$\vec{F}_m = -\mu_0 V M(H) \cdot \nabla H \qquad (2)$$

where $\mu_0$ – free space permeability, $V$ – bubble volume, $M$ – magnetic fluid magnetization, $H$ – magnetic field intensity. Thus, if the inertia and drag forces are neglected, the force balance results in [4]:

$$\vec{F}_b + \vec{F}_m = \vec{F}_s \qquad (3)$$

when buoyancy force and magnetic force act in the same direction. In this case the bubble departure diameter is:

$$D_{r,m} = f(\beta)\sqrt{\sigma/(\rho_L - \rho_G)g \pm \mu_0 M \nabla H} \qquad (4)$$

the sign is depending on the relative orientation of buoyancy force and magnetic force.

## 3. Experimental bench

The experimental bench, presented in Fig.1, was designed to study the phenomena related to the growth and departure of bubbles injected from a flat surface in magnetic fluid and the effects of an applied magnetic field. A non-uniform magnetic field is generated using profiled, V-shaped, electromagnetic poles, which give rise to a constant gradient of the magnetic field, $\nabla H$, parallel with the gravitational field, $\vec{g}$, with the same orientation as $\vec{g}$, or opposite orientation to $\vec{g}$, if the V-shaped poles are switched up-side-down. Prior to actual experiments, the magnetic flux density was measured along the symmetry axis of the air gap, with a 10 mm step. The field measurement was carried out using a Hall probe (6) and Bell Gaussmeter (5). The resulted field gradient at the hole site (50 mm up from the bottom of the poles) was 79.6 kA/m$^2$.

The experimental cell (9) is a cylinder with glass walls ($\Phi_{ext}$ = 38 mm and wall thickness 3 mm) and plexiglass bottom cap. The level of magnetic fluid in the cell was 55 mm. The injection hole was drilled in the center of the bottom cap. Three cells, with different hole diameters, $d$, of 0.3, 0.7 and 1.5 mm, were tested.

The magnetic nanofluid sample was a colloidal suspension of magnetite nanoparticles dispersed in hydrocarbon oil (TR-30), with density 1470 kg/m$^3$. The magnetization of the fluid sample was measured using a VSM magnetometer (DMS/ADE Technology, USA), the saturation value being 44.747 kA/m.

Using the experimental procedure described in [5], we measured the instantaneous relative pressure during the bubble growth and departure, close to the injection hole, and the injected gas flow rate.

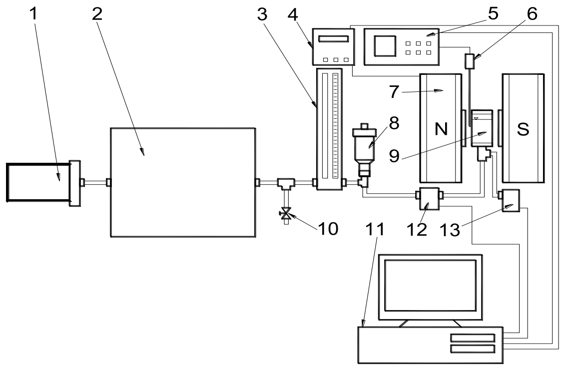


Fig.1: 1 – compressor; 2 –gas reservoir; 3 – manometer; 4 – magnets power supply; 5 -gaussmeter; 6 – Hall probe; 7 – magnetic poles; 8 - micrometer valve; 9 – experimental cell; 10 – flow rate valve; 11 – PC computer with data acquisition system; 12 - flow rate transducer; 13 – pressure transducer

The relative pressure was measured with a differential pressure transducer, accuracy ± 1 %. A flow rate sensor, accuracy ± 1 %, measured the injected gas flow rate. All data were recorded using a computer equipped with a NI DAQ system using the LabView software. By measuring the time period between two peaks we get the bubble emission period, $\tau_b$, and then the bubble frequency, $f$. By averaging the value of the measured flow rate over the acquisition period, we get the average gas flow rate. The average bubble volume, $V_b$, and further, the equivalent bubble diameter (of an equivalent spherical bubble of volume equal to $V_b$), $D_{ech}$, are obtained.

## 4. Results and discussion

The experiments showed that the applied magnetic field is influencing the bubble generation frequency, as well as the average equivalent bubble diameter. For the injection hole $d$ = 1.5 mm, the average frequency is increasing with the applied field when the field gradient has the same orientation as gravity and if the orientation is reversed, the frequency is decreasing. The values plotted in Fig.2 show the variation of $f$ from approximately -25% to + 55%, taking as reference the bubble generation frequency at zero field. The dependences obtained for the average equivalent diameter in the same case are presented in Fig.3. For the investigated field range, $D_{ech}$ ranged from -16 % to + 12 % of the reference value at zero applied field. Results reported by Bashtovoi et al [6], using a magnetic nanofluid of similar composition and saturation magnetisation, and capillary tubes of 0.8 to 1.8 mm diameter, showed that by applying a much higher field gradient, of different values and about 10 times higher than in this experiment, a corresponding much higher variation of the bubble volume can be obtained.

However, if the injection hole diameter was decreased, the case of $d$ = 0.7 mm and $d$ = 0.3 mm, the bubble generation frequency followed the ascending trend only to a certain magnetic field, after which the bubble generation frequency started to decrease, as shown in Fig.4. A possible explanation could be that from a certain value of the applied field inertia and drag forces have to be accounted for, as the bubble departure diameter lowers. Also, the characteristic times of the phenomena may play a role. Nucleate boiling experiments of a kerosene based magnetic fluid [7] in uniform field showed a similar trend, by increasing the boiling fluid temperature and the applied magnetic field, the bubble generation frequency increases at first and then decreases.

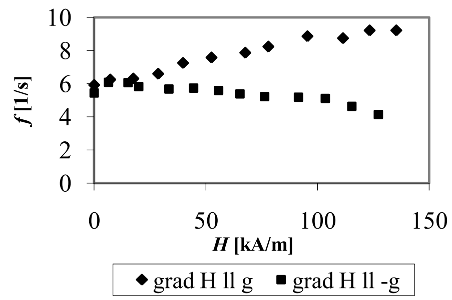


Fig.2. Average bubble generation frequency as a function of the applied magnetic field and its gradient orientation, $d$ = 1.5 mm

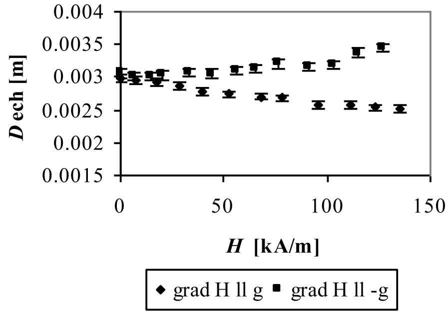


Fig.3. Average equivalent bubble diameter as a function of the applied magnetic field and its gradient orientation, $d$ = 1.5 mm

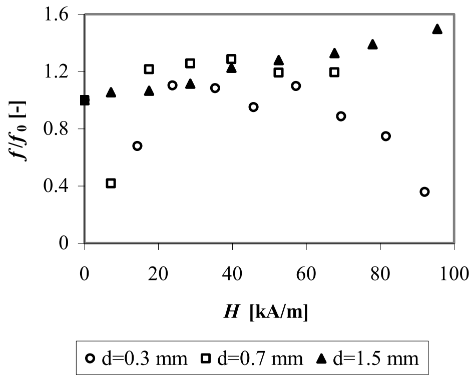


Fig.4. Bubble generation frequency as a function of the diameter of the injection hole, for grad H ll g

## 5. Conclusions

The experimental results showed that the bubble departure diameter and bubble frequency are influenced by the magnetic field, according to the force balance accounting for surface tension, buoyancy and magnetic force. Also, it was observed that the injection hole size might affect the bubble frequency and, consequently the bubble departure diameter, in correlation with the applied field.

## Acknowledgement

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# Magnetizable colloids on strongly polar carriers – preparation and manifold characterization

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**Abstract** The aim of this paper is to present methods applied to obtain and to investigate the properties of magnetic fluids on strongly polar carrier liquids, such as short-chain-length alcohols and water. The high degree of colloidal stability of these colloids is achieved by double-layer sterical stabilization of $Fe_2O_3$ and $CoFe_2O_4$ nanoparticles dispersed in the carrier liquid, the adequate choice and efficient adsorption of the surfactant(s) used being one of the key problems to be solved in each particular case, in order to obtain high-quality magnetic fluids. The samples were investigated using a vibrating-sample magnetometer, a rheo/magnetorheometer with various measuring cells, as well as by small-angle neutron scattering, in order to detect magnetic-field-induced changes at the nanometric level and qualitative differences in the macroscopic behaviour of various samples. The conclusions refer to the dependence of the colloidal stability on the composition and volumic concentration of the magnetic fluid samples, as well as on the applied magnetic field.

**Keywords** Magnetic nanoparticles · Magnetic fluids · Preparations · Properties

## Introduction

Magnetic fluids are a special category of colloids consisting of magnetic nanoparticles, such as $Fe_3O_4$, $CoFe_2O_4$, Co or Fe, stably dispersed in a carrier liquid. Owing to their high degree of colloidal stability, achieved by specific stabilization procedures, these colloids behave macroscopically as a homogeneous magnetizable liquid, even in strong and nonuniform magnetic fields. Consequently, these kinds of colloids, usually called magnetic fluids or ferrofluids, are smart colloidal systems, which manifest simultaneously fluid and magnetic properties. Macroscopically, the introduction of a controllable magnetic force into the fundamental hydrodynamic equations for the quasihomogeneous magnetizable liquid medium gives rise to the magnetohydrodynamics of magnetic fluids, known also as ferrohydrodynamics and opens an entire field of new phenomena [1, 2, 3]. From a microscopic point of view, the interactions between magnetic nanoparticles have to be adequately controlled in order to ensure the required high colloidal stability of the system in various operating conditions.

In the case of sterically stabilized nanoparticles in various liquid carriers, the type and quality of surfactants used will determine the efficiency of particle surface covering and, consequently, the balance between attractive and repulsive interactions between particles. The attractive interactions may lead to various types of

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# Comparative study of convective heat transfer in water and water based magnetizable nanofluid for thermal applications

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An experimental research carried out to investigate the convective heat transfer in a water based magnetizable nanofluid by natural convection is reported. The hot wall was a flat disk, heated from below. The open air played the role of the cold wall, as the upper surface of the fluid was free, at atmospheric pressure and temperature. Comparative tests were conducted using distilled water and water based magnetizable nanofluid. Several heating regimes were tested. The addition of nanoparticles in a usual heat transfer fluid as water led to a decrease in the heat transfer performance by natural convection.

(Received February 25, 2008; accepted April 2, 2008)

*Keywords*: Magnetizable nanofluid, Natural convection heat transfer, Nanoparticles

## 1. Introduction

The use of magnetic nanofluids (widely known as ferrofluids or magnetic fluids) – a special class of nanomaterials, as heat transfer fluids, had become a topic of intensive research starting about a decade ago [1-9]. The possible applications envisaged the use of phase-change heat transfer (boiling/condensation) or forced convection heat transfer modes. Both terrestrial and microgravity applications were taken into consideration due to the possibility to replace the gravitational field by the magnetic field in micro-g environments. Examples of such possible applications are: cooling systems for electric transformers, magnetocaloric heat pipes, pulsating heat transfer tubes and heat sinks. It should be noted also that, opposite to usual magnetic liquids prepared for their traditional applications (sensors, sealings etc), the magnetizable nanofluids for heat transfer should have a low concentration of magnetic nanoparticles in order to make them competitive with the non-magnetic nanofluids. On the other hand, an advantage of using magnetizable nanofluids, beside the possibility of control by an applied magnetic field, is the vast experience in preparation of such complex fluids gained over more than three decades [e.g. 11-14].

Recent results presented in the open literature state that among the possible mechanisms that may affect the convective heat transfer in nanofluids (similar to the case of magnetizable nanofluid in zero magnetic field) are the transport mechanisms associated to the relative (slip) velocity developed by the nanoparticles with respect to the carrier fluid, such as: inertia, Brownian diffusion, thermophoresis, Magnus effect, fluid drainage and gravity. A model proposed by Buongiorno [15] for convection transport in nanofluids states that, when the turbulent transport of nanoparticles dominates, the particles are carried by turbulent eddies, while if the opposite case occurs, Brownian diffusion and thermophoresis may become important slip mechanisms. Also, several other mechanisms are related to the larger increase in the effective thermal conductivity for a very low volume fraction ($\Phi \leq 1\%$) of solid nanoparticles of less than 10 nm in size, like ballistic transport of energy carriers within nanoparticles, formation of nanoparticle structures through agglomeration (in fractal-like shape), clustering and networking [16].

Natural convection in usual heat transfer fluids was widely studied both experimentally and numerically, for various types of configurations. However, for various reasons (like low heat transfer coefficient, uniqueness of the problem in closed cavities configuration), in the case of nanofluids this heat transfer mode was less approached [16]. Our work has as final target a new type of heat exchanger for automotive thermal management applications using a magnetizable nanofluid as working fluid and an applied magnetic field to control the heat transfer process. The study reported here envisaged the evaluation of the natural convection heat transfer characteristics for a magnetizable nanofluid of low concentration in comparison with the carrier fluid, for a certain configuration of cavity that may be suitable to accomplish our target.

## 2. Experiment

The water-based magnetizable nanofluid tested in this work is part of a series of magnetizable nanofluids (water-based and hydrocarbon-based) specially prepared and characterized within the framework of our research project [14,16]. The sample properties at 20 ºC are as follows: density $\rho_{MNF}$ = 1082 kg/m$^3$, viscosity $\eta_{MNF}$= 2.4·10$^{-4}$ Pa·s, specific heat capacity $c_{p,MNF}$= 3863.044 J/kgK, saturation magnetization $M_s$ = 50 Gs, volume fraction of magnetite ($Fe_3O_4$) nanoparticles $\Phi$ = 1.02 %. In Fig. 1 is shown the experimental setup used to analyze the natural convection heat transfer in a tube, heated from below.

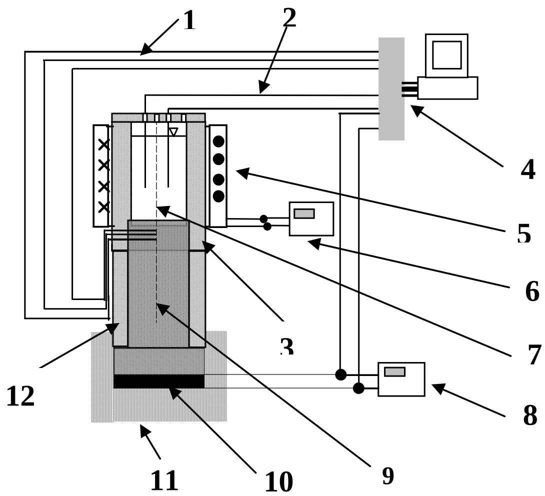


*Fig. 1. The setup for the natural convection experiment.*

The experimental cell (3) is a cylinder made of acrylic resin ($d_{int}$ = 16 mm, $H$ = 50 mm). The heating surface (9), made of aluminum ($d_{surf}$ =18 mm) is placed at the bottom side of the cell. A nickel heater (10) of resistance R = 0.14 Ω powered by a power supply (8), is used to heat the surface. The temperature inside the magnetizable nanofluid (7) and in the heating surface was monitored by K-type thermocouples (1,2). The cell and aluminum bar were insulated by acrylic resin (12), while the resistance heater was placed in a ceramic insulating frame (11). The effect of an applied DC magnetic field generated by a coil (5) can be also studied using the same setup. The coil is powered by a power supply (8). The experimental data were collected using a data acquisition system NI 6042E (4), embedded in a PC using a dedicated LabView program. A SCXI 1000 amplifier was used to achieve high accuracy temperature measurements.

The experiments were carried out at constant heat flux. To determine the heat flux and the heated surface temperature, a set of three thermocouples were placed in the axis of the aluminum bar at known distances (3, 5 and 5 mm), close to the heated surface. The heat flux was estimated from the Fourier law, based on the temperature gradient between two thermocouples ($T_{p1}$ mounted at 13 mm and $T_{p3}$ at 3 mm, from surface):

$$\dot{Q} = \frac{\lambda_{Al}}{x}\left(T_{p1} - T_{p3}\right) \quad [W] \tag{1}$$

where $\lambda_{Al}$ = 235 W/m·K is the aluminum thermal conductivity and $x$ = 10 mm is the distance between the position of thermocouples in the axis of the bar.

The heated surface temperature was determined using the indication of the thermocouple placed nearest to the surface (at 3 mm) and the heat flux given by Eq. (1):

$$T_p = T_{p3} - \dot{q}\frac{\delta}{\lambda_{Al}} \quad [K] \tag{2}$$

where $\delta$= 3 mm.

The average liquid temperature at stationary conditions, far from the surface ($T_\infty$), was determined from the readings of the set (2) of thermocouples in Fig. 1 ($T_{l1}$ and $T_{l2}$):

$$T_l = \left(T_{l1} + T_{l2}\right)/2 \tag{3}$$

The heat transfer coefficient, $h$, was determined based on the Newton's law:

$$h = \frac{\dot{q}}{\left(T_p - T_l\right)} \quad \left[W/m^2K\right] \tag{4}$$

where $\dot{q} = \dot{Q}/A$ and $A = \pi d_{\text{int}}^2/4$ .

The experiments were run at first with distilled water, for several regimes of heat flux (heating of the surface) to test the experimental cell and compare the results with known empirical correlations. Then, there were repeated using the sample of water-based magnetizable nanofluid for the same heat flux conditions.

## 3. Results

The results obtained for the natural convection heat transfer using distilled water were compared with a known correlation from literature. In this type of heat transfer mode the deciding factor is the Rayleigh number:

$$Ra = Gr \cdot \Pr = \frac{g\beta\Delta T l^3}{\nu^2} \cdot \frac{\nu}{\alpha} \tag{5}$$

where $g$ is the gravitational constant, $\beta$ is the volume expansion coefficient, $l$ is the characteristic length ($l = 0.9d_{int}$), ν is the kinematic viscosity, $\alpha$ is the thermal diffusivity. There are a considerable number of empirical correlations in literature for natural convection heat transfer, for different types of geometries and fluids. Most of these have the form:

$$Nu = CRa^n \tag{6}$$

where $Nu$ is the Nusselt number ( $Nu = hl/\lambda$ ), C and n being constants, depending on the value of Ra.

In Fig. 2 is shown a comparison between the experimental results and a well known correlation for natural convection from a plate heated from below [17]:

$$Nu = 0.54Ra^{1/4} \tag{7}$$

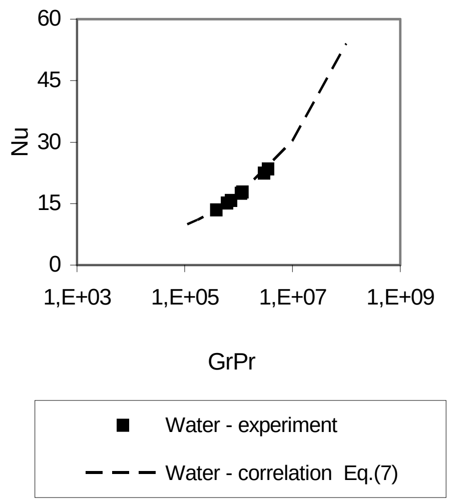


*Fig. 2. Comparison of experimental results for distilled water with correlation (7).*

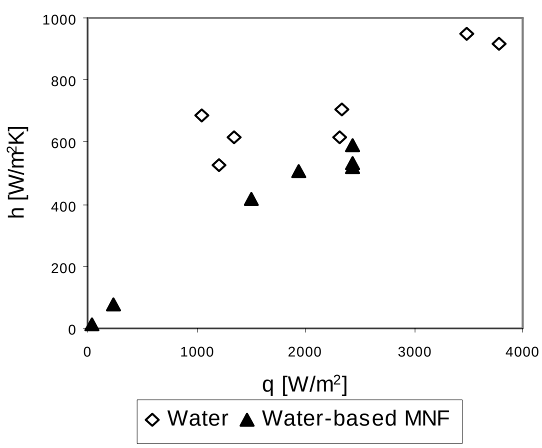


*Fig. 3. Comparison of experimental results of water and magnetizable nanofluid at steady state conditions.*

One can observe that the present experimental results are well described by Eq. (7).

In Fig. 3 are shown the experimental results for water and the magnetizable nanofluid sample at steady state. It was found that, for the same input of heat flux, the heat transfer coefficient of the magnetizable nanofluid is lower in comparison with that of water. Thus, the effect of addition of solid metallic nanoparticles in water is negative for natural convection heat transfer, similar to other experimental results using non-magnetic water-based nanofluids (Ti-O2 nanofluids, CuO nanofluids) [18,19].

## 4. Discussion

The analysis of our experimental results, using measured or estimated values of the thermophysical properties of the magnetizable nanofluid and literature data for water to calculate the Grashof and Prandtl numbers show an interesting behavior, for the same average temperature:

$$T_{\text{med}} = \left(T_l + T_p\right)/2 \tag{8}$$

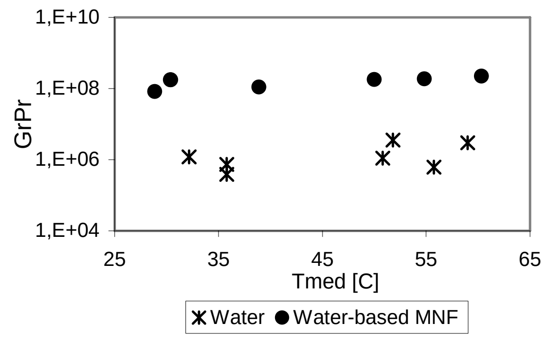


*Fig. 4. The influence of the thermophysical properties of the magnetizable nanofluid and water on Gr·Pr.*

As shown in Fig. 4, the value of Gr·Pr is in average $10^3$ times higher for the magnetizable nanofluid but, also due to a higher thermal conductivity of the magnetizable nanofluid, the value of Nusselt number is lower than that for water. It means that in order to obtain a value of the natural convection heat transfer coefficient for the magnetizable nanofluid similar to that of water, in the same working conditions, the turbulence should be further increased. That is, what actually “makes the difference” (influence the convective heat transport) in nanofluids are their thermophysical properties.

The application of a time-varying (e.g. rotating) magnetic field in the case of a nanofluid with particles having rigid dipole moment might give a solution to the problem.

## 5. Conclusions

The goal of the present research is the development of a new type of heat exchanger for automotive thermal management system using a magnetizable nanofluid as heat transfer fluid of low concentration, specially prepared for this application. This paper presents the results of the evaluation in the case of natural convection heat transfer.

We have tested the heat transfer performance of a magnetizable nanofluid ($\Phi = 1.019$ %) for a certain range of heat flux density and surface average temperature that are of interest for our case and using a configuration suitable for this purpose.

In the explored range of heat flux density, we obtained lower values of the heat transfer coefficient for the magnetizable nanofluid than those for the carrier fluid (water), the relative difference between the corresponding coefficients ranging from 4 to 16%. These results agree with other experimental data for non-magnetic water-based nanofluids, in the case of natural convection heat transfer mode [18,19].

The influence of the addition of nanoparticles in the carrier fluid on the thermophysical properties reflected in the values of the characteristic numbers Grashof and Prandtl, for the same average temperature of the nanofluid and carrier fluid, is determined.

**Acknowledgments**

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# Experimental Study of Natural Convection Enhancement Using a Fe3O4-Water Based Magnetic Nanofluid

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## Abstract

The effect of nanoparticles dispersed in a carrier fluid on the natural convection heat transfer is still raising controversies. While the reported experimental results show no improvement or even worsening of the heat transfer performance of nanofluids, the numerical simulations show an increase of the heat transfer coefficient, at least for certain ranges of Ra number. We report an experimental investigation regarding the natural convection heat transfer performance of a Fe3O4-water based nanofluid, in a cylindrical enclosure. The fluid was heated linearly from the bottom wall using an electric heater and cooled from the upper wall by a constant flow of water, such that a constant temperature difference between the upper and bottom walls was obtained at steady-state. The experiment was also carried out using water, in order to observe the effect of the addition of Fe3O4 nanoparticles on the heat transfer coefficient. Several regimes were tested, both for water and nanofluid. The experimental results showed that values obtained for the heat transfer coefficient for Fe3O4-water nanofluid were higher than those for water, at the same temperature difference. The present experimental results are also compared with our previous work and the reference literature.

## Keywords

**Author Keywords:** Natural Convection; Magnetic Nanofluid; Heat Transfer Coefficient
**KeyWords Plus:** HEAT-TRANSFER; FLUID; FIELD; ENCLOSURE; FLOWS; WATER

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# A Novel, Ferrofluid-Cooled Transformer. Electromagnetic Field and Heat Transfer by Numerical Simulation.

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***Abstract*—A ferrofluid-cooled low power, single-phased electric transformer was designed and prototyped with the aim of investigating the performance that such an apparatus may exhibit. The nanometric, colloidal, super-paramagnetic fluid used as coolant has specific electric, magnetic, and thermal properties, and presents an overall better stability and capacity to withstanding electromagnetic and thermal stress. This paper addresses also the electromagnetic and heat transfer processes that occur. First, the physical, mathematical, and numerical models are introduced. Numerical simulation results suggest that the magnetization body forces may add to the thermal, buoyancy body forces in providing for better heat transfer. To outline this, several numerical models that may conveniently be treated numerically within the current hardware and software limits, while still providing for satisfactory accuracy were developed. The results may be utilized also in the design phase of the transformer.**

## I. INTRODUCTION

Ferrofluids are utilized in a number of important industrial applications: "silent" coils (for noise reduction), sensors, (*e.g.*, accelerometers, flowmeters, sensors for inclination, pressure, level, *etc*.), sealing systems, different types of contacts [1], *etc*. Recently, it is observed a growing interest in their usage in high power devices for electrical engineering, in particular transformers with colloidal ferrofluids. Magnetizable nanofluids that are usable in heat transfer applications, as an alternative to the regular nonmagnetic fluids, present a lower concentration of magnetic nanoparticles.

The ferrofluids possess heat transfer and dielectric properties that are superior to their classical counterparts (*e.g.*, transformer oils), and may be utilized for improving the heat flow within the aggregate active part contributing thus to increasing their withstanding capacity to faults such as electromagnetic impulses. The ferrofluids may be driven by external magnetic fields, and the magnetization body forces within the ferrofluids may be controlled by adequately adjusting the incident magnetic field [2–7].

Finer details, such as local spectra of electromagnetic field, flow and heat transfer, and the system's response (the working ferrofluid) to changes in the incident magnetic field and, or the heat transfer rate are sometimes discernable by numerical simulations only [2], [5], [7].

This paper presents the design of an experimental, low power, single-phased transformer, cooled by natural convection, for medium voltage installations that uses ferrofluid in lieu of the standard oil. The ferrofluid was designed at the Laboratory for Magnetic Fluids at the Timişoara branch of the Romanian Academy (LMF-TB-RA), investigated by LMF-TB-RA and NRCSCF–UPT, and produced at ROSEAL. The transformer prototype was designed and fabricated by ICPE-CA and ICMET. The physical, mathematical, and numerical models developed a University POLITEHNICA of Bucharest (UPB) were aimed at investigating the heat transfer. The numerical simulation results evidence the heat transfer processes that occur under the combined action of the thermal, buoyancy forces and the magnetization body forces that occur in the ferrofluid used for cooling the transformer. They provide valuable information for the electromagnetic and thermal design of the transformer.

## II. THE FERROFLUID

Ferrofluids have been shown to provide higher capacity to sustain overvoltage, and present better resilience at degradation in time due to the humidity as compared to classic oils. Previous work [3] proves that replacing the transformer oil with a magnetic nanofluid (transformer oil sustained) may be beneficial to the thermal and dielectric performance of the transformer.

The magnetic nanofluid prepared for experiments is a colloidal dispersion of magnetite ($Fe_3O_4$) nanoparticles in transformer oil TR-40 with oleic acid as surfactant. Laboratory investigations were conducted to obtain a magnetic fluid having surfacted magnetic nanoparticles

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# Utilization of the magnetogranulometric analysis to estimate the thermal conductivity of magnetic fluids

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ABSTRACT

In this study, the semi-empirical equation for the effective thermal conductivity of the Holotescu–Stoian model was applied to a set of four dilutions of a transformer oil based magnetic fluid with magnetite nanoparticles as magnetic phase, using the results obtained for the size distributions from the magnetogranulometry analysis, followed by a comparison with the measured values of the effective thermal conductivity obtained by the hot ball method. The link between the size distribution by number and by volume used in the magnetogranulometry analysis and the Holotescu–Stoian model adaptation to the lognormal distribution were presented. The comparison between the results given by the model and the corresponding experimental data showed that by using the approximated size distribution to calculate the effective thermal conductivity the analytical results much closer to the experimental ones are obtained, compared to those given by the Maxwell classical model.



## 1. Introduction

One of the main parameters that influence heat transfer in various technical applications is the thermal conductivity. Usually, if cooling of a system is needed, the conventional solution is to use liquid like water, ethylene glycol, mineral or synthetic oils and refrigerants. Colloidal suspensions of metallic or non-metallic nanoparticles in the aforementioned liquids named "nanofluids" have higher thermal conductivity compared to that of the carrier liquids, an advantage that makes them a potential replacement for usual cooling fluids.

The use of nanofluids based on transformer oil and stably dispersed metallic nanoparticles as coolant of the power transformers requires the necessity to maintain their insulating properties in allowable limits [1,2]. This requirement limits the possibility to increase the nanofluid effective thermal conductivity by increasing the volume fraction of metallic nanoparticles, so that solutions to enhance the heat transfer for a specified volume fraction need to be found.

Both theoretical and experimental results proved that the size distribution of nanoparticles does influence the effective thermal conductivity of the nanofluid [3–5]. The mechanisms involved are not yet fully elucidated, most probably due to lack of a unitary way to characterize and report the size distributions.

In fact, the size distribution is an approximation that includes simplifying assumptions regarding the shape of the particles that determine the description of the particle using a single descriptor, the equivalent diameter. This leads to major differences between the results obtained using various methods to determine the size distribution, which refer to equivalent diameters specific to each measuring method.

The size distribution analysis of ferrofluids, using various accepted methods (magnetogranulometry, X-ray, electron microscopy, phonon correlation spectroscopy, torsional-pendulum method, etc.), showed also that certain differences exist between the results of various methods [6], even in the case of using the same method [7]. The magnetogranulometric method is based on the analysis of the magnetization curves and the choice of a type of size distribution of nanoparticles. The lognormal [8–11] and gamma [12–15] mono-modal size distributions are the most used ones due to their simplicity and because these depend only on two parameters that can be simply determined using the asymptotic behavior of the magnetization curve.

In the first part of the paper we present the simplest version of the magnetogranulometric method, based on the Langevin behavior of the magnetic fluid (valid for low volume fractions), and outline that depending on the way the lognormal size distribution is interpreted as being by volume [8] or by number [9], different results are to be obtained. This fact requires the necessity of details when results are reported so it can be converted according to a certain case study.

A large number of analytical models for evaluating the effective properties of colloidal suspensions are available, such as mixture

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# Characteristic Properties of a Magnetic Nanofluid Used as Cooling and Insulating Medium in a Power Transformer

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*Abstract*- **Magnetic nanofluids (widely known as ferrofluids or magnetic liquids) have a unique property – they are responsive to the application of a magnetic field, which allows for the possibility of controlling the flow and the convective heat transfer. This paper presents the characteristic thermo-physical, magnetic and dielectric properties of a transformer oil based magnetic nanofluid, specially prepared for use as a cooling and insulating medium in a power transformer.**

***Keywords*: power transformer, cooling, insulation, magnetic nanofluid, saturation magnetization, electric permittivity, thermal properties**

## I. INTRODUCTION

The insulation fluids in power transformers perform two main functions: insulation, to prevent the flow of electric current between conductive components, and cooling, to transfer the heat out of transformer windings and core. The heat transfer rate from the transformer components to its walls and its subsequent dissipation into surroundings are factors that limit the current density in the windings and define its size and weight for a given power rating. Well purified mineral oils (e.g. transformer oil) are characterized by low thermal conductivity, so their efficiency as cooling agent is limitted. Therefore, finding an insulating and cooling medium with enhanced electrical and thermal properties, leading to more efficient and environmentally safer power transformers for both energy distribution and industrial applications, has been a goal of the research in the field over the last decade [1-4]. Thus, synthetic oils, mixtures of mineral and synthetic oils were developed for replacing the traditional transformer oil [3-6]. At the same time, during the last decade a new type of coolant for power transformers was proposed and tested: the transformer oil based magnetic nanofluid (MF_UTR) [1, 5]. The unique feature of MF_UTR over any other type of coolant is that is responsive to the magnetic field. This characteristic, that enables the magnetic field lines to close inside the transformer due to the presence of the dispersed magnetic nanoparticles, can improve the electric performances. In the case when a MF_UTR is used, both thermo-physical properties and heat transfer coefficient can be influenced by an applied magnetic field, such that an active control of the heat transferred in an equipment can be obtained, if the laws of dependence between each property and the applied magnetic field are known. Therefore, the study of their thermo-physical, magnetic and electrical properties have to be carried out both with respect to the temperature dependence and the effect of the applied magnetic field (AC/DC, magnitude, AC field frequency). Moreover, knowledge of the laws of variation for the thermo-physical, magnetic and electrical properties with respect to the volume fraction, magnetic field magnitude and working temperature, offers the premises of a realistic elaboration and validation of a thermal model for a transformer, using this nanofluid as cooling and insulating medium. In this paper are presented the characteristic magnetic, rheological, thermal and electrical properties of a transformer oil based magnetic nanofluid, prepared especially for use as insulating and cooling medium in a power transformer.

## II. PREPARATION OF THE NANOFLUID SAMPLE

A MNF sample was prepared, based on transformer oil UTR 40 and magnetite ($Fe_3O_4$) nanoparticles, stabilized with a hydrophobic single layer of OA (oleic acid). The synthesis procedure used the co-precipitation method developed by D. Bica, described in detail in [7, 8].

Density measurements were carried out using an Anton Paar DMA 35N density meter, at room temperature, 25°C. The results were $\rho_{UTR} = 0.867$ g/cm$^3$ and $\rho_{MNF} = 0.937$ g/cm$^3$. The solid volume fraction of the magnetite nanoparticles, $\varphi$, dispersed in the carrier liquid was calculated using

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# Experimental study of cooling enhancement using a $Fe_3O_4$ magnetic nanofluid, in an applied magnetic field



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# Experimental study of cooling enhancement using a $Fe_3O_4$ magnetic nanofluid, in an applied magnetic field

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**Abstract**. This paper presents the results of an experimental study that envisaged the evaluation of the cooling capabilities of a transformer oil based magnetic nanofluid with the solid volume fraction of magnetite nanoparticles equal to 0.0162, in an AC applied magnetic field (f = 50 Hz). The heating and cooling regimes of a coil immersed in the magnetic nanofluid were compared to that corresponding to the base fluid (transformer oil). The results of our study indicate that the temperature rise rate of the magnetic nanofluid is lower than that corresponding to the transformer oil and a lower stationary temperature is obtained in the coil core, where the magnetic flux density is the largest.

## 1. Introduction

Researches regarding the use of nanofluids in thermal applications carried out worldwide are based primarily on the findings that their effective thermal conductivity is enhanced relatively to that of the carrier liquid [1,2]. This offer in turn the possibility to obtain a larger heat transfer coefficient in those devices and equipments where the heat transfer fluid is replaced with an application-compatible nanofluid. The magnetic nanofluids (widely known as ferrofluids or magnetic liquids) have an additional property – they are responsive to the application of a magnetic field, which allows for the possibility of controlling the flow and the convective heat transfer [3-5]. Magnetic nanofluids heat transfer related research is ranging from heat removal in magneto-fluidic devices for maintaining the desired magnetic properties, to their use as heat transfer fluids [3-7]. A field of research that gained promising results up to date is that of cooling and insulation of power transformers and other types of electromagnetic devices using magnetic nanofluids [7-12]. In this case, the magnetic field generated by the windings of a power transformer is used also to generate the flow of the magnetic nanofluid (the magneto-convection), thus enhancing the heat removal from the windings [11,12].

The aim of this work was to evaluate the cooling potential of a magnetic nanofluid for use as cooling medium in a power transformer. To accomplish this, the cooling of a coil powered by a 50 Hz AC power supply using a specially prepared $Fe_3O_4$ transformer oil based magnetic nanofluid [13], was investigated experimentally.

## 2. Materials

A magnetic nanofluid (MNF) sample and its carrier fluid – the transformer oil (TO-40A, producer MOL) were used in this experimental study. The MNF consisted of a stable colloidal dispersion of magnetite ($Fe_3O_4$) nanoparticles in TO-40A, with oleic acid (Vegetable oleic acid, 65-88 %, Merk) as surfactant, and was prepared using an established procedure developed by Bica et al [5,14].

The volume fraction of magnetite nanoparticles was determined based on the measured values of the transformer oil density and magnetic nanofluid density (indicated in table 1) and magnetite density, taken equal to 5180 kg $m^{-3}$. The resulting volume fraction is $\Phi$ = 1.62 %. The details of the preparation procedure and characterization of the magnetic, electric, rheological and thermal properties of the MNF are given in [13]. A summary of the characteristic properties for the MNF and TO-40A, at 25 °C, is given in Table 1.

**Table 1.** Physical properties.

| | $\rho$ kg $m^{-3}$ | $\eta$ mPa s | $k$ W m $K^{-1}$ | $c_p$ J $kg^{-1}$ $K^{-1}$ | $\beta$ $K^{-1}$ | $\varepsilon$ F $m^{-1}$ | $M_s$ A $m^{-1}$ |
|---|---|---|---|---|---|---|---|
| **Magnetic nanofluid (MNF)** | 937 | 18.5 | 0.133 | 1743.39 | 6.62 $10^{-4}$ | 2.25 $\varepsilon_0$ | 2785.3 |
| **Transformer oil (TO-40A)** | 867 | 17.5 | 0.127 | 1915.12 | 7.15 $10^{-4}$ | 2.2 $\varepsilon_0$ | - |

The properties in table 1 are as follows: $\rho$ is the density, $\eta$ –dynamic viscosity, $k$ – thermal conductivity, $c_p$ - heat capacity, $\beta$ – thermal expansion coefficient, $\varepsilon$ – dielectric constant, $M_s$ - saturation magnetization.

## 3. Experimental Setup

The cooling potential of the fluids was tested in an experimental setup presented in figure 1. A coil (4) of R = 680 Ω was placed in the center of the measurement cell – a cubic vessel (1) with Plexiglas walls of size 60 x 60 x 60 $mm^3$. The coil has the windings disposed on a rectangular plastic housing (3) and the internal air core dimensions are 15 mm x 15 mm x 18 mm. The coil housing is set on four legs on the bottom of the cell such that the fluid can circulate from the coil core to the outside bulk. The test fluid (2) was consecutively, TO-40A and MNF. The same volume of fluid, $V_f$ = 130 $cm^3$ was used. The coil was powered by a 50 Hz AC power supply (7), the working voltage being set at 40 V. Six temperature measurement points were established from the external side of the cell wall to the center of the coil core, as follows: the temperature of the external side ($T_1$) and of the internal side ($T_2$) of the measurement cell wall, the temperature on the external wall ($T_4$) and internal wall ($T_5$) of the coil, the temperature in the fluid ($T_3$) at the middle point between $T_2$ and $T_5$, and the temperature in the fluid in the central axis of the coil core ($T_6$). All measurement points are in the same horizontal plan. The six T – type thermocouples (Omega GmbH, 0.5 mm, Teflon insulated, standard error of ±1ºC or ±0.7%) were introduced through plastic tubes inserted in a foam lid, placed on top of the measurement cell (not drawn in the schematic, for simplification reasons). Each thermocouple was connected through a NI SCC TC-01 module to a data acquisition system (6) consisting of a NI DAQ PCMCIA 6062E card and the NI SC 2345 connector block. The acquisition system was connected to a laptop computer (8) and the temperature measurements were recorded using the software package LabView 8.6. The sampling rate was 1 sample/s.

The coil magnetic flux density, B, was measured with a FW Bell 5080 Gaussmeter, before the heat transfer experiments. Using the axial and transversal Hall probes, the magnetic flux density was measured in several point of interest in the measurement cell for the applied voltage, as follows: the middle of the coil core axis (A), the top center of the core coil (B), the point situated 15 mm above the top center of the coil (C) and the point situated 15 mm above the top of the core corner (D), as indicated in figure 2. The obtained values are listed in Table 2.

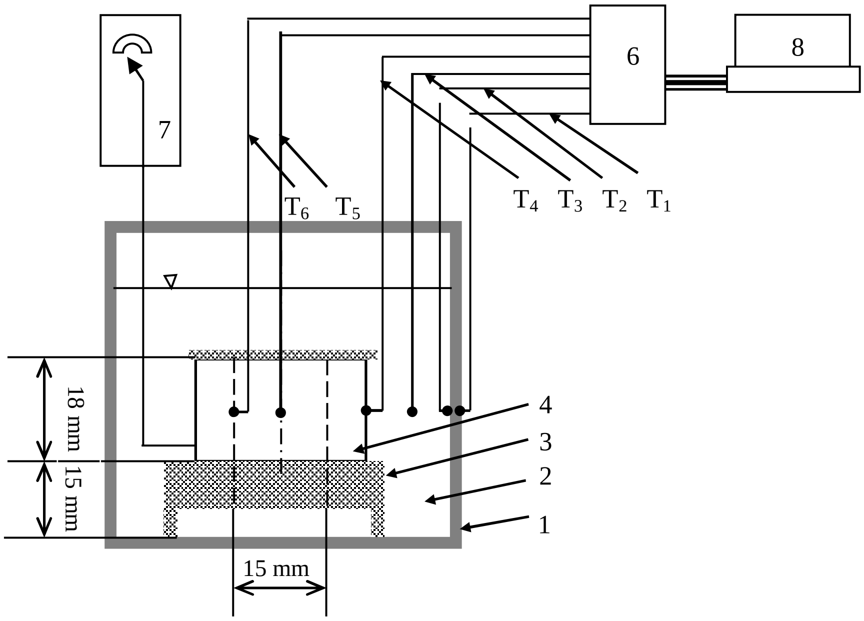


**Figure 1.** Experimental setup

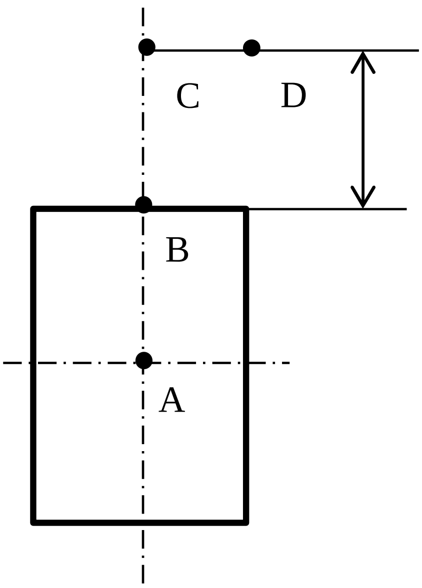


**Figure 2**. Indication of the magnetic flux density measurement points in the coil core and above it

**Table 2**. Measured magnetic flux density values.

| Point | B [mT] |
|---|---|
| A | 8.1 |
| B | 4.9 |
| C | 1.4 |
| D | 1.0 |

Using Vizimag software for visualising the magnetic field with the characteristics of the coil and measured magnetic field data for calibration, it was obtained a model for the magnetic field lines and the magnetic flux density contours of the coil, which are presented in figure 3. It can be observed that the effect of the magnetic field generated by the coil is limited to the coil core and its vicinity.

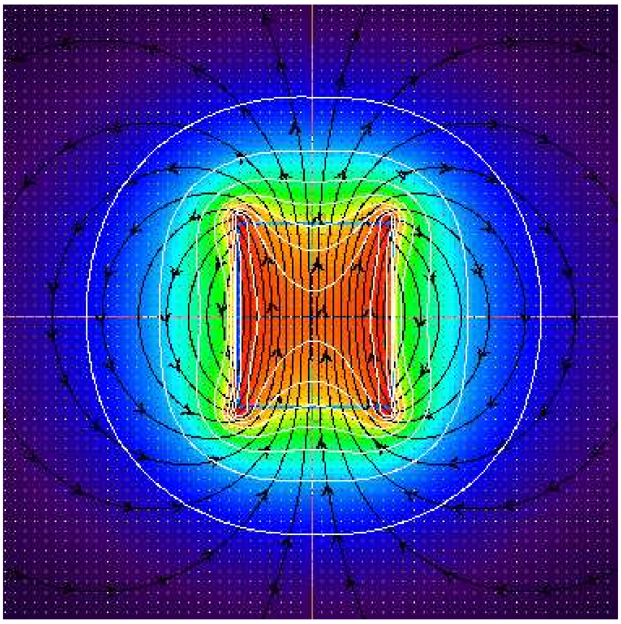

**Figure 3.** Model of the coil magnetic field lines (black lines with arrows) and the flux density contours (white lines)

## 4. Results and Discussion

The measurement session for each fluid was divided into three periods: (I) – a non-stationary heating regime characterised by a temperature rise rate, (II) – a stationary heating regime, and (III) cooling regime characterised by a temperature decrease rate.

In each experiment, the temperatures measured by the six thermocouples were continuously recorded by the data acquisition system, starting from the room temperature (28±1.0 ºC) and until the end of the cooling regime. During the measurement session, the start of the stationary heating regime was established as the beginning of the period when the temperatures varied less than the standard error (that is less than ±1.0 º C). The stationary heating regime was attained after about 130 minutes from the start of the experiment. After a stationary period of at least 10 minutes, the power supply was turned off and the experimental system entered the cooling regime until it returned at the initial temperature.

The results of the temperature measurements were compared for the two tested fluids and are presented in figures 4 to 7. Figures 4 and 5 show that, when comparing the stationary values of temperatures $T_1 – T_6$ for the two test fluids, the main differences are obtained for $T_5$ - the temperature measured in the coil core. The average values of the measured temperatures in the stationary regime are presented in table 3.

**Table 3.** Average temperatures at the measurement points, in the stationary heating regime.

| **Working fluid** | $T_{1,avg}$ [°C] | $T_{2,avg}$ [°C] | $T_{3,avg}$ [°C] | $T_{4,avg}$ [°C] | $T_{5,avg}$ [°C] | $T_{6,avg}$ [°C] |
|---|---|---|---|---|---|---|
| **TO-40A** | 35.7 | 36.7 | 39.4 | 39.8 | 40.6 | 39.4 |
| **MNF** | 35.3 | 37.6 | 39.1 | 40.4 | 37.2 | 40.7 |

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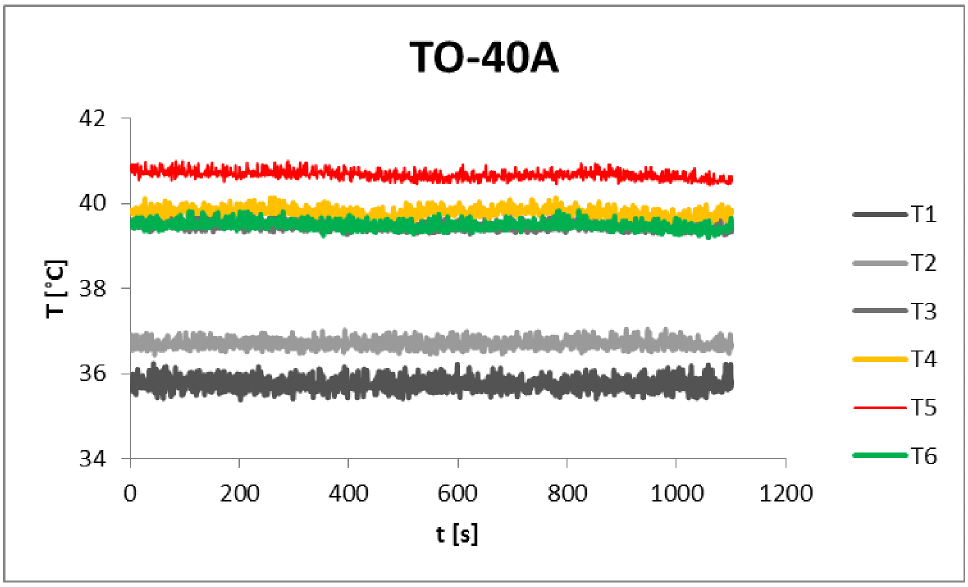


**Figure 4**. Stationary heating regime for the transformer oil

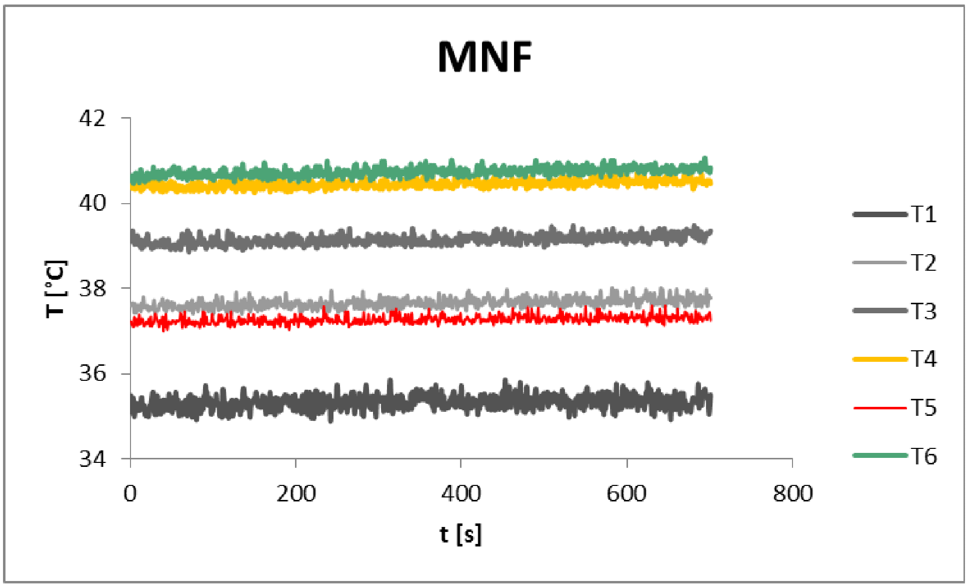


**Figure 5.** Stationary heating regime for the magnetic nanofluid

The coil external and internal walls temperatures ($T_4$ and $T_6$) are slightly higher in the case of magnetic nanofluid test. A possible explanation might be the adherence of some nanoparticles at the coil walls. Due to the low value of the magnetite volume fraction and the low magnetic field outside the coil, there is no significant difference between the corresponding average temperatures in the fluid outside the coil ($T_{3,avg}$). The only clear difference for the temperature measured in the fluid was inside the coil core ($T_{5,avg}$). Here, a difference of 3.4 °C in the corresponding values was obtained. Thus, the effect of the magneto-convection could be observed only in the coil core region, characterised by larger values of the magnetic field density (as indicated by measurements and simulation).

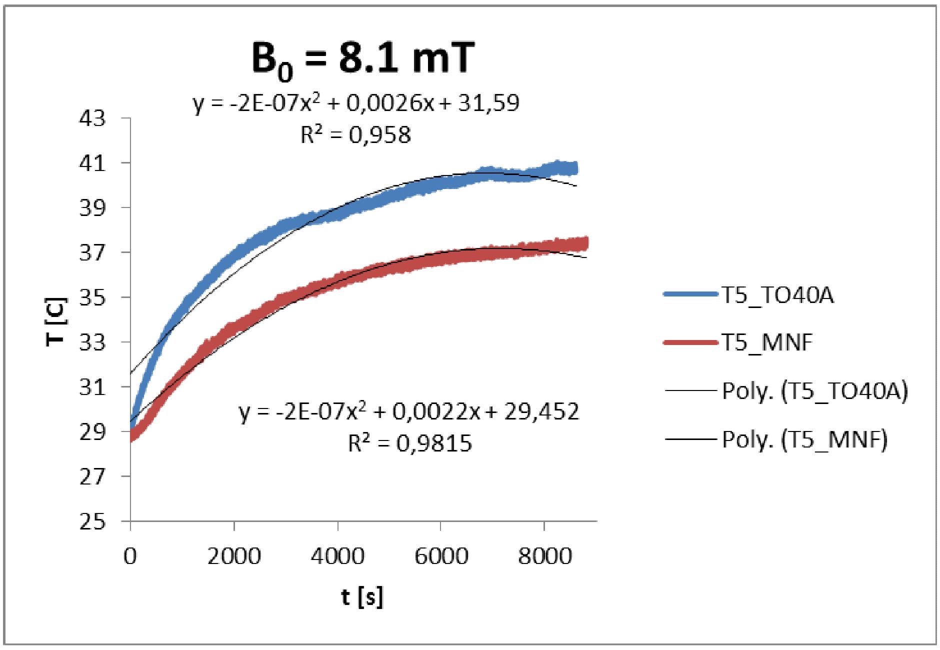


**Figure 6.** Comparison of heating curves in the central section of the coil core

To study further the heat transfer inside the coil core, the heating curves for TO-40A and MNF at the temperature measurement point $T_5$ (axis of the coil core) and their polynomial trend lines are compared in figure 6. The magnetic flux density at the measurement point is the one corresponding to the core centre (point A in figure 2). The results of the cooling process using both test fluids at the same point ($T_5$) are compared in figure 7. The temperature rise rate was calculated from each trend line equation displayed in figure 6 and the temperature decrease rate was calculated from the trend line equations displayed in figure 7. The obtained results are presented as a function of temperature in figure 8. The temperature rise rate of MNF for the explored temperature range is lower than that of the TO-40A. Also, the stationary regime of MNF it is approached at a lower temperature compared to TO-40A case, as observed from figure 5. This result is due to the magneto-convection, a combined effect of the addition of nanoparticles dispersed in the transformer oil, the temperature gradient inside the nanofluid and the applied external field.

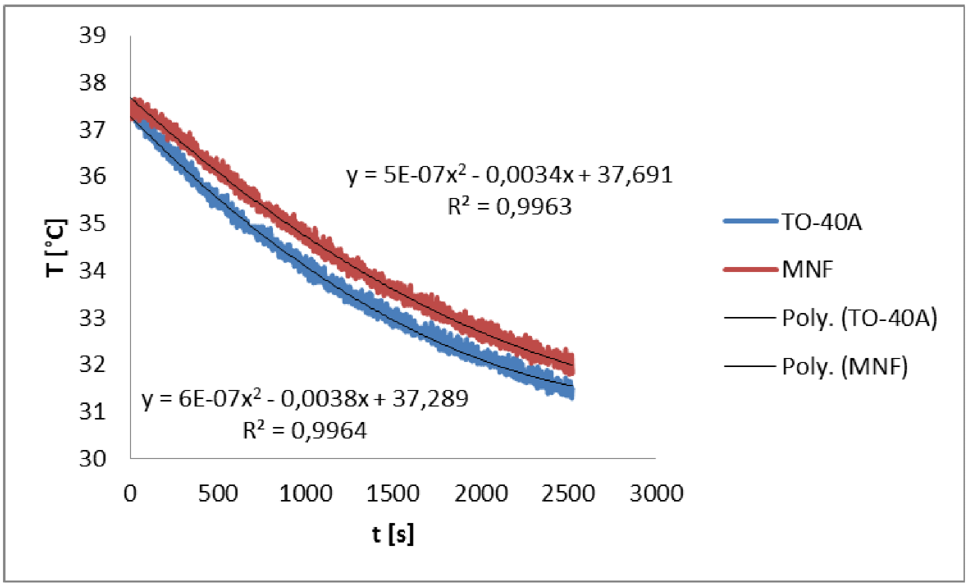


**Figure 7.** Comparison of the cooling curves in the central section of the coil core (with the coil being powered off)

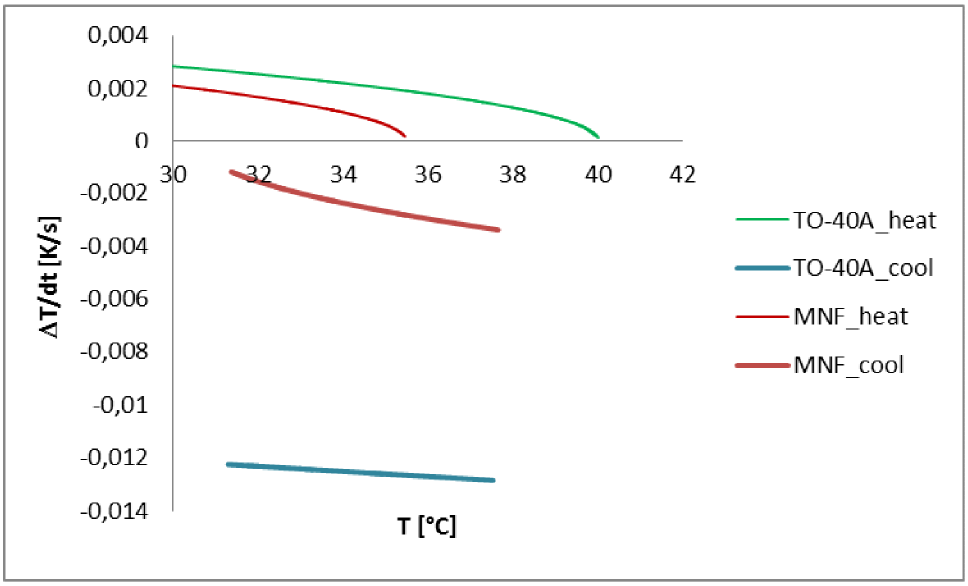


**Figure 8.** Temperature rise rate (subscript -“heat”) and temperature decrease rate ( subscript – “cool”) in transformer oil and magnetic nanofluid

The MNF temperature decrease rate for the explored temperature range is larger than that corresponding to the TO-40A. That is, due to higher viscosity of magnetic nanofluid compared to that of transformer oil and the absence of the magnetic field, MNF has a lower heat transfer rate.

## 5. Conclusions

The cooling of an air cored coil powered by an AC source (f = 50 Hz) with magnetic nanofluid and, for comparison, with transformer oil (its base fluid) have been investigated. The obtained results indicated that the magneto-convection inside the coil core led to a decrease of the temperature rise rate and of the stationary temperature at the related measurement point ($T_5$). If the magnetic field is low or it is off, the heating and cooling temperature data are similar. The tested magnetic nanofluid has potential to be used as cooling medium in a power transformer, if magneto-convection is generated by the transformer windings magnetic field in the bulk of the fluid. The experimental results will be used as reference for a numerical study dedicated to the exploration of other geometrical configurations for the experimental cell in order to increase the magneto-convection outside the coil.

**Acknowledgements**

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