

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

F D Stoian and S Holotescu

Faculty of Mechanical Engineering and Research Center for Engineering of Systems
with Complex Fluids, Politehnica University Timisoara, 1 Mihai Viteazu Bv., 300222
Timisoara, Romania

E-mail: floriana.stoian@upt.ro

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.

	ρ kg m^{-3}	η mPa s	k W m K^{-1}	c_p $\text{J kg}^{-1} \text{K}^{-1}$	β K^{-1}	ε F m^{-1}	M_s A m^{-1}
Magnetic nanofluid (MNF)	937	18.5	0.133	1743.39	$6.62 \cdot 10^{-4}$	$2.25 \varepsilon_0$	2785.3
Transformer oil (TO-40A)	867	17.5	0.127	1915.12	$7.15 \cdot 10^{-4}$	$2.2 \varepsilon_0$	-

The properties in table 1 are as follows: ρ is the density, η –dynamic viscosity, k – thermal conductivity, c_p - heat capacity, β – thermal expansion coefficient, ε – 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 $R = 680 \Omega$ was placed in the center of the measurement cell – a cubic vessel (1) with Plexiglas walls of size $60 \times 60 \times 60 \text{ mm}^3$. The coil has the windings disposed on a rectangular plastic housing (3) and the internal air core dimensions are $15 \text{ mm} \times 15 \text{ mm} \times 18 \text{ mm}$. 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, $V_f = 130 \text{ cm}^3$ 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 $\pm 1^\circ\text{C}$ or $\pm 0.7\%$) 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.

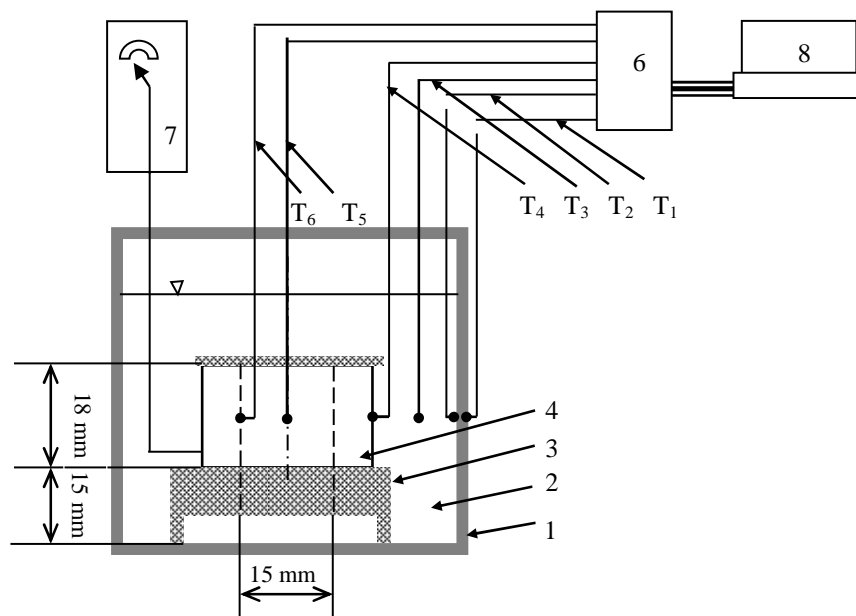


Figure 1. Experimental setup

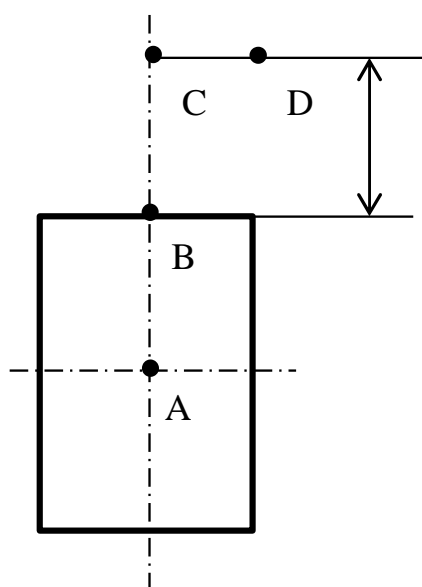


Table 2. Measured magnetic flux density values.

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

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

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.

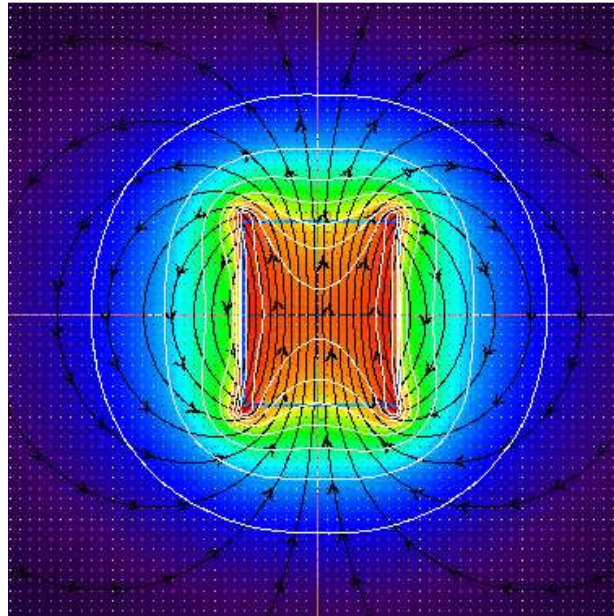


Figure 3. Model of the coil magnetic field lines (black lines with arrows) and the flux density contours (white lines)

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 °C) 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 °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

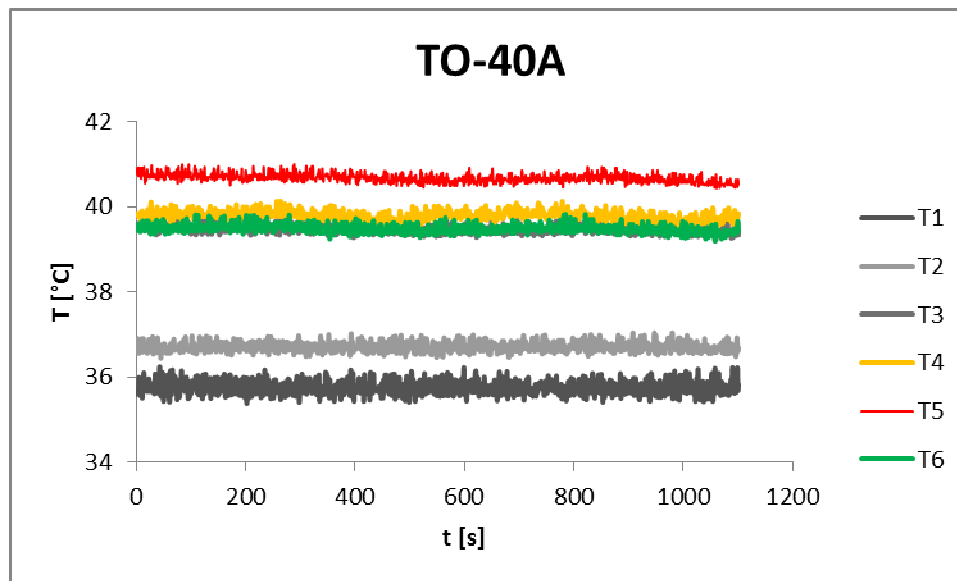


Figure 4. Stationary heating regime for the transformer oil

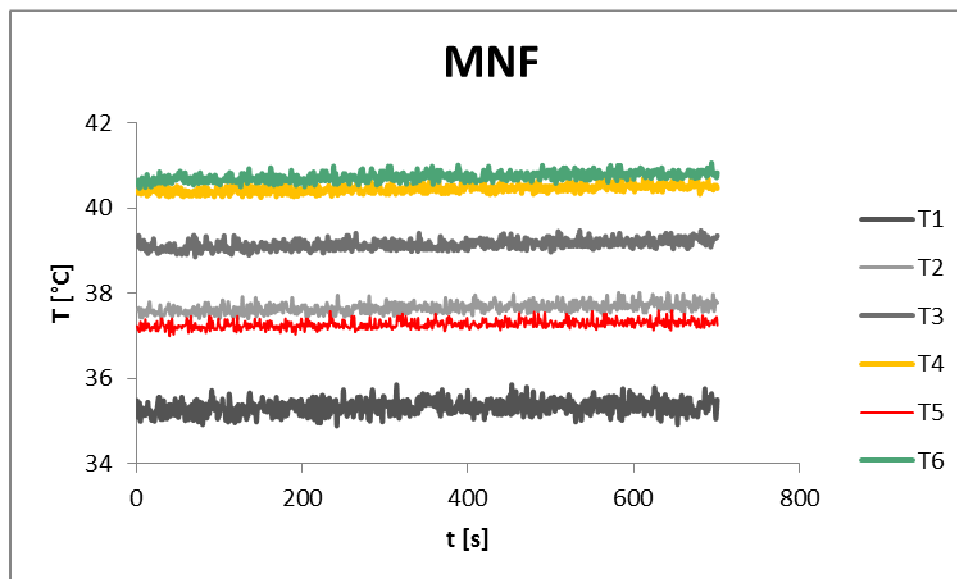


Figure 5. Stationary heating regime for the magnetic nanofluid

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).

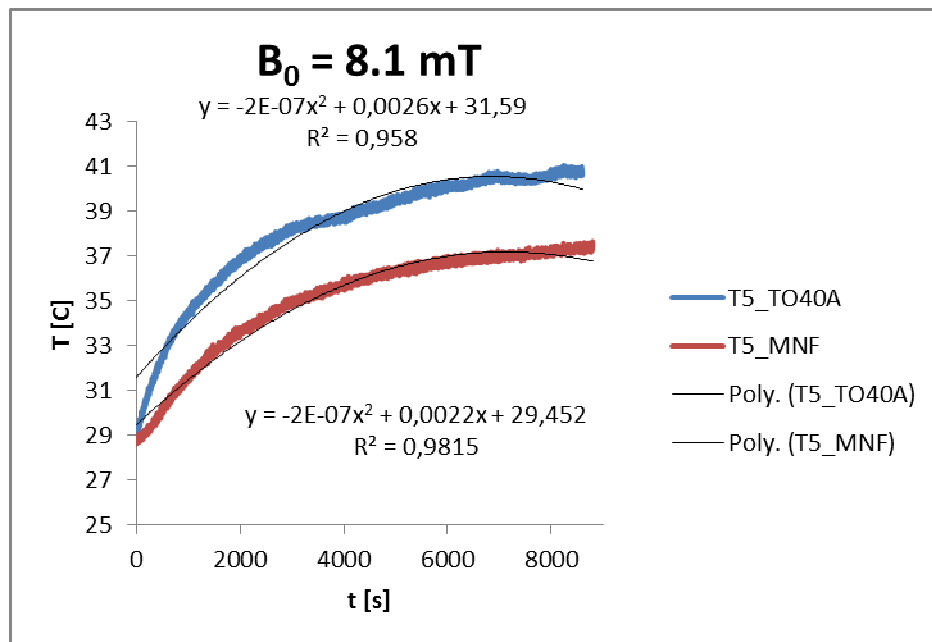


Figure 6. Comparison of heating curves in the central section of the coil core

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.

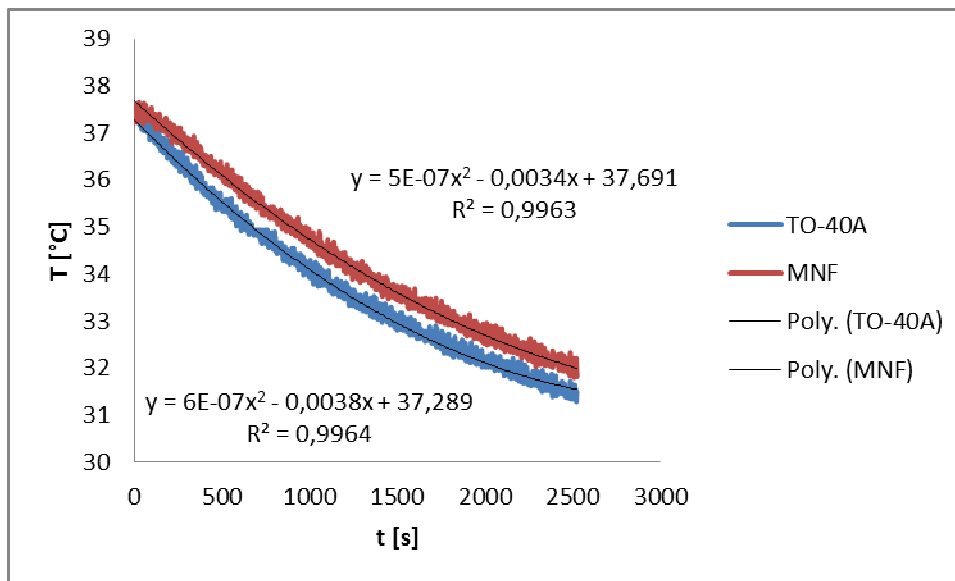


Figure 7. Comparison of the cooling curves in the central section of the coil core (with the coil being powered off)

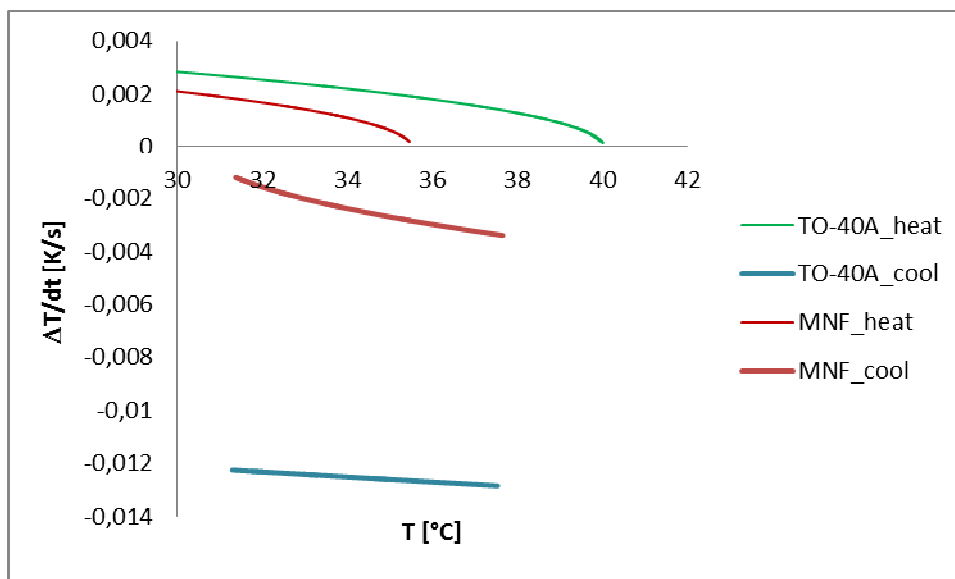


Figure 8. Temperature rise rate (subscript -“heat”) and temperature decrease rate (subscript -“cool”) in transformer oil and magnetic nanofluid

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.

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