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FEM-based development of measurement system for magnetic fluid characterization

***Abstract**. In this article we describe the FEM based development of measurement system for determination of magnetic fluid heating effect when exposed to ac magnetic field. In the design phase several different geometries of excitation coils has been tested with the aim of achieving the homogeneity of the magnetic field, using FEM magnetic analysis. Furthermore thermal FEM analysis has been performed with intention of selecting suitable materials in the measuring system to achieve thermal stability.*

***Streszczenie.** W artykule opisany jest system pomiarowy bazujący na metodzie elementów skończonych (FEM) dla określenia efektu cieplnego w płynie magnetycznym wystawionym na pole magnetyczne AC. W fazie projektowej kilkanaście geometrii cewek wzbudzających zostało przetestowanych przy użyciu metody elementów skończonych w celu osiągnięcia jednorodności pola magnetycznego. Ponadto, analiza cieplna za pomocą FEM została przeprowadzona dla wyselekcjonowania materiałów pozwalających na osiągnięcie cieplnej stabilności. (**Rozwój systemu pomiarowego wspomaganego metodą elementów skończonych dla analizy płynu magnetycznego**).*

Keywords: Magnetic fluids, ac losses, heating effect, FEM analysis.
Słowa kluczowe: płyny magnetyczne, straty AC, efekt grzania, analiza MES.

Introduction

Magnetic fluids are relatively new material, distinguished by some specific properties. Besides the obvious, that they are magnets in a liquid state offer many other properties that over the years had found many applications in the industrial applications as well as in biomedicine. In doing so, we can mention some applications such as targeted dosage of active substances by using magnetic fluids, magnetic resonance imaging contrast agents, and promising alternative cancer treatment with so-called hyperthermia [1]. This is a process in which the bio-compatible magnetic fluid is introduced into a tumour and exposed to alternating magnetic field, where various acting losses mechanisms results increase of the temperature of the tumour loaded tissue [2]. The goal is aimed at the heat destruction of tumour cells, which is achieved with a temperature of between 42 - 46 °C.

When magnetic fluids are used in such applications, the first requires good knowledge of this material and by that we mean primarily the acting of the various loss mechanisms that cause warming in the ac magnetic field and their dependence on the properties of the sample. Therefore the heat production mechanisms and their definition are presented in this paper, as well as measurement system for experimental determination of magnetic fluid heating power.

We will present the construction of such a measurement system where we used the results of finite element method (FEM) magnetic and thermal field analysis. In the planning stage we changed the geometry and used materials in such manner, that we have satisfied the technical requirements for determining heating power of magnetic fluids.

Specific heat determination of magnetic fluids

Magnetic fluids for heating applications differ according to the parameter of heating power per unit of weight. According to three different methods to obtain the heating power, different denotations are used; power losses *P*, specific absorption rate (SAR) and specific heating power (SHP) as explained in [2]-[3].

Power losses is a parameter that is calculated from relaxation losses. They are caused by the relaxation mechanisms of magnetic nanoparticles, which are gradual alignment of magnetic moments during the magnetization process. The relaxation process of magnetic fluid may occur through two distinct mechanisms. The first one consists of the rotation of the single-domain particles and it is related to the Brownian motion. The second one is the so called Néel relaxation and it is considered when the particle is immobile. The magnetic fluid may exhibit both of these mechanisms, where each has a proper weight. The relaxation time according to [5] of Brownian motion is

$$\tau_B = \frac{4\pi R_H^3 \eta}{k_B T} \tag{1}$$

and the Néel relaxation time is

$$\tau_N = \tau_0 \exp\left(\frac{KV}{k_B T}\right) \tag{2}$$

where η is a basic fluid viscosity, R_H is a hydrodynamic radius of the particle, k_B is Boltzmann's constant τ_0 is time constant (τ_0 ~ 10-9 s), *T* temperature of the fluid, *K* is the magnetic anisotropy energy density and *V* is the volume of magnetic particle core. Because Brownian and Néel relaxation take place parallel to one another, the effective relaxation time τ is given by

$$\tau = \frac{\tau_B \tau_N}{\tau_B + \tau_N} \tag{3}$$

and the power losses corresponding to effective time

$$P = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}\ . \tag{4}$$

Power losses can also be determined via permeability of the magnetic fluid μ, which is a complex quantity and express the loss of energy which occurs as the magnetism alternates. The loss mechanism causes the magnetic flux density *B* to lag behind an applied field *H* by phase angle δ, also know as the dissipation factor

$$\tan\delta = \frac{\mu^{//}(\omega)}{\mu^{/}(\omega)} \tag{5}$$

where the components of permeability can be expressed in terms of susceptibility χ as $\mu^{//}(\omega) = \chi^{//}(\omega)$ and $\mu^{/}(\omega) = \chi^{/}(\omega) + 1$, where $\omega = 2\pi f$ is field pulsation and with frequency *f*, the corresponding power factor in terms of $\chi^{/}(\omega)$ and $\chi^{//}(\omega)$ is

$$\tan\delta = \frac{\chi''(\omega)}{1+\chi'(\omega)} \quad (6)$$

and the power losses, in terms of complex susceptibility

$$P = \pi\mu_0 H^2 f\chi'' \quad (7)$$

Secon approach in determination of heating power is via calorimetric method, where parameter of specific absorption rate (SAR) is determine as

$$\mathrm{SAR} = \frac{\rho C_s}{m_{\mathrm{Fe}}}\left(\frac{\Delta T}{\Delta t}\right)_{t=0}, \quad (8)$$

where C_s is the sample specific heat capacity, m_{Fe} is the total content of maghemite ($g_{\mathrm{Fe}}/cm^3_{\mathrm{sample}}$) and $\Delta T/\Delta t$ is the temperature change, respectively the initial slope of measured temperature rise curves.

And the third approach, in determination of heating power, is via magnetic measurements to determine the specific heating power (SHP). These losses can be determined in a well known manner by integrating area of hysteresis loop according to (9)

$$\mathrm{SHP} = \left(\frac{f}{\rho}\right)\int_0^T H(t)\left(\frac{\mathrm{d}B(t)}{\mathrm{d}t}\right)\mathrm{d}t, \quad (9)$$

where $H(t)$ is the magnetic field strength and $B(t)$ appurtenant magnetic induction. To generalize expressions (8) and (9) using (10), which represents a link between the methods.

$$P = \mathrm{SAR}\rho\varphi. \quad (10)$$

In this paper we will show development of measurement system capable of determining heating power of magnetic fluid using these methods while meeating all the necessary requirements regarding magnetic field and measurements.

Computer-aided design of measurement system using FEM

Our goal in this paper was to design a measurement system capable of magnetic fluid losses determination using three different methods using (7), (8) or (9).

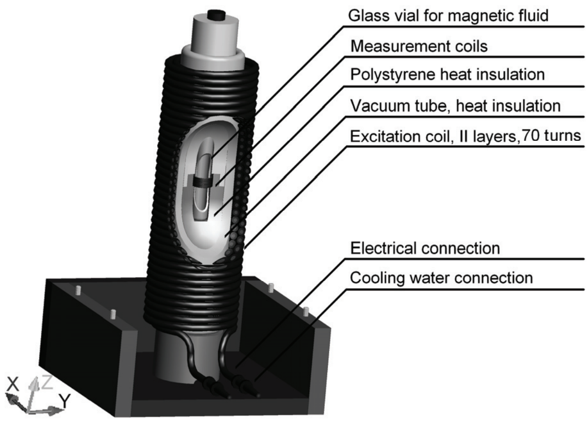

Fig. 1. 3D model of the measurement system used in FEM analysis; cut out only for the presentation.

Regardless of the used method measurement system has to satisfy certain requirements about the magnetic field distribution and temperature insulation described below. For this the FEM analysis was used in changing the design in such manner that we determine the shape of the measuring system to meet these requirements. The desired distribution of magnetic field has been investigated by varying number of turns of excitation coils, while testing of various heat insulating materials best thermal isolation of the measurement system has been investigated. The result of both FEM analyses is design of the excitation coil and selection of used materials as seen in 3D model of measurement system in Fig. 1. This model has been built and it is presented in Fig. 2, while the results of the determination of losses have been presented in [6].

Fig. 2. Constructed Measurement system.

A: Magnetic field analysis

In some articles [7] and [8] on topic of magnetic fluid loss characterization authors have been using measurement systems, where the sample has been exposed to different local values of fields, which means that losses have been defined as the average value of a given field. To avoid this anomaly the homogeneity of the field must be ensured via relatively long axial length of the coil.

In this study, we have been testing different axial lengths or coils by increasing the number of coil turns using FEM software *Vector Fields OPERA*. Turns of the coil have been added until the desired field deviations of less than 0.5% of the amplitude H have been achieved for the area, where the sample of magnetic fluid is placed. Fig. 3 shows two examples of magnetic FEM analysis, which shows the magnetic field strength at the zx-plate in the center of the measurement system.

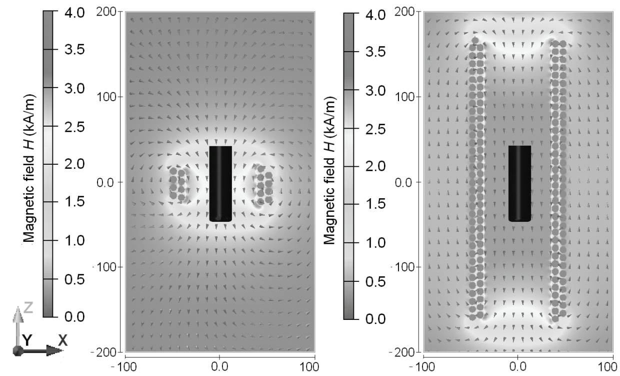

Fig. 3. Results of FEM analysis; magnetic field intensity in the measurement system for 8 and 70 turns of excitation coil.

These results show that in the case of a smaller number of turns, magnetic field in the region of the sample is clearly not homogeneous; in addition to creating the same value of H higher values of excitation current is needed.

Fig. 4 displays the per unit values of H along the z-axis for variety of excitation coil turns. It is obvious that examples with a smaller number of turns results greater field deviation. Ideally homogeneity can be achieved only using the infinitely long coil but in our case satisfactory tolerance is set to be less than 0.5% of the amplitude of which was obtained for the case with 70 turns.

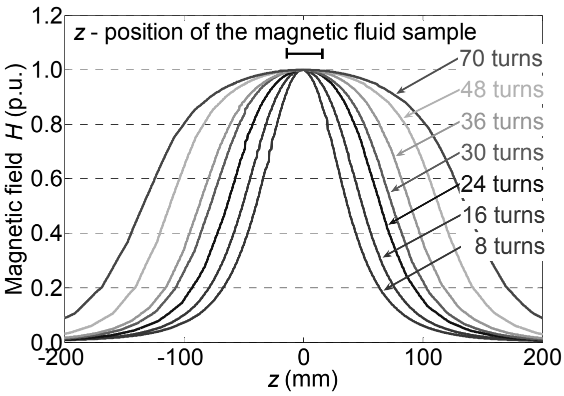

Fig. 4. Magnetic field intensity per unit along z-axis for different numbers of excitation coil turns.

The accuracy of magnetic field analysis has been verified after building a measurement system. For several different values of supply current *I* the magnetic field strength in the centre of the measurement system has been determine via measurement coils. Resulting dependence between the current *I* and field *H* is linear while using the FEM calculation identical values of *H* have been obtained for selected excitation current.

B: Thermal field analysis

Beside magnetic calculation in the design process of the measurement system a thermal analysis has been preformed to assure heat insulation in the system and also temperature stability of the sample in case of outside temperature disturbances. Several papers [7] and [8] in field of magnetic fluid heating power characterization did not focus on thermal isolation of their systems, which could result improper temperature measurements. Resulting temperature increase of the sample can also be the consequence of heat transfer from heated excitation coil. Therefore sufficient thermal insulation must be included into the system in such manner, that generated temperature increase is merely result of desired heating mechanism, which is power loss of the magnetic fluid sample.

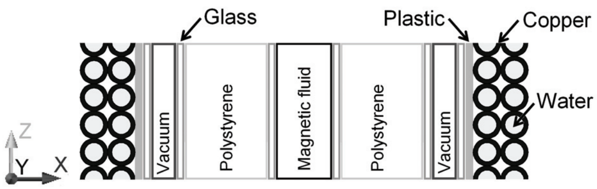

Fig. 5. Cross section of the measurement system, used materials overview.

For this part of paper excitation coil with 70 turns has been selected and thermal analysis for different examples have been performed. Fig. 5 displays a part of *xz*-cross-section of the measurement system and the use of the materials. The first influence that has been looked at was the impact of warming excitation coil to the temperature of the magnetic fluid sample. We took into consideration the heating of excitation coil due to the Joule losses and magnetic fluid for heating due to the aforementioned heating mechanisms. Given the maximum output of power supply the maximum coil current has been set and by knowledge of the coil resistance the maximum loss of excitation coils has been determined and also the heating power of the measuring sample has been determine. The second influence that has been looked at was the influence of the cooling water in the measuring system, since the plan was to make water-cooled coil. And the last influence that has been looked at was the presence of glass vacuum tube visible in Fig. 3 and the presence of polystyrene as an insulating material on the same figure.

For the analysis of these effects several FEM calculations have been performed and they are presented in the Table 1 below. For this research we did not changed any of the dimensions but only presence or absence of materials and water cooling of supply coil.

Table 1. Examples of thermal analysis

Example	ex. A	ex. B	ex. C	ex. D
Heat source Sample fluid (mW/mm^3)	10	10	10	10
Heat source Supply coil (mW/mm^3)	1e^{-4}	1e^{-4}	1e^{-4}	1e^{-4}
Cooling water *T* (°C)	no	no	no	yes
Polystyrene	no	no	yes	yes
Vacuum tube	no	yes	yes	yes
T_{max} (°C)	152	148	129	110
T_{avg} (°C)	147	139	121	108

The first comparison is between different insulating materials in the interior of the measuring system; only air inside the system (example A), added a glass vacuum tube (example B) and polystyrene insulation and a vacuum tube (example C). In all three cases the heat source of magnetic fluid and losses of excitation coils are included in calculation.

If the observe the temperature along the x-axis it is obvious, that example C results the lowest value in comparison to the other two. If we examine the heat flux seen in Fig. 7 on the same *x*-axis (*z*=0) we see the impact of the coil as a source of heat and also visible boundaries between materials. According to these calculations is definitely a better choice to use an insulating material than just air, which we considered in the construction of the system.

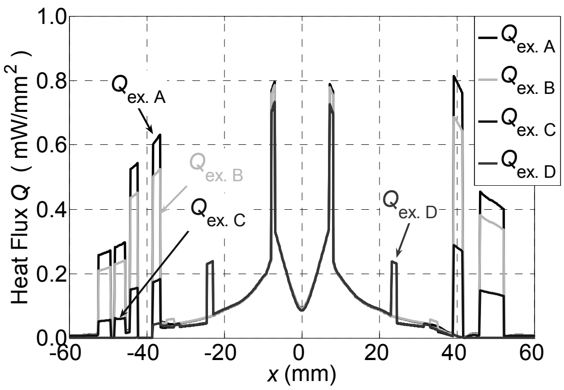

Fig. 6. Results of FEM analysis; heat flux along the *x*-axis for examples A, B and C.

And the other comparison in this paper is the impact of cooling water in the hollow excitation coil. Water has a constant temperature of 20 °C and due to the good thermal conductivity of the copper coil it means that the coil is almost at that temperature. Fig. 7 shows the temperature on the *x*-axis (*z*=0) and we see that in the case of a water-cooled coil (example D) the maximum temperature is lower than (example C). If we now observe the Heat flux on the x-line Fig. 6, we see that *Q* is actually zero in location of excitation coil.

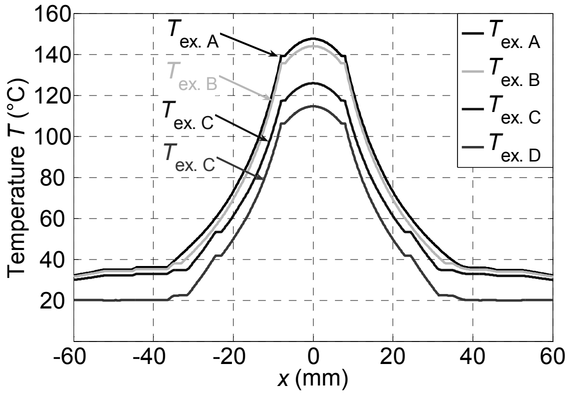

Fig. 7. Results of FEM analysis; temperature along the *x*-axis for examples A, B, C and D.

The result of one thermal analysis for example C is seen in Fig. 10, which shows a) the temperature distribution in the measuring system on the *xz*-cross-section, b) and heat flux.

From these results it is clear water cooled coil is necessary if we want to minimize the impact of heating coils, while we have a constant ambient temperature, which is an advantage in the characterization of magnetic fluids.

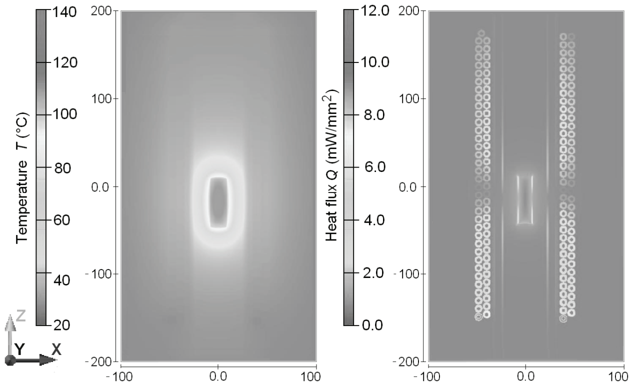

Fig. 8. FEM thermal analysis, results of temperature distribution *T* in the system for example C and heat flux Q.

Results of FEM have been used in the construction of the measuring system, which is presented in Fig. 2.

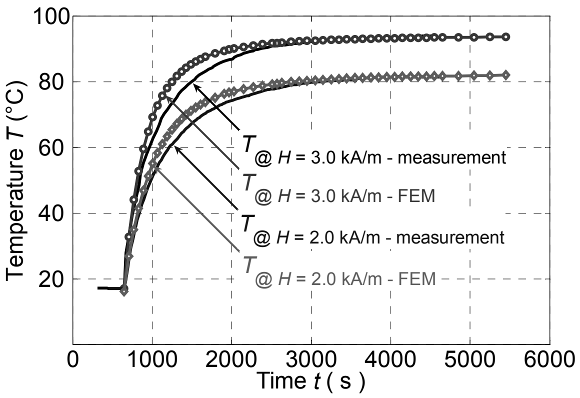

Fig. 9. Temperature rise of magnetic fluid sample; comparison between measurements and FEM transient analysis for 100 kHz frequency and amplitudes of 2.0 and 3.0 kA/m

For verification of these results, the actual experiment of magnetic fluid heating has been carried out, which confirmed that warming depends on the amplitude and frequency magnetic field. Heating curves of the magnetic fluids sample for two different amplitudes of magnetic field at frequency of 100 kHz are presented in Fig. 9. The accuracy of the FEM model has been tested so; that transient FEM analysis of magnetic fluid heating power has been performed. Fig. 9 shows the correlation between the calculated and measured temperature rises exhibits good agreement which implies to correct choice of materials constants in the FEM calculations. Also this results indicate, that by knowing the magnetic fluid heating power its heating capabilities could be calculated in any arbitrary environment, including human body in case of hyperthermia cancer treatment.

Conclusions

Presented paper is showing the use of the finite element method results to build a measurement system for determining the heating power of magnetic fluids. FEM magnetic field analysis helped us to decide about actual shape of excitation coil in order to fulfil necessary requirements about magnetic field. Selected design of the coil enabled us to construct other parts of measurement system and perform a thermal FEM analysis. It helped us in selection of the used materials in such manner, that system is now able to properly conduct measurements necessary in determine magnetic fluid heating power.

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