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Assessment of magnetic fluid losses out of magnetic properties measurement

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Abstract. In this paper an improved measurement system for experimental assessment of magnetic fluid losses is presented. When fluid is exposed to AC magnetic field, three different losses mechanisms are active; relaxation, hysteresis and resonance mechanism. In this paper not individual contributions where studied but combine acting which can be determine as specific power losses (SPL). SPL of the sample is obtained for a variety of amplitudes and frequencies of magnetic field with presented method of measurement of field parameters where results revealed $f{\cdot}H^2$ dependence for fixed temperature of the sample. Temperature dependence of SPL is examined with calorimetrical measurements, where heating of magnetic fluid at fixed value of applied field and various frequencies is examined and results revealed linearly decreasing temperature dependence.

1. Introduction

Magnetic fluid is a colloidal suspension of single domain magnetic particles dispersed in a liquid carrier and stabilized by means of a suitable organic surfactant. Particles have radii ranging form 5-15 nm and when they are in suspension, their magnetic properties can be described by the paramagnetism theory of Langevin, suitably modified to cater towards a distribution of particle size [1].

In recent years, magnetic nanoparticles have found increasing interest in biomedical applications [2-3] e.g. magnetic fluid hyperthermia, where magnetic particles in form of colloidal suspensions are injected into the tumour tissue and irradiated with an external AC magnetic field to increase the temperature in the tumour to 41-46 °C.

The heating effect of suspended nanoparticles when subjected to AC magnetic field is due to several mechanisms of energy dissipation. These mechanisms are: hysteresis losses, relaxation losses and resonance losses. Latter usually occurs at very high frequencies (e.g. GHz range) and they can be neglected in this research. Hysteresis losses results from hysteresis properties of magnetic material and for large magnetic particles above 40 nm, their role increases due to the strongly size dependant correctively H_c [4-5]. For magnetic fluids with particle radius below 40 nm, prevailing heating mechanism are relaxation losses. They occur in an external AC magnetic field either to loss processes during reorientation of the magnetization or frictional losses if the particle can rotate in an environment of sufficiently low viscosity. From the theoretical analysis [5-7] it is obvious, that the heating of magnetic fluids is not only dependent on the magnetic field amplitude H and frequency f but also strongly depends on physical properties of the material. These are for instance particle size distribution, particle shape and microstructure, magnetocrystalline anisotropy as well as the dynamic

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size and viscosity of the fluid. For the theoretical evaluation of the losses a great deal of information about the sample is required and it they are not always available, therefore measurement represents helpful alternative.

The main purpose of this paper is experimental study of associated hysteresis and relaxation losses of magnetic fluid sample subjected to various amplitudes and frequencies of applied magnetic field with constant monitoring of the sample temperature.

2. Measurement system

For assessment of magnetic fluid losses, an improved measurement system regards to [9-11] was built as shown in figure 1. A sample of magnetic fluid is placed in a glass vial in the centre of surrounding supply coil. Some authors use coils with only 2 or 3 turns, where homogeneity of magnetic field is questionable; therefore the length of this coil is twice the length of a glass vial to assure homogeneous field in the centre, which was checked with a simple 3D finite element method calculation of the measurement system.

Special attention was focused on planning of this system to prevent thermal disturbances of surroundings to the measured sample. For that reason, glass vial is placed in the heat insulation polystyrene to delay heat dissipation from sample to surroundings and vice versa. Preliminary temperature measurement reveals that Joule losses, form supply coil, caused increase of the temperature, which disrupts the measurement; therefore coil is water cooled with cooling water at 17 °C with steady flow of 40 l/h. To furthermore prevent temperature disruption a vacuum tube is placed between sample and coil. Supply coil with its inductance of L = 0.1015 mH is connected parallel to variable capacitor C to assure resonance conditions in the circuit, as seen in figure 2. LC circuit is supplied via 700 W power oscillator with frequency range from 10 kHz to 1 MHz.

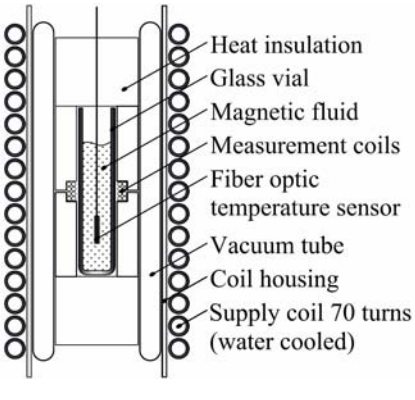

Figure 1. Measurement system

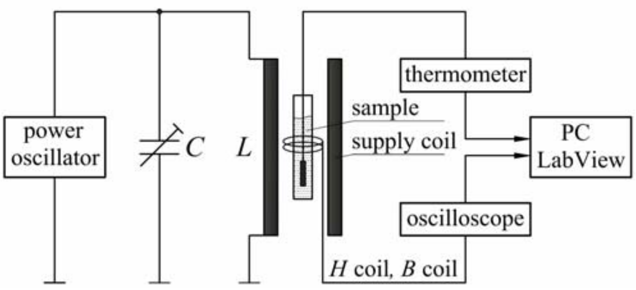

Figure 2. Measurement scheme

Experimental setup is equipped with measurement systems, which consist of thermal properties measurement and electrical measurement. Thermal measurements include monitoring of cooling water and recording temperature of magnetic fluid where temperature probe is submerged in the sample. Both measurements are carried out using fibre optic thermometers since conventional resistance thermometers preformed inaccurately in presence of magnetic field. Electrical measurement consists of current probe for setting current frequency and amplitude and two measurement coils wound around a glass vial for measurement of induced voltage placed in the centre as seen in figure 1. Integrating the induced voltages u_{i1} and u_{i2} results in the magnetic field intensity $H(t)$ and magnetic flux density $B(t)$ according to (1) [7], where k_1 and k_2 are constants of measurement coils determined in moderated magnetic field, and c_1 and c_2 are constants of integration

$$B(t) = k_1 \int u_{i1}(t)\,\mathrm{d}t + c_1 \text{ and for } H(t) = \frac{k_1 k_2}{k_1 + k_2}\frac{1}{\mu_0}\int \left(u_{i2}(t) - u_{i1}(t)\right)\mathrm{d}t + c_2\,. \qquad (1)$$

Specific average power loss (SPL) per unit mass according to [8] can be calculated with (2), where f is frequency of applied field and ρ is magnetic fluid density.

$$P = \left(f / \rho\right) \int_0^T H(t)\left(\mathrm{d}B(t) / \mathrm{d}t\right) \mathrm{d}t \tag{2}$$

3. Results and discussion

For this research, commercially available sample of magnetic fluid is used, where preliminary testing was performed only to determine several basic structural properties of the fluid. Results of transmission electron microscopy revealed that sample contained magnetic particles maghemit γ-Fe_2O_3 with mean diameter of 10.9 nm, dispersed in mineral oil. Magnetization curve measurement revealed saturation magnetization of the sample at M_s = 42.3 kA/m at 300 kA/m of applied field. According to ratio $M_s/M_{s\ \mathrm{bulk}}$ volume fraction of magnetic particle is revealed and it is to be 9.45 % for $M_{s\ \mathrm{bulk}} = 400$ kA/m. To determine SPL of the sample a measurement system in figure 1 is used. Different amplitudes of magnetic field strength where set while B and H are measured. Plotting the dependence $B = f(H)$ reveals hysteresis loop shown in figure 3 for three examples of magnetic field at fixed frequency of 50 kHz. Integrating the loop according to (2) results SPL, which are for increasing values of magnetic field showed in figure 4. SPL obey the quadratic power law $f{\cdot}H^2$ what was checked for five different frequencies. For all presented measurements temperature of the sample was 17 °C.

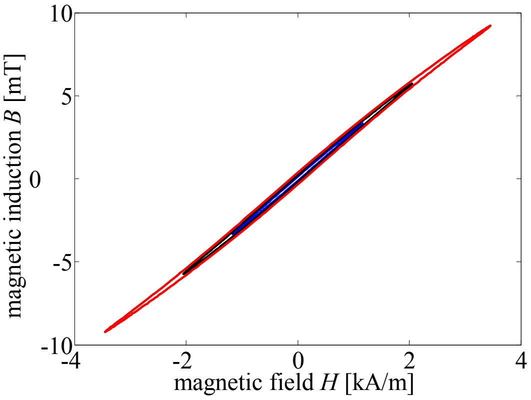

Figure 3. Hysteresis loops for three different applied magnetic fields at frequency of 50 kHz.

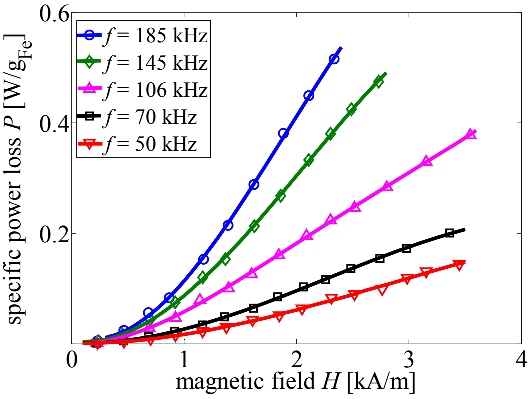

Figure 4. Magnetic field dependence of SPL curves for different frequencies at 17 °C.

To research the SPL temperature dependence a set of calorimetric measurements is carried out using a calorimeter, which is by definition an instrument that allows heat effects in it to be determined by direct measurement of temperature. In this case, calorimeter is a measurement system and heat effects are losses of magnetic fluid when subjected to an AC magnetic field. Measurement principle for calorimetric measurements requires stable temperature of the sample before magnetic field is switched on. For that reason measurement is divided into two parts, where in the first part, from 0 to 10 minutes only cooling water of supply coil is applied to stabilize the sample temperature at the value of water temperature. In the second stage from 10 to 60 minutes, supply coil is turned on at constant frequency and regulated current set up magnetic field at desirable value. Measurement last until temperature steady state is reached or when heat production equals heat dissipation. Measurements are performed for fixed amplitude of magnetic field 1.5 kA/m and various frequencies and results of temperature rise, for the two part measurement, are presented in figure 5. Sample of magnetic fluid warms up from initial 17 °C to its terminal temperature dependent on the selected frequency, where maximal temperature increase $\Delta T_{\max}$+54.5 °C is achieved at maximum frequency of 200 kHz. Throughout entire second part of the measurement B and H are calculated every 20 seconds to enable calculation of SPL according to (2). Their temperature dependence is presented in figure 6, where it is evident that they are not temperature independent but linearly decreasing dependence is noticed.

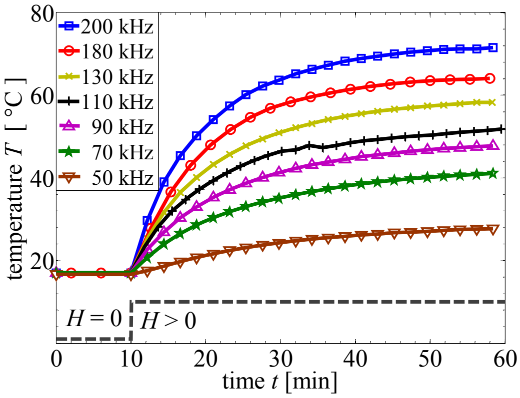

Figure 5. Time dependant temperature rise curves of magnetic fluid sample subjected to various frequencies at $H = 1.5$ kA/m.

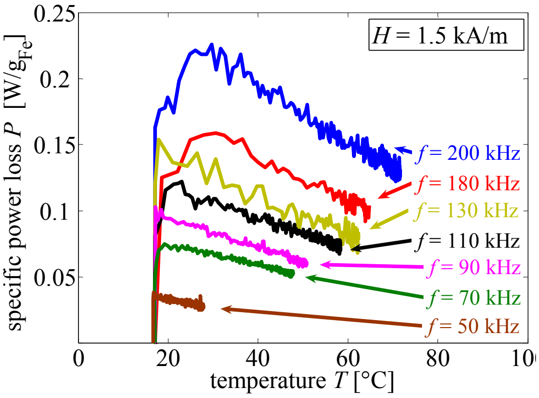

Figure 6. Temperature dependant SPL curves for various frequencies at $H = 1.5$ kA/m.

4. Conclusion

This paper presents measurement system for experimental evaluation of magnetic fluid properties. Its improvements with regards to other systems are better thermal insulation of the measured sample and its surroundings, therefore more accurate results of temperature measurements. Additional advantage of the system is measurement of magnetic field strength and magnetic induction, resulting information of hysteresis loop at any time of the measurement. For evaluation of the system commercially available sample of magnetic fluid with γ-Fe_2O_3 magnetic particles is used. First set of measurements revealed $f{\cdot}H^2$ dependence of SPL where sample was exposed to different frequencies of magnetic field and fixed temperature of the sample. Second set of measurement where calorimetrical where sample of fluid was exposed to a constant value of magnetic field for variety of frequencies. Results revealed linearly decreasing SPL temperature dependence.

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