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A comparison of the heating effect of magnetic fluid between the alternating and rotating magnetic field

Miloš Beković *, Mladen Trlep, Marko Jesenik, Anton Hamler

University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor 2000, Slovenia

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ABSTRACT

Magnetic fluids are distinct magnetic materials that have recently been the subject of extensive research precisely because of their unique properties. One of them is the heating effect when exposed to alternating magnetic fields, wherein the objective is to use this property in medicine as an alternative method for the treatment of tumors in the body. In this paper, we focus on two methods of magnetizing magnetic fluids, firstly using the alternating magnetic field (AMF), and secondly with the rotational magnetic field (RMF). The effects of the first are scientifically well-established, whilst the impact of RMF has not as yet been investigated as presented in this article. So far the effects of RMF have only been studied at low frequencies and high amplitudes, or vice versa. This article presents the results of heating at high frequencies and high magnetic field amplitudes, and the results compared with AMF. This paper presents the construction and implementation of a measuring system which is suitable both types of magnetic field.

1. Introduction

Recently, magnetic fluids have been studied, in particular, for the purpose of applications in medicine. In doing so, they are at the forefront of applications for MRI imaging, drug delivery, and local hyperthermia [1]. The latter represents the exposure of diseased tissue to the high frequency magnetic field whilst the magnetic fluid is injected into it. The objective is to heat the target tissue, above the critical temperature, destroy the diseased cells whilst at the same time minimizing any damage to the surrounding healthy cells. The design and interpretation of such treatment is theoretically presented in [2], where the finite-element calculations showed the heating of healthy and diseased tissues. The temperature rise originates from the magnetic properties of the magnetic fluid, where each cycle of magnetization results in losses which cause heating of the material. Determination of the losses within the magnetic field is presented in [3–5], and is based primarily on the measurement of temperature rises of the fluid based on the calorimetric method, or in determining the quantities of the magnetic field by measuring the hysteresis-loop area or complex susceptibility.

The differences when magnetizing with rotating magnetic field (RMF) and with the alternating magnetic field (AMF) are known and have been the subject of great interest regarding the behavior of magnetic nanoparticles exposed to both, as studied by Dieckhoff et al. for low frequencies [6] by means of phase-lag research. We believe that magnetic fluids exposed to RMF exhibit more intense heating than the AMF, as will be proven.

The dynamic behavior of magnetic fluid was studied by Yoshida et al. [7] by performing numerical simulations based on Fokker–Planck equations. Their results for time-dependent magnetization were compared with the measured. Their measurement system was similar to the one used during this research whilst, however, this one enables much higher amplitudes and frequencies of the magnetic fields. The numerical model for the behavior of magnetic fluid in RMF was studied by [8] and [9] but only for low frequencies.

Our goal was to build a system which would be able to discover the differences in the magnetic heating of fluids when subjected to both AMF and RMF. The systems are already in place for AMF, whilst for the RMF system the idea of a Helmholtz coil was used as presented in [10] and modified, as they did in [11] for another application. This form is used only for the design, but in fact a quite inhomogeneous magnetic field of relatively small amplitude could be achieved.

The authors in [12] were determined the SAR values of magneorehological fluid (large particles in μm size) but it was never stated as to how they performed the measurements. In [13] a system for measuring magnetic properties is carried-out but it is only used for small samples and exposed to low frequency fields.

This paper presents the idea and realization of a system capable of creating AMF that remedies the deficiencies of the previously discussed systems. It also presents calorimetric loss measurements

* Corresponding author.
E-mail addresses: milos.bekovic@uni-mb.si (M. Beković), anton.hamler@uni-mb.si (A. Hamler).

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of magnetic fluids at the two frequencies of AMF and RMF showing results with different values, which is a matter for further research.

2. Measurement system

2.1. Measurement system coil assembly and power-supply

A new measurement system was developed for this research. It is based on a previously developed system for determining the losses of magnetic fluids in an AMF, as presented in [5]. In the case when the AMF is required a single solenoid excitation coil is sufficient, whilst two coils are required for generating the RMF. These two coils must be geometrically displaced by 90° in such a way that they are perpendicular to one another. Obviously, this is geometrically impossible to implement due to physical overlapping, and thus both coils have to be divided into two series-connected half-coils with free space in between. This distribution represents the 2D Helmholtz system [10]. The layout regarding the basic distribution of both half-coils is shown in Fig. 1, where the sample of the measured magnetic fluid is placed at the center for both coils.

Such a system enables various combinations of the two coils power supplies in order to achieve a variety of magnetic fields. Fig. 2 shows the time courses of four different magnetic field intensities in the center of the system. The amplitude of the magnetic field strength in the x-direction (H_x solid blue line) varies over time according to the sinusoidal supply-current's changes. In the y-direction the magnetic field amplitude may also be a sinusoidal change (not plotted) or cosine change (H_{y1} dashed red line). We can see that the signals H_x and H_{y1} have a time-lag of Δt_1 which is at a given frequency 2.5 μs, but in general $\Delta\varphi = 90°$.

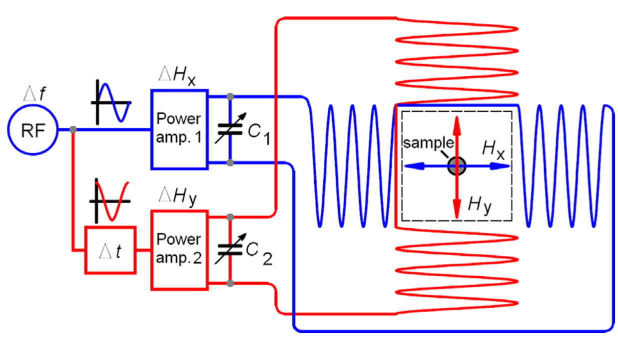

Fig. 1. Arrangement of the supply-coils of the measurement system and the position of the sample in the center.

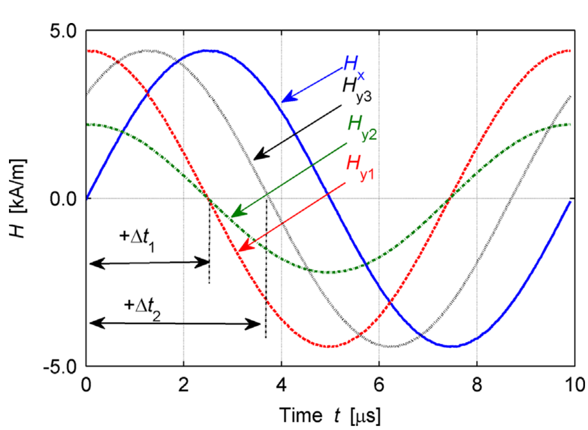

Fig. 2. The time courses of magnetic field intensities in the x and y directions for RMF and AMF.

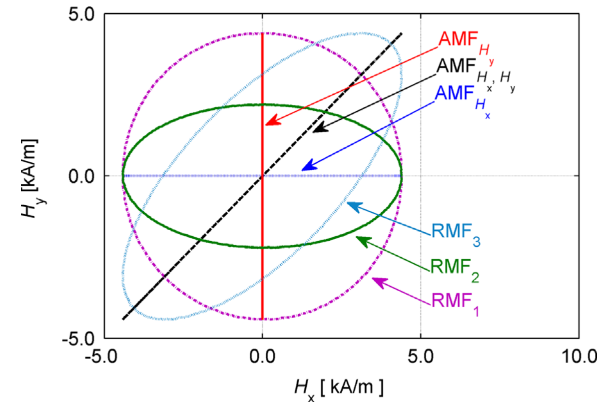

Fig. 3. Magnetic-field intensity in the x and y directions regarding the results for AMF and RMF results.

The next possible combination of magnetic field strength represents different sinusoidal amplitudes, as shown and symbolically represented by the signal H_{y2} (green dash-dot line). The last presented option is an arbitrary angle between the signals in the x and y directions. This option shows the curve H_{y3} (black dot line), ahead of the signal H_x by some arbitrary $\Delta\varphi$.

Since the presented system of coils is a dual-axis system, we observe only the central point of the system of coordinates (0, 0, 0) within this section, while detailed analysis of the magnetic field is carried out as below.

As already mentioned, the AMF is achieved by means of the single coil power-supply. Fig. 3 shows the three possibilities; the blue dashed-line AMF H_x where only the x-coil is powering the resulting magnetic field only in the x direction. The red-solid line AMF H_y is similar but in this case only the y-coil is powered. And the third example shows the sinusoidal powering of both coils resulting in AMF at the 45° angle and $\sqrt{2}$ higher amplitude. All three examples do not differ from the examples in [5] if we observe only the direction of the magnetic field at the central point of the system.

In order to achieve RMF in the center it is necessary to supply both coils with phase-shifted signals for the Δt, respectively $\Delta\varphi = \pm 90$ (H_x and H_{y1} from Fig. 2). This provides a magnetic field of constant amplitude and a circular changing direction in accordance with the frequency of the power supply signal. An example of such a field is represented by the curve RMF_1 in Fig. 3. This figure also shows the curves RMF_2 and RMF_3, where in both cases the shape of the magnetic field is elliptical. The direction of the magnetic field is still changing circularly, while its amplitude is no longer constant. In the case of RMF_2; such a field is obtained where two coils are powered with 90° phase-shifted signals of different amplitudes (H_x and H_{y2} from Fig. 2). In the case of RMF_3; the coils are powered with signals of the same amplitude and arbitrary phase shift (H_x and H_{y3} from Fig. 2).

In order to achieve the dual power supply for two coils (x and y directions), we used two AC power suppliers, namely the Amplifier Research 700 W and Power Amplifier model AG 1024 2000 W. The trigger signal for both AC power supplies was obtained using a single 2 MHz function RF501A generator to ensure equal frequencies within both coil-systems. This allows us to continuously change frequencies over a wide range, but in fact we are limited by the maximum frequencies of both power supplies (700 kHz max). The magnetic field strength amplitude ΔH within the system can be changed by adjusting the amplitude of the electrical current in a circuit simply by changing the gains of both power supplies.

The range of magnetic field of the presented measurement system is conditioned in two ways, with a frequency range and the amplitude range. The frequency range is currently limited to