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The comparison of magnetic circuits used in magnetic hyperthermia

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ABSTRACT

The magnetic nanoparticle hyperthermia experiments require a precise system of magnetic field generation. In this article we present the design of three circuits that can generate an alternating magnetic field (the double-layer solenoid, Helmholtz coils, the inductor with C-shaped ferromagnetic core) and one system of rotating magnetic field. The theoretical calculations have been made to compare the magnetic field intensity distribution along the axis of the coils. Also the inhomogeneity of the magnetic field was determined. Similar calculations have been made for ferromagnetic core inductor. It was also shown the relationship between the intensity of magnetic field and the air gap width of ferrite core. Moreover, it was made a proposal of rotating magnetic field generator consisting of three pairs of phase-tuned inductors. In the experimental section we presented the results of calorimetric measurements performed on water dispersion of SPIONs.

1. Introduction

The main trend in the magnetic hyperthermia research is focused on the design and synthesis of biocompatible magnetic fluid (MF) that exhibits the best heating efficiency. It is mainly motivated by possible *in vivo* applications of magnetic hyperthermia. Heating of magnetic fluid with the use of alternating magnetic field (AMF) is used to treat tissues containing tumor cells. Such cells are more temperature-sensitive than normal cells and increased temperature (45 ÷ 42 °C) makes tumor cells to be more responsive for radio- and chemotherapy. Degenerated cells reduce its multiplication rate in raised temperatures [1]. Magnetic hyperthermia allows a local temperature increase – the temperature rise is observed only within the volume containing magnetic nanoparticles (MNP) and closely adjacent tissues [2].

There are several designs of magnetic field generators used in experimental studies on magnetic hyperthermia. Custom made and commercial setups always contain one of the following components: single or multilayer solenoid, flat coil, Helmholtz coils or systems with ferrite parts. They are designed to generate AMF of high amplitude which is later converted into heat by relaxational or hysteretic processes occurring in magnetic fluid (MF) [3,4]. Each of mentioned designs has its advantages and disadvantages mainly related to magnetic field homogeneity and amplitude. In this article we present and compare the spatial uniformity of magnetic field amplitude and the maximum amplitude in the point where the test samples are usually placed in the mentioned generator designs.

Recently it was made a research proving that a rotating magnetic field (RMF) generates more heat than AMF in magnetic nanoparticle hyperthermia [5]. In this work we also suggest a simpler thus cheaper setup that can generate RMF. Finally, we are also present the results of calorimetric measurements performed on MF sample with the use of two-layer solenoid generator design.

2. Construction and parameters of magnetic circuits

2.1. The two-layer solenoid

The first example of a circuit generating AMF is a two-layer solenoid which cross-section is shown in Fig. 1. For the construction of the solenoid it was used a copper wire consisting of several thin wires with a total cross-section of 2.5 mm^2. The outer diameter of the cable with its insulation was Δl=3.6 mm. The number of the turns in the first and second layers is n_1=47 and n_2=45 respectively. The first layer has a diameter D_1=44 mm and is wound on a plastic bobbin (D_b=40 mm) while the second diameter is D_2=51.5 mm. The inner diameter of the solenoid is big enough to enwrap the sample vial with polyurethane foam providing sufficient thermal insulation. The lengths of the solenoid

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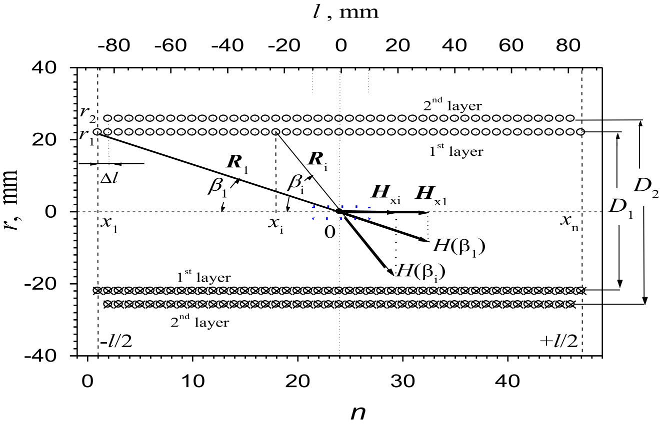

Fig. 1. Outline of the two-layer solenoid.

layers are $l_1 = 170$ mm and $l_2 = 163$ mm, respectively. Self-inductance of this solenoid is $L = 93.5$ μH (measured using *RLC* bridge type MT 4080). Applying 300 W power amplifier AL-300-HF-A, the provided current amplitude is $I_{max} = 15$ A and achieved magnetomotive force is 1380 A-turns. In order to calculate the amplitude of the magnetic field inside the solenoid we can use the Biot–Savart law [7]. According to this law, the current I flowing through the single turn of radius r produces at x point on the axis by a distance x from the turn component of the field H_x:

$$H_X = \frac{I}{2r} \cdot \sin^3(\beta). \tag{1}$$

In this case, the resultant amplitude of the magnetic field is a sum of $(n_1 + n_2)$ components originating from all turns. Successive the angles β_1, β_2, β_3, and etc. between the axis of the solenoid and the radii R_1, R_2, R_3, and etc. are determined:

$$\tan(\beta_1) = \frac{r_1}{x_1} = \frac{2r_1}{l}, \tag{2}$$

$$\tan(\beta_2) = \frac{2r_1}{l - 2 \cdot \Delta l}, \tag{3}$$

$$\tan(\beta_3) = \frac{2r_1}{l - 4 \cdot \Delta l}. \tag{4}$$

Generally consecutive angles β_i for the 1st layer of solenoid are

$$\beta_i = a\tan\left[\frac{r_1}{\frac{l}{2} - \Delta l \cdot (i - 1)}\right]. \tag{5}$$

The calculated components of the amplitude from Eqs. (2)–(5) of the magnetic field H_i inside the solenoid and generated by all turns are shown in Fig. 2. The sum of these components determined for the maximum current amplitude of the power generator ($I_{max} = 15$ A) is $\sum_{i=1}^{i=n} H_i = 7901$ A·m^{-1}. According to Eq. (4) in order to achieve a high magnetic field inside the solenoid it is recommended to choose the small radius r of the bobbin. In turn, the amplitude distribution of magnetic field intensity along the x axis of the solenoid for the two layers can be calculated from the expressions (6a, 6b and 6c) [6,7]:

$$H(x) = H_1(x) + H_2(x), \tag{6a}$$

$$H_1(x) = \frac{n_1 \cdot I}{l_1}\left[\frac{l_1 + 2x}{2\sqrt{D_1^2 + (l_1 + 2x)^2}} + \frac{l_1 - 2x}{2\sqrt{D_1^2 + (l_1 - 2x)^2}}\right], \tag{6b}$$

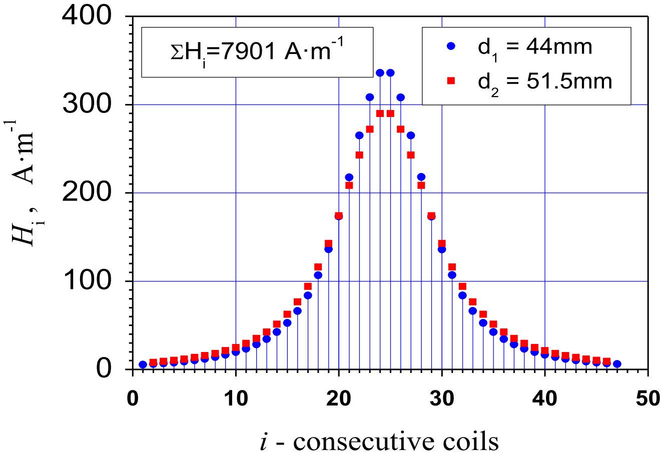

Fig. 2. The components of the amplitude of the magnetic field H_i inside the solenoid generated by all the turns.

$$H_2(x) = \frac{n_2 \cdot I}{l_2}\left[\frac{l_2 + 2x}{2\sqrt{D_2^2 + (l_2 + 2x)^2}} + \frac{l_2 - 2x}{2\sqrt{D_2^2 + (l_2 - 2x)^2}}\right]. \tag{6c}$$

For the parameter values occurring in this case the course of the function $H(x)$ are shown in Fig. 3(a).

Assuming that the amplitude of the current flowing through the solenoid is $I = 15$ A, the amplitude of the magnetic field strength reaches in the center of the bobbin the value of $H_o \cong 7963$ A m^{-1}. Taking into account the length of the sample in a vial about 20 mm, a reduction in the magnetic field reaches $\Delta H = -12.5$ A m^{-1} and is related with the non-linearity of the magnetic field This change can be considered as sufficiently low value. Therefore, the relative change $\delta = (H_o - H_x)/H_o$ of the magnetic field over a distance of ± 10 mm from the center of the bobbin is not more than 0.16%. In turn, Fig. 3(b) shows the derivative dH/dx of the amplitude of the magnetic field along the x axis of the solenoid. In the middle of the coil dH/dt reaches the value of zero.

2.2. The Helmholtz coils

Another solution shown in Fig. 4 allows to obtain a homogeneous magnetic field [8]. The Helmholtz coils consist of two identical short coils connected in series, wherein the magnetic fields are directed in the same direction. At their mutual distance $l = r$ obtained in the central region of the good homogeneity of the magnetic field. Between the coils there is enough space for proper thermal insulation of the sample which can be realized with the use of polystyrene or polyurethane foam. Distribution of the magnetic field intensity along the x axis of the two coils is described by the Eq. (7) while the graphic course of this function is illustrated in Fig. 5.

$$H(x) = \frac{n \cdot I}{2} \cdot r^2\left[\left(r^2 + (0.5 \cdot r + x)^2\right)^{-3/2} + \left(r^2 + (0.5 \cdot r - x)^2\right)^{-3/2}\right] \tag{7}$$

Shown in Fig. 5(a) the course of the function $H(x)$ is plotted for a radius equal to the average radius values r_1 and r_2 of double-layer solenoid from Fig. 1. With the same number of ampere-turns (1380 A turn) as in the coil of Fig. 1 generated magnetic field reached only a value of 2904 A m^{-1}. This is significantly less than in the case of two-layer coils (7963 A m^{-1}). In Fig. 5(b) is presented a derivative of the magnetic field along the axis of Helmholtz coils. At a distance of 10 mm from the center of the Helmholtz-coil the value of magnetic intensity is reduced only by 0.1 A m^{-1}. However, at the same distance from the center of the