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ACOUSTOMAGNETIC REGISTRATION OF MAGNETIC NANOPARTICLES IN A LIQUID MEDIUM

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The technique and results of experiments on the registration of magnetic nanoparticles in a colloidal solution using the combined effect of ultrasound and a direct magnetic field are presented. The possibility of using this technique to control the content of magnetic nanoparticles in a biological substance is discussed.

KEY WORDS: *magnetic nanoparticles, ultrasound, direct magnetic field, biological substance, colloidal solution*

1. INTRODUCTION

In present-day medicine, research and application of the currently available scientific advances in the field of physical properties of materials, biological chemistry, means of recording processes in a living organism, and surgical instruments are becoming more widespread. Amoung these are nanomaterials, pharmaceutical products that can maintain immunity, target-oriented drug supply to a given organ of the body, remote digital registration methods processes in the body and surgery, laser, ultrasound and radiation surgical instruments [1–4].

The presented work is aimed at solving one of the problems arising in the implementation of targeted drug delivery to the pathological area of the human body. This problem is target-oriented (i.e., in a short time) ensuring the high accuracy of the in vivo determination of drug concentrations in the purpose area [5]. To date, one of the known principles of objective drug delivery is their combination with magnetic

nanoparticles (MNPs) [6]. Magnetite particles (Fe_3O_4) with sizes ranging from 5 to 100 nanometers [7] are the most well-known in experimental practice of MNPs and they are innocuous for the human body.

Earlier studies being carried out with the help of the magnetic resonance tomography (MRT) showed that recording by this method of electromagnetic excitation spectra of biological molecules of the human body, which are sensitive to a direct field of MNP, is the most advanced method today. It provides information on the distribution of MNP in space and, therefore, the concentration of drugs, associated with them [8]. The features of the MRT method are: the high cost of the used homographs and the associated lack of accessibility and efficiency of the procedures; a large permanent magnetic field (B_0) that acts on the patient (three or more Tesla) and is unhealthy for him; the possibility of only mediated (through intermediate physical processes) and only a qualitative assessment of the concentration of MNPs. The latter feature may limit the accuracy of this method.

The objective of this work is to test the possibility of detection of the MNPs in a model fluid simulating a biological substance using the our proposed acoustomagnetic method (AMM). Preliminary theoretical assessments of the feasibility of implementing the new method turned out to be encouraging [9,10]. This work is the first stage of our experimental research of AMM. In case of positive results of the research cycle, a scientific basis for the development of an acoustomagnetic tomograph (AMT) is in sight. It is assumed that, unlike MRT equipment, the new tomograph will be simpler and more accessible, have a safety level of a constant magnetic field (B_0 less than 1 T) and provide a direct quantitative determination of the MNP concentration in biological objects.

2. MODEL OBJECT OF STUDY

At this stage of work, a colloid solution of magnetic toner particles commonly used as a powder for printing in laser printers in a mixture of oleic acid and kerosene was chosen as a model sample of the biological medium with MNP. Toner was chosen due to its availability and the presence of magnetic Fe_3O_4 nanoparticles in the granules of this powder [11]. Paraffin core provides a basis for the toner granules. The nanoscale additives are contained inside the shell. Reast a portion of these additives are magnetic ones.

Oleic acid prevents powder particles from sticking together in solution, and kerosene provides its necessary viscosity [12]. In the biophysical practice of MNPs, it is recommended to use solutions with a MNP concentration of not more than 5%. In our experiments, the weight concentration of the powder in the solution was 0.3%. Considering that the specific weight of magnetite is 3-4 times higher than the specific weight of the other components of the powder granule, and the total volume of the MNP is several times smaller than the volume of the non-magnetic components. It can be assumed that the weight concentration of the actual magnetite is not more than

0.15%. The viscosity of the solution was chosen close to the viscosity of the blood ($5x10^{-3}$ Poise).

3. EXPERIMENTAL SETUP

The experimental unit is intended for the generation of ultrasound (US) in a solution with an MNP, in which a direct magnetic field (DMF) can be simultaneously established. Direct magnetic field was created by permanent magnet. The reaction of the solution to the ultrasound and DMF is detected by an induction coil of an alternating magnetic field located in the vicinity of a test glass tube containing the solution. The electrical signal of the coil in the form of alternating voltage is measured by a highly sensitive voltmeter. The installation diagram is shown in Fig. 1.

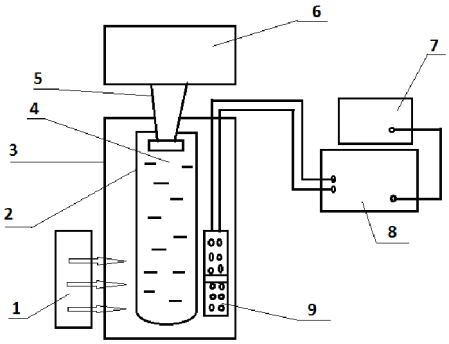


FIG. 1: Diagram of the experimental setup: 1 - permanent magnet (⇨ - magnetic field line), 2 - test glass tube, 3 -copper screen, 4 - colloid solution, 5 - dispersant acoustic duct, 6 - ultrasound generator (disperser), 7 - oscillograph, 8 - micro voltmeter, 9- induction coil

The ultrasonic disperser UZDM-2T with the ultrasound frequency $f > 22\,\text{kHz}$ was used as the ultrasonic source. The ultrasonic generator provides for the possibility of smoothly regulating the intensity of ultrasound up to $0.25\ \text{W}-\text{cm}^{-2}$. A vertically mounted metal duct disperser was introduced into the upper part of a glass test tube with a solution having an internal diameter of 18 mm and a length of 100 mm. A flat induction coil with 2600 turns (w) of copper wire was attached to the lower outer part of the tube. The coil plane was parallel to the axis of the tube. The outer diameter of the coil was 30 mm. The diameter D of the coil was chosen on the basis of the relation $D \leq \lambda / 2$, where λ is the US wavelength [12]. A test tube with a solution and a coil was placed inside an electromagnetic screen made of copper foil to reduce the influence of external parasitic electromagnetic fields on the MNPs. The coil pins were connected to a V6-9 selective micro voltmeter using a coaxial cable. The shape and magnitude of

the alternating voltage amplified by a micro voltmeter at the frequency of the oscilloscope. Shown in Fig. 2 is the external view of experimental setup.

FIG. 2: External appearance of the disperser and test glass tube inside n electromgnetic screen.

4. THE METHOD OF EXPERIMENTS

The principle of MNPs registration in a liquid is based on the implementation of the movement of the entire ensemble of magnetic particles with uniformly oriented magnetic moment vectors with respect to an external fixed magnetic detector. In this case, a combination of MNPs creates a changing magnetic field outside their location. In its turn, this field excites (in accordance with the Faraday law on electromagnetic induction) electrical voltage U at the detector in the form of an induction coil. The resulting voltage should be proportional to the magnitude of the total magnetic field (B_1) of the MNP at the location of the magnetic detector (coil) and their speed relative to the detector. This field and voltage are proportional to the concentration (K) of the MNPs in the solution being moved. In the specific case of the described experimental setup, the solution with the MNP is moved to the presence of an ultrasonic wave, and the magnetic moments of the MNP are oriented in the required direction using a alternating magnet located near the test tube. In this case, the speed of movement of the MNPs will be proportional to the intensity I (power) of the ultrasonic. Thus, the set of dependencies of the voltage at the coil on the parameters of the elements of the measurement system when all the MNPs are oriented in the direction perpendicular to the plane of the coil can be described by the field B by the relation:

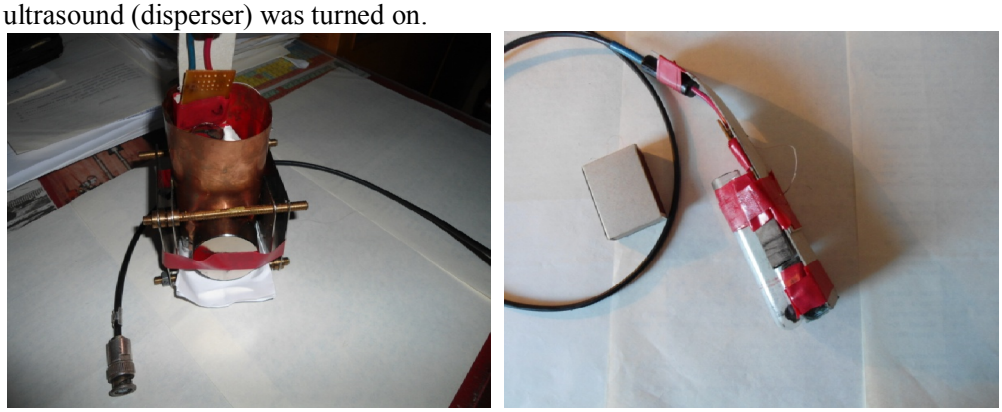
$$U = \left(\frac{d\Phi}{dt}\right) \cdot w = \frac{dB_1}{dt} sw \,..B_1 \cdot s \cdot w \cdot f \sim k_1 (N \cdot J \cdot I) \cdot (s \cdot w \cdot f) \quad (1)$$

where φ is the coil flux of the magnetic field B_1 created by the MNP at the coil location; t is time; s is the coil area; f is ultrasound frequency; N is the number of MNP creating the magnetic field B_1 in the area of the coil; J is the magnetization of one MNP , and k_1 is the magnetic coupling coefficient of the magnetic field created by the MNP with the coil turns. The number of nanoparticles N can be obtained from (1), if we measure the value of U. The concentration K of the MNP is equal to:

$$K = \left(\frac{NV\sigma}{m} \right) \cdot 100\%, \quad (2)$$

where V is the volume of one MNP, σ is specific weight of MNP, and m is the total mass of solution.

Test tube with the coil was installed in an electromagnetic screen and secured with an insulating tape in a special device made of nonmagnetic materials, which is shown in Fig. 2, in a vertical position. The device was installed coaxially with the conduit of the dispersant and the sound duct was lowered into the solution to a depth of about 5 mm from its surface. On the outer side of the device for fixing the tube, a permanent magnet of a cylindrical shape was installed (Fig. 3(a)), creating a magnetic field B_0 with a diameter of 45 mm and a thickness of 15 mm. The magnetic induction vector B_0 of the magnet was directed perpendicular to the axis of the tube and to the plane of the turns of the coil. Measurement of the constant field B_0 of the magnet showed that its value at the location of the tube was about 0.1 T. The assembly of the tube with the measuring coil without a screen is shown in Fig. 3(b). The cable from the inductance coil was connected to a selective micro voltmeter B6-9 and then the source of the ultrasound (disperser) was turned on.



a) b)

FIG. 3: The external appearance of the screen with a magnet (a) and a glass tube with a coil (b)

5. THE RESULTS OF EXPERIMENTAL STUDIES AND DISCUSSION

Figure 4 shows the dependence of the effective value of the alternating voltage (U) at the inductor versus the intensity (I) of the ultrasound. The vector of the direct field B_0 was perpendicular to the plane of the coil.

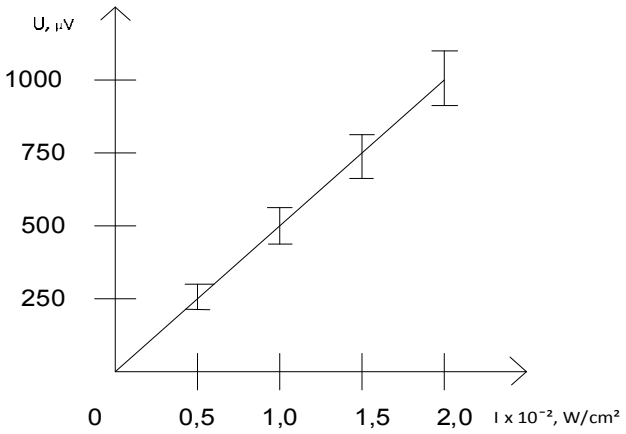


FIG. 4: Experimental dependence of the voltage (U) at the induction coil on the intensity (I) of ultrasound. The segments of vertical straight lines indicate the magnitude of the interference voltage caused by the own electromagnetic field of the ultrasonic generator (disperser).

As indicated by Fig. 4 the voltage U increases in linear proportion to the intensity I. This proves the correctness of theoretical prerequisites about the processes occurring in a solution with MNPs and are represented by relation (1). Thus, this confirms the possibility of to register the MNPs using the acoustomagnetic method proposed in this paper.

At the same time, it was found out that the ultrasonic source UZDM-2T disperser creates a noticeable own electromagnetic field in the area of the object under study, which is an obstacle in measuring the U (I) dependence. The magnitude of this interference voltage is shown in Fig. 4 in the form of vertical line segments. As can be seen, the magnitude of the interference also increases in proportion to the ultrasound intensity. The reason for this phenomenon is the principle of the formation of ultrasound in this type of ultrasonic generator. This principle is based on the use of the phenomenon of magnetostriction of ferromagnetic materials with the necessary frequency. This requires the use in the circuit of such a ultrasound generator of an electromagnetic field, the effect of which, for example, on nickel wire, causes its periodic compression and expansion with an ultrasound frequency. The greater the amplitude of the alternating magnetic field, the greater the amount of compression and expansion of the magnetostrictor and the greater the intensity of the ultrasound. With the help of the acoustic duct of the dispersant, these mechanical vibrations are transmitted to the liquid medium. At the same time, the interference also increases. In

spite of this, the reliability of the measurements performed for the U (I) dependence is confirmed by a sufficiently large signal-to-noise ratio, that equal to $U / U_n = 4 - 5$ (where U_n is the interference voltage).

To exclude this type of electromagnetic interference in the further studies, it is scheduled to eliminate the piezoelectric type of ultrasonic generator.

In the course of experimental studies, the effect of a change in the direction of a constant magnetic field on the spatial magnetic orientation of MNP and the corresponding change in voltage on an inductor was tested. For this, the magnet was installed relative to the test tube in such a way that the vector of its magnetic induction was directed along the axis of the test tube and, accordingly, along the plane of the coil. In this case, the vector of the magnetic moment of the ensemble of magnetic particles (like the needle of a magnetic compass) changed direction and ceased to be perpendicular to the plane of the turns of the coil. In consequence of this, the magnetic flux being initiated by set of oscillating MNP, shown a decrease and recorded AC voltage on the coil tends to diminish as well. This experimental result fully justifies the theoretical assumptions on the dependence of the excited (according to the Faraday law) voltage on the direction of the alternating magnetic field relative to the plane of the turns of the induction coil. This experiment is another proof of the possibility of controlling the total magnetic moment of the MNP using an external constant magnetic field and, in combination with the oscillatory action of the ultrasound, also the possibility of recording the MNP in a liquid medium by the acoustomagnetic method.

The measured voltage (U) on the coil also makes it possible to estimate the magnitude of the alternating magnetic field B_1 created by synchronously oscillating MNP in the region of the coil location. This can be obtained using the relation (1):

$$B_1 \approx \frac{U}{swf}. \tag{3}$$

In particular, for our parameters of the coil and the concentration of MNP at a voltage on the coil equal to 1 mV, the value of the alternating field B_1 is 2×10^{-8} T or 0.2 mGauss. In accordance with (1) and (2), this field can be increased, first of all, by increasing the coefficients k_1 and K.

6. CONCLUSIONS

An experimental procedure and appropriate measuring equipment have been developed to ensure the registration of magnetic nanoparticles in a colloidal solution.

The possibility of detecting magnetic nanoparticles in a colloidal solution using the joint action of ultrasound and a constant magnetic field on the solution was experimentally proved for the first time.

Registration of magnetic nanoparticles was carried out by measuring an alternating (with ultrasonic frequency) electrical voltage on an induction coil as a result of the

action of an alternating magnetic field created by collective oscillations of magnetic nanoparticles oriented by an external DMF relative to the coil. In this case, the coil was located in the immediate vicinity of the vessel with the magnetic nanoparticles.

The main calculated and estimated ratios were obtained that determine the dependence of the recorded voltage on the parameters of the magnetic nanoparticles, ultrasouns, and variable magnetic field, as well as the measurement setup.

The amplitude of the resulting voltage depends on the intensity of the ultrasound and the magnitude of the variable magnetic field acting on the coil.

For the first time, the results of research and development of the measurement setup are important to the development of a new acoustomagnetic method for determining the concentration of MNP in a biological substance**,** what may be an alternative to the MRT method.

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