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ELASTIC PROPERTIES OF BACTERIAL MAGNETITE NANOPARTICLES SUSPENSION

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The objective of the work is to study the biological magnetic nanoparticles (magnetosomes) as a product of the biomineralization process of magnetotactic bacteria Magnetospirillum sp.AMB-1. This paper presents an ultrasound method based on the measurements of compression wave velocities and determination of the phase velocity of a wave. The obtained data allow determination of the mechanical characteristics of the suspension. The study of elastic properties shows that the bulk modulus of a bacterial magnetosome suspension increases with the increase of temperature like in a chemically synthesized magnetite nanoparticle suspension.

1. Introduction. Currently, there is great interest in the preparation of functional magnetic nanoparticles with respect to their application in various fields of biomedical diagnostics and nanosciences. The nanoparticles are usually synthesized in a process involving the co-precipitation of metal salts in an alkali aqueous base. However, synthetic nanoparticles, which have been used almost exclusively for biomedical applications, do not fully match the high requirements with respect to uniform size and morphology, biocompatibility, and high magnetization capabilities. By contrast, biogenic magnetoparticles, such as bacterial magnetosome particles, derived from various magnetotactic bacteria, such as Magnetospirillum magnetotacticum, have a number of advantages. Magnetosome particles are organelles consisting of magnetite crystals enclosed by the phospholipid membrane that offers a high degree of biocompatibility [1]. L. Han *et al.* [2] showed that magnetosomes had a better biocompatibility than synthetic magnetite. All better properties of magnetosomes isolated from bacteria suggested that they might be widely used in biomedical fields as a synthetic magnetite in the future [2]. Magnetotactic bacteria are successfully cultivated in a laboratory [3–5]. Extensive knowledge about the behaviour of a new kind of magnetic nanoparticles is always required prior to their practical applications.

Magnetosomes are bacterial magnetic nanoparticles containing iron mineral crystals of magnetite ($\mathrm{Fe_3O_4}$) or greigite ($\mathrm{Fe_3S_4}$). They are the size of a nanometer ($\sim 50\,\mathrm{nm}$), disperse very well because they are covered with a stable biological membrane - a phospholipid bilayer mixed with proteins [3].

Ultrasonic methods have been successfully applied to study chemically synthesized ferrofluids [6–9]. Now these methods are used to measure the properties of magnetosome suspensions. The usefulness of ultrasonic methods lies in their relative simplicity and non-invasive nature. Using acoustic spectroscopy, we have investigated the elastic properties of bacterial magnetite nanoparticle suspension. The speed of sound c is a mechanical property of a fluid and linked to thermodynamics by isentropic compressibility. All real fluids are compressible, and compression waves can propagate in most fluids. The isentropic (adiabatic) compressibility (the volume changes consecutively to a pressure change at constant entropy S) is a thermodynamic parameter of fundamental significance. It enables direct access to the liquid structure in terms of particle packing density and interparticle forces [10]. According to the well-known Laplace equation:

$$\beta_S = \frac{1}{\rho c^2}, \tag{1}$$

the isentropic compressibility of a fluid is related to its density ρ and sound velocity c. The inverse of the compressibility gives the bulk modulus K of the substance.

2. Material and methods. Bacterial magnetosomes were synthesized by a biomineralization process of magnetotactic bacteria Magnetospirillum, strain AMB-1. Magnetotactic bacteria produce their magnetic particles in chains. A detailed description of the cultivation process of magnetotactic bacteria and isolation of magnetosomes from bacteria is given in our previous articles [11]. The isolated magnetosome particles form stable, well-dispersed suspensions in an aqueous solution of HEPES (4-(2-hydroxyethyl)-1-piperazineethanesulfonicacid). After isolation from these bacteria, those chains are arranged in bent chains to minimize their stray field energy. The chain can be regarded as a long rod with interacting alternating elastic (organic substance) and non-elastic (magnetite particles) elements. It is a well-known phenomenon that an elastic rod is subject to instability if an external compressive force exceeds a critical value F_{cr} [12]. The samples were sonicated using an ultrasonic oscillator (Branson model 450; 20 kHz 120 W) to break the magnetosome chains into individual nanoparticles.

Acoustic properties were measured by a resonance method using a ResoScan™ System (Germany) apparatus. The ultrasonic velocity was determined from a series of resonance frequencies of the resonator cells. The deviations of the observed frequencies from the ideal resonator model and the fit of these deviations to a special transfer function of the ultrasonic resonator permitted a determination of the parameters required. The absolute ultrasonic parameters were found for every cavity. After the evaluation of the orders of the resonances, one resonance is selected automatically as a pilot-resonance and the measurements are made at the resonance peak [13]. The operating frequency of the transducers was 8 MHz. The resolution of the ultrasonic velocity was 0.01 m/s. The temperature of the samples was controlled within ±0.005 K by a Peltier thermostat. The density was measured using a DMA-38 oscillating U-tube microprocessor densitometer from Anton Paar, which is operated by the method proposed by Kratky.

3. Experimental results. The application of ultrasonic methods to study colloidal suspensions involves measuring of the ultrasound velocity as a function of particles concentration, temperature, or frequency of the wave. In the linear propagation regime (tiny perturbation or small wave amplitude), the speed of sound is a characteristic of the medium. It is independent on the wave amplitude and can be determined from the material and geometrical properties of the medium [14]. In fluids, the elastic modulus is given by the adiabatic bulk modulus of elasticity K, the reciprocal of the adiabatic compressibility β_S. The propagating waves are the compression waves. K physically corresponds to the force opposing compression of the fluid. Compressibility is the relative change in volume when the pressure changes by one unit [14].

Fig. 1 presents the ultrasonic wave propagation velocity c as a function of temperature T for the bacterial magnetosome suspension and carrier liquid. This dependence can be described by the equation, $c = c_0 - k(T_0 - T)^2$, similar to the

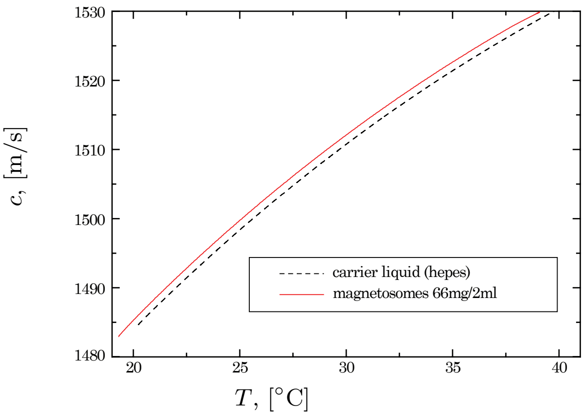

Fig. 1. The ultrasonic wave propagation velocity c as a function of temperature T in the magnetosome suspension and carrier liquid.

Willards function for water. Experimental studies have shown that the ultrasonic wave propagation velocity in the bacterial magnetic particle suspension is higher if compared with the liquid carrier (HEPES solution) – $c = 1511.68\,\mathrm{m/s}$ for the magnetosome suspension and $c = 1510.78\,\mathrm{m/s}$ for the carrier liquid at 30°C – which shows that the presence of bacterial magnetite nanoparticles influences the ultrasonic velocity. Previous studies [6, 9, 15, 16] have shown that the ultrasonic propagation velocity in magnetic fluids with chemically synthesized Fe_3O_4 particles is smaller than that in the carrier liquid. The magnetosome suspension behaves inversely, probably, due to the natural biological membrane, which surrounds magnetosome. This membrane contains neutral lipids and free fatty acids, glycolipids, sulfolipids, and phospholipids. Phospholipids include phosphatidylserine and phosphatidylethanolamine. Therefore, there were some amino and carboxyl groups on the surface of the magnetosome membrane [2].

The density of a magnetosome solution decreases with the temperature and increases after additional components (magnetosomes) are added to the carrier liquid.

Using the experimental data on the ultrasonic wave propagation velocity c and density β, the bulk modulus K and the adiabatic compressibility β_S were calculated. Fig. 2 shows the temperature dependence of K and β_S determined from ultrasonic measurements. The addition of magnetosomes leads to significantly greater values of the bulk sample modulus and smaller isentropic compressibility in comparison with the carrier liquid. The bacterial magnetite nanoparticles suspension behaves the same as a chemically synthesized magnetite nanoparticles suspension [6].

4. Conclusions. Acoustic studies have shown that the propagation velocity of an ultrasonic wave in the bacterial magnetic particle suspension is higher in comparison with the liquid carrier (HEPES solution). The magnetosome suspension behaves inversely if compared with the magnetic fluids with the chemically synthesized Fe_3O_4. The study of elastic properties shows also that the bulk modulus of a bacterial magnetosome suspension increases with the increase of temperature like in a chemically synthesized magnetite nanoparticles suspension.

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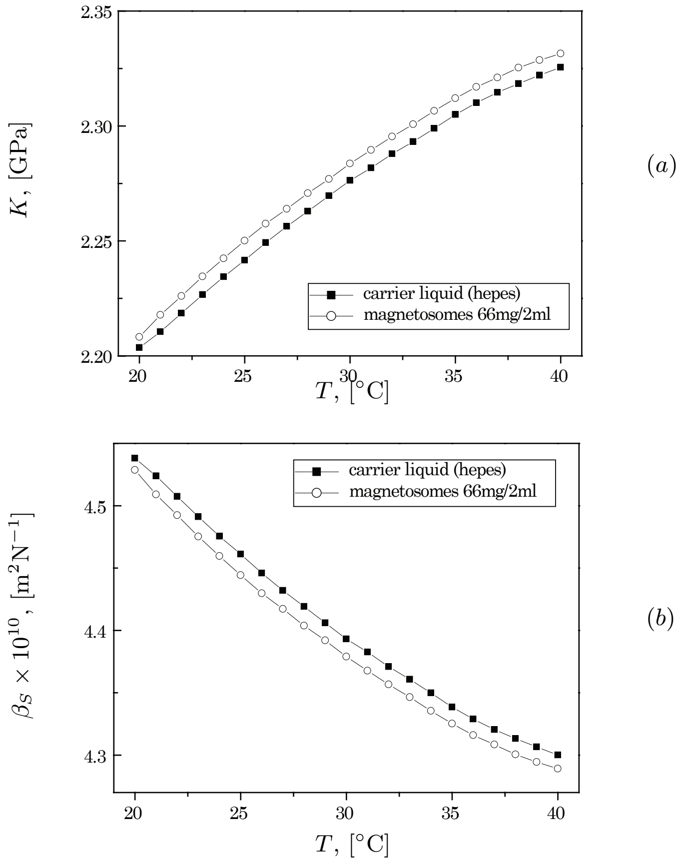

Fig. 2. Temperature dependence of the bulk modulus K and adiabatic compressibility β_S determined from ultrasonic measurements.

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