

Показано що найбільш перспективними матеріалами для захисту від електромагнітних полів є композити. Розроблено технологію магнітної обробки текстильного матеріалу магнітною рідиною та технологію ультразвукової обробки суміші латексу та залізорудного концентрату. Це підвищило насиченість волокон текстильного матеріалу наночастинками магнітної рідини, дисперсність залізорудного концентрату, а також ізотропність рідкого металополімера. У результаті використання такої технології витрати магнітної рідини на оброблення тканини знизилися з 45–50 г/м² до 35 г/м² з підвищенням екрануючих властивостей. Експериментально встановлено, що один шар металотекстильного матеріалу знижує магнітне поле промислової частоти у 6 разів, електричне поле промислової частоти – у 1,5 рази; металополімерний матеріал має показники відповідно 3 і 2. Визначено, що електромагнітне поле частотою 2,45 ГГц знижується одношаровим металотекстильним матеріалом у 3,6 рази, металополімерним – у 5,7 рази. Показано, що металотекстильний матеріал з такими властивостями придатний для виготовлення засобів індивідуального захисту персоналу з експлуатації електротехнічного та радіотехнічного передавального обладнання. Металополімерний матеріал придатний для виготовлення засобів колективного захисту. Запропоновано розрахункове оцінювання ефективності захисних матеріалів. Воно базується на визначенні коефіцієнтів екранування конструкцій стандартної форми. Це надає можливість визначення електрофізичних та магнітних властивостей матеріалу і використання їх у проектуванні захисних матеріалів з необхідними коефіцієнтами екранування. Обґрунтована необхідність оптимізації коефіцієнтів екранування в умовах одночасного впливу електромагнітних полів різних джерел

Ключові слова: композиційні матеріали, електромагнітне поле, електромагнітний екран, магнітна рідина, ультразвукова обробка, коефіцієнт екранування

UDC 537.87:669.162.12(045)

DOI: 10.15587/1729-4061.2020.201330

DEVELOPMENT AND STUDY OF PROTECTIVE PROPERTIES OF THE COMPOSITE MATERIALS FOR SHIELDING THE ELECTROMAGNETIC FIELDS OF A WIDE FREQUENCY RANGE

V. Glyva

Doctor of Technical Sciences, Professor, Head of Department
Department of Civil and Industrial Safety*

N. Kasatkina

Doctor of Technical Sciences, Head of Department
Department of Doctoral and Post-Graduate
National University of Food Technologies
Volodymyrska str., 68, Kyiv, Ukraine, 01601

V. Nazarenko

Doctor of Biological Sciences, Senior Researcher, Head of Laboratory
Laboratory of Study and Standardization of
Physical Factors of Working Environment
State Institution «Kundiiev Institute of Occupational Health of the National
Academy of Medical Sciences of Ukraine»
Saksahanskoho str., 75, Kyiv, Ukraine, 01033

N. Burdeina

PhD, Associate Professor**

N. Karaieva

PhD, Associate Professor***

L. Levchenko

PhD, Associate Professor***

O. Panova

PhD, Associate Professor, Head of Department**
E-mail: elenapanova169@gmail.com

O. Tykhenko

PhD, Associate Professor

Department of Ecology*

E-mail: okstih@ua.fm

B. Khalmuradov

PhD, Professor

Department of Civil and Industrial Safety*

O. Khodakovsky

PhD, Associate Professor***

*National Aviation University

Liubomyra Huzara ave., 1, Kyiv, Ukraine, 03058

**Department of Physics

Kyiv National University of Construction and Architecture

Povitroflotsky ave, 31, Kyiv, Ukraine, 03037

***Department of Automation of Projection of

Power Processes and Systems

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»

Peremohy ave., 37, Kyiv, Ukraine, 03056

Received date 25.02.2020

Accepted date 20.04.2020

Published date 30.04.2020

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N. Karaieva, L. Levchenko, O. Panova, O. Tykhenko, B. Khalmuradov, O. Khodakovsky

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1. Introduction

Much attention is paid to the development and study of protective properties of materials for shielding electromag-

netic fields. This can be explained by the growth of electromagnetic load on the production equipment and personnel and environment [1]. In particular, there is a tendency towards higher amplitudes and a broader frequency spectrum

of electromagnetic fields. In such circumstances, conventional metal magnetic shields have significant drawbacks: lack of controllability of protective properties, high factors of electromagnetic wave reflection, and, in many cases, excessiveness of shielding factors [2]. Under modern conditions, along with the protection of people and electronic equipment against electromagnetic fields, it is necessary to ensure the smooth operation of wireless communication means [3]. It is also unnecessary to shield the natural geomagnetic field [4]. Therefore, composite materials are the most promising means of protection. Their advantages include the controllability of shielding factors by varying concentration of the shielding substance in the base material (fabric or polymer) and the thickness of the material. However, the complexity of the technology used for the manufacture of composites and the high cost of the latter are their main disadvantages. Also, there are problems with the practical application of such materials in lining surfaces of large area and serial production of special protective clothing for personnel.

Therefore, the development of technologies for the manufacture of composite materials while providing a reduction of their component costs is an urgent problem. Also, materials must have physical characteristics acceptable for practical application (weight, thickness, etc.) and be suitable for rational use under the effect of electromagnetic fields of various origin.

2. Literature review and problem statement

International specification for electromagnetic safety [5] includes the provision of the personnel working under conditions of exposure to electric, magnetic, and electromagnetic fields with means of collective and individual protection. The mandatory annex to this document substantiates the need to apply protective measures from a medical point of view and provides valid maximum permissible field strength levels in all frequency ranges. The process of improvement and creation of materials for shielding electromagnetic fields must take into consideration present-day technogenic trends of changes in the spectrum and magnitude of the electromagnetic load on the human body. The growing share of mobile communication and industrial frequency in production is particularly noticeable. The relevance of this issue primarily determines the frequency range of experimental studies [6, 7]. Today, composites are the most promising materials for protection against electromagnetic fields. Most of them are polymers containing shielding substances such as metals, ferrites, or carbon. The efficiency of a material with a polymeric matrix and evenly distributed ferrite particles was studied in [8]. The disadvantage of this material includes its poor efficiency in the high-frequency section of the electromagnetic spectrum. Inefficiency in terms of industrial frequency of the electromagnetic field is caused by the large size of the shielding particles. A wide-range shield [9] was made of cellulose with some moisture content, so such design was prone to degradation in the course of operation because of water loss. It is known that shielding efficiency of both low-frequency and high-frequency electromagnetic fields increases with an increase in the dispersity of the shielding filler. Nanocarbon filler was used in the research and development work [10]. However, the cost of such a material was too high to be applied in lining large surfaces and the polymer base was unsuitable for the manufacture of clothing. The

same applies to the study [11] in which polypropylene was base material for the nanocomposite. Saturation of the material fibers with ferromagnetic nanoparticles is promising. It was theoretically substantiated in [12], however, no experimental data have been provided. It is known that the effect of the magnetic field on ferromagnetic materials contributes to the quality of mechanical treatment and structure isotropy [13]. In this case, it is possible to control the shape of the hysteresis loop which is very important for improving the efficiency of magnetic shields in protection against magnetic fields of low frequencies, mainly industrial frequency, and its harmonics. Implantation of nanoparticles into fibers of a cloth impregnated with magnetic fluid and applying a constant magnetic field was implemented in [14]. However, leaching of the surfactant material (oleic acid) has resulted in a significant loss of shielding nanoparticles. Taking into consideration the high cost of magnetic fluid, it is expedient to improve the technology of magnetic material treatment. Textile-based protective materials without the addition of polymers are suitable for the manufacture of personal protective means [14]. However, metal-polymer materials are the most effective for collective protection (lining the wall and ceiling surfaces, shielding individual electrical and electronic devices). It was shown in [15] that the addition of iron ore powder in the process of latex production makes it possible to obtain a material with high factors of shielding magnetic fields of industrial frequency and electromagnetic fields of ultra-high frequency. However, acceptable shielding factors are achieved with material thicknesses of 5–10 mm. As it was shown in structural studies, material quality can be improved by a more even distribution of the shielding particles. Mixing the starting mixture in a special Brabender mill does not prevent the iron ore particles from sticking together. The known method of ultrasonic material treatment helps to increase the physical and mechanical properties of materials. An increase in the strength of metallic materials by their exposure to ultrasonic radiation was shown in [16]. Results of improving the homogeneity of the melt of metal alloys by ultrasonic pre-crystallization treatment were presented in the study [17]. The above indicates the possibility of improving the quality of metal-polymer materials due to the ultrasonic treatment of initial mixtures.

The published data analysis gives grounds to conclude that the improvement of the materials intended for shielding electromagnetic fields is advisable to be realized in two directions. The first of them is the qualitative improvement of metal textile materials for making personal protective means. The second direction consists in bettering the protective properties and reducing weight and dimensional parameters of metal-polymeric materials for constructing collective protection structures.

3. The aim and objectives of the study

The study objective is to develop metal-textile and metal-polymer materials for shielding electromagnetic fields and study their protective properties in fields of ultra-low and ultra-high frequencies.

To achieve this objective, the following tasks were set:

- to develop a technology for the production of a metal-textile protective material;
- to develop a technology for the production of a metal-polymer protective material;

- to determine shielding factors of metal-textile protective materials in electromagnetic fields of ultra-low and ultra-high frequencies;
- to determine shielding factors of metal-polymer protective materials in electromagnetic fields of ultra-low and ultra-high frequencies.

4. Technologies of production of protective materials for shielding electromagnetic fields

4.1. The technology of production of metal-textile materials for shielding electromagnetic fields

Serial linen fabric recommended in Ukraine for the production of special protective clothing was used to make samples of the metal-textile material. It has adequate strength and thermodynamic properties in terms of using in the manufacture of a material intended for protection against the effect of electric, magnetic, and electromagnetic fields. Fiber porosity is its advantage. This makes it possible to realize the irreversible implantation of metal and metal-containing nanoparticles into the fabric structure.

Magnetic fluid as a source of nanoparticles was provided by Ferohydrodynamic Ltd, Mykolaiv, Ukraine. The magnetic fluid used in the study is a stable colloidal solution of solids in a liquid carrier (aviation kerosene). The choice of kerosene is due to its volatility which makes it possible to dry samples without first washing away the main fluid. The dispersed phase of the solution consists of ferromagnetic particles (magnetite, iron ferrites) measuring 3–10 nm. According to the manufacturer, the content of nanoparticles in solution was 9 wt. %. Fatty oleic acid was used as a surfactant that prevents particles from their sticking together.

To enhance the protective properties of the metal-textile material, maximum saturation of the moist linen fabric with ferromagnetic nanoparticles is necessary. In addition, taking into consideration the high cost of the magnetic fluid, it requires an increase in efficiency of its use, that is, a greater number of its particles in the fabric and their irreversible fixation in fibers.

It is known that in a magnetic field, magnetic force F_m acts on magnetic particles contained in the magnetic fluid. The magnitude of this force depends on both the magnitude of the field characterized by the value of magnetic induction B and the spatial derivatives of these field components. Therefore, the magnitude of the magnetic force F_m is proportional to the value $|B| \text{grad}(|B|)$. The direction of this force action depends on the direction of the vector $\text{grad}(|B|)$. In the case of the creation of a non-uniform magnetic field with its gradient directed perpendicular to the surface of the textile material, an additional mechanism is created that enhances the penetration of magnetic particles into the material fibers. This improves its magnetic properties. The schematic view of such a device is shown in Fig. 1.

In this device, the permanent magnet 4 creates a non-uniform magnetic field and the tooth structures on the magnetic conductor 5 make it possible to create a non-uniform magnetic field in the zone of magnetic fluid. The presence of an additional magnetic conductor 6 makes it possible to increase the strength of this field. This design of the magnetic system results in the appearance of magnetic force F_m in the magnetic fluid. This force acts on magnetic particles and is directed perpendicularly to the material surface which leads to an intense penetration of particles into fibers.

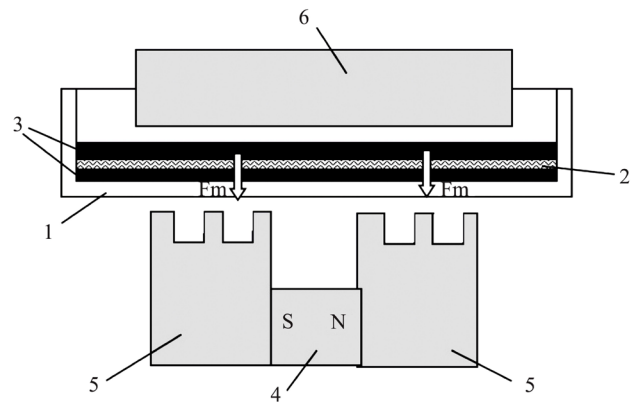


Fig. 1. Schematic view of a device for magnetic treatment of textile material with magnetic fluid: 1 – a vessel made of non-magnetic material; 2 – textile material; 3 – magnetic fluid; 4, 5 – permanent magnet with a magnetic conductor; 6 – additional magnetic conductor

Following the magnetic treatment, the textile material is subjected to drying in an air stream to remove kerosene. To remove oleic acid and kerosene residues, the dried material is treated with a fat removing detergent, in this case, HG detergent manufactured by HG International b. v. (Netherlands).

The dried textile material becomes suitable for the manufacture of personal protective means.

4.2. The technology of manufacturing a metal-polymer material for shielding electromagnetic fields

For the production of a metal-polymer material, standard NRL food-grade latex produced by Vytx (USA) was selected as polymer. This material is made in a liquid state and is widely used due to its low cost. The iron ore concentrate obtained by the flotation method at Poltava Mining and Treatment Plant (Ukraine) was used as the shielding substance. Composition of the concentrate: 72–73 % Fe, 8–20 % FeO, Fe₃O₄. Average dispersion: 150–200 μm.

A cheaper substance (iron ore concentrate) was used as a shielding substance for the manufacture of collective protective means, for example, materials for lining large surfaces. As noted, the main objective of improving the material quality consists in a uniform distribution of shielding particles in the volume of medium (liquid latex).

In the first step, dry iron ore concentrate was added to latex (in this case, 20 wt. %) and mechanically mixed. After that, the mixture was subjected to ultrasonic treatment (Fig. 2).

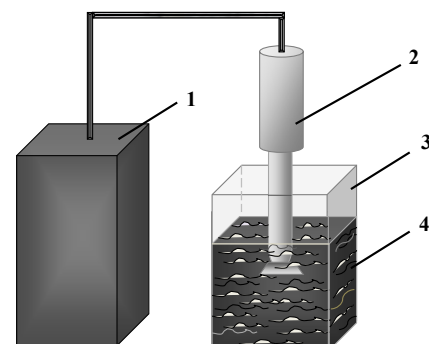


Fig. 2. Schematic view of an installation for ultrasonic treatment of metal-polymer mixture: 1 – ultrasonic generator; 2 – ultrasonic oscillator; 3 – vessel with the source fluid; 4 – a mixture that is exposed to ultrasound

The advantage of such treatment consists in the large amplitudes of sound pressure at low power consumption. The working volume acts as an oscillating system that operates on forced oscillations in an elastic wave mode. A standing wave occurs in the working volume when the distance between two reflecting surfaces corresponds to the condition $n\lambda/2$, n is an integer, and λ is the length of the mechanical wave. In this case, resonant phenomena appear in the fluid volume. As the amplitude of oscillations of the medium particles increases, oscillatory velocity and amplitude of the sound pressure grow, that is, the intensity of the oscillatory process in the working volume increases without self-excitation. An 80 W generator was used for ultrasonic treatment, and amplitude of ultrasonic vibrations was 45–50 μm . Treatment was carried out at a frequency of 23 kHz which corresponds to a wavelength of about 0.014 m. Thus, the above condition of occurrence of the resonant phenomena is always ensured in a vertical movement of the ultrasonic emitter.

After the treatment of 0.5 l of mixture for 10 min., it was applied to the substrate. The presence of the base is not required but, in this case, it is possible to obtain a material of small thickness. Linen fabric was also chosen as a base for the unification of protective materials. The fabric with a metal-polymer mixture applied to it is rolled with rolls. Depending on the rolling pressure, a 0.5–1.0 mm thick material can be obtained. The material is then dried and gets ready for use.

5. Studying the properties of composite materials as a protection against electromagnetic fields of ultra-low and ultra-high frequencies

5.1. Determining the shielding factors in shielding electromagnetic fields of ultra-low and ultra-high frequencies with the metal-textile protective material

Measurements of material efficiency (shielding factors) in protection against low-frequency electromagnetic field were performed using a calibrated Spectran NF 5035 electromagnetic spectrum analyzer (Germany) according to the operating instructions. The maximum primary error in measurements did not exceed 1%. To determine shielding factors in protection against electromagnetic fields of ultra-high frequency, a calibrated P3-31 electric-flux density meter (Russian Federation) was used according to the operating instructions. The maximum major error did not exceed 2.7 dB. Shielding factors were measured for geometrically closed shields that completely enveloped the measuring antennas. During measurements, the background strength of the electric field of industrial frequency did not exceed 10 V/m and that of the magnetic field 0.1 A/m. The background power flow density did not exceed 0.265 $\mu\text{W}/\text{cm}^2$ in the frequency range of 0.3–30 GHz.

Protective properties of the obtained materials (determination of the shielding factors) were studied for electromagnetic fields of ultra-low frequencies (industrial frequency, its harmonics, and interharmonics) and electromagnetic fields of the ultra-high frequency of 2.45 GHz. This is a non-licensed working frequency used in microwave ovens. It is intermediate between the working frequency of wireless Wi-Fi networks (2.4 GHz) and 4G mobile communication (2.6 GHz). That is, the degrees of protection are almost indistinguishable because of the proximity of frequencies used in these sources.

Taking into account the quasi-stationarity of ultra low-frequency electromagnetic fields, their levels were determined separately in terms of magnetic and electrical components of the field.

The results obtained in testing the metal-textile material for shielding magnetic field of ultralow frequency are shown in Fig. 3.

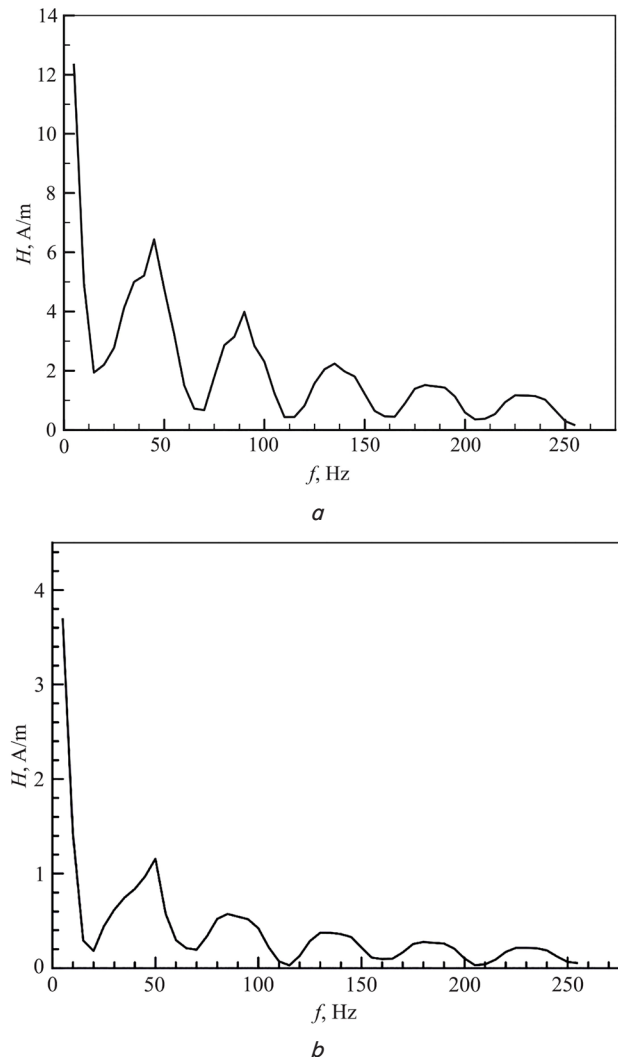


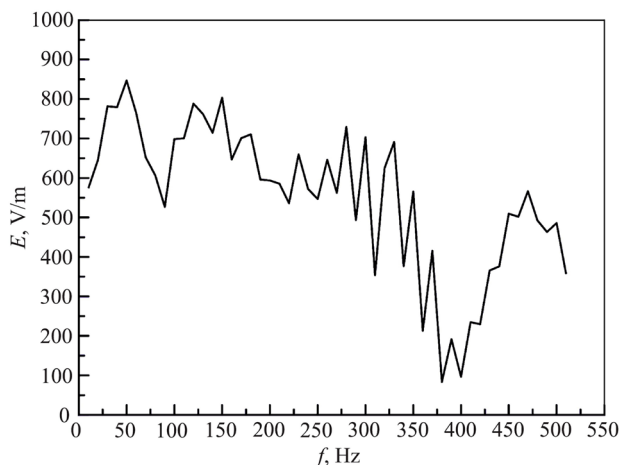
Fig. 3. Shielding of the ultra low-frequency magnetic field with protective materials: *a* – starting spectrum of the magnetic field; *b* – spectrum of the magnetic field shielded by a metal-textile material

As can be seen from the above data, at a frequency of 50 Hz, the magnetic field was reduced 6 times by the metal-textile material and 3 times by the metal-polymer material. Practically similar results were obtained for industrial-frequency harmonic and interharmonic fields. Taking into account that the maximum permissible levels of magnetic fields in production conditions are almost never exceeded more than 2–3 times [14], this result can be considered satisfactory.

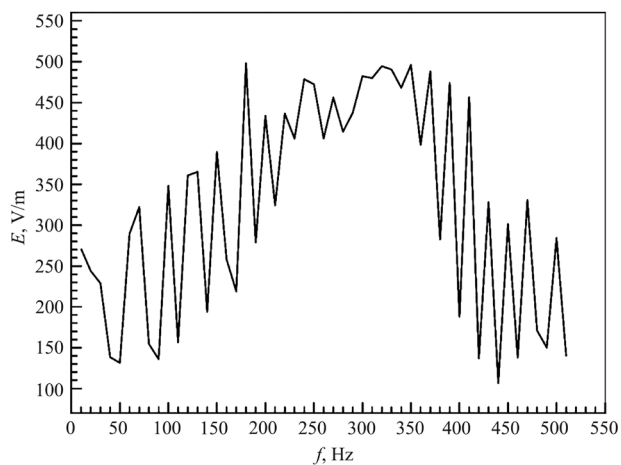
The results of measuring the variations taking place in the electrical component of the electromagnetic field of ultralow frequency are shown in Fig. 4.

The above results show that the electric field of ultra low-frequency is guaranteed to be reduced 1.5 times by metal-textile material. This result was expected because

the shielding substance had low conductivity which reduced the electric field shielding factors. However, the magnetic field is considered to be more critical in influencing biological objects. In addition, shielding the electric field in production conditions, unlike shielding the magnetic field is not difficult because of the possibility of using any solid metal material.



a



b

Fig. 4. Shielding of an electric field of ultralow frequency with protective materials: initial spectrum of the electric field (a); spectrum of the electric field shielded with metal-textile material (b)

Shielding factors of the obtained material in protection against ultrahigh-frequency electromagnetic fields were determined (Table 1).

Table 1

Shielding of the ultrahigh-frequency electromagnetic field by metal-textile material*

n	$S_f, \mu\text{W}/\text{cm}^2$	$S_s, \mu\text{W}/\text{cm}^2$	K_s
1	200–210	56–60	3.6
2	200–210	26–36	7.4

Note: n is the number of layers of the protective material; S_f is energy flux density (Poynting vector) of the electromagnetic field source; S_s is energy flux density in the shielded area; K_s is shielding factor ($K_s=S_f/S_s$)

The obtained factors of shielding the electromagnetic field of ultrahigh-frequency can be considered satisfactory taking into consideration the thickness of the fabric which can be used for the manufacture of protective clothing.

5.2. Determining the shielding factors in shielding electromagnetic fields of ultralow and ultrahigh frequencies with the metal-polymer protective material

Protective properties of the metal-polymer material were studied using the same equipment as for the metal-textile material and for the same frequencies.

The initial spectrum of the magnetic field of industrial frequency is shown in Fig. 3, a and that of the electric field of industrial frequency in Fig. 4, a.

The results obtained in the tests of shielding the magnetic field of the ultralow frequency with metal-polymer material are shown in Fig. 5.

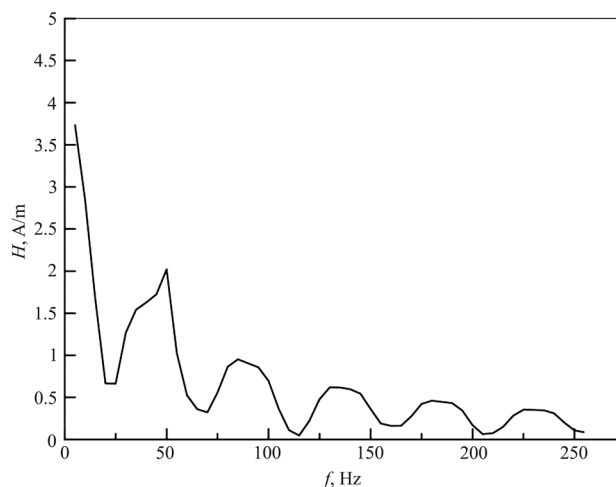


Fig. 5. Shielding the magnetic field of the ultralow frequency with a metal-polymer material

As can be seen from the above data, the 50 Hz magnetic field was reduced by 3 times by means of a metal-polymer material (Fig. 3, a).

The results obtained in measuring the variation of the electric component of the electromagnetic field of ultralow frequency are shown in Fig. 6. The initial spectrum is shown in Fig. 4, a.

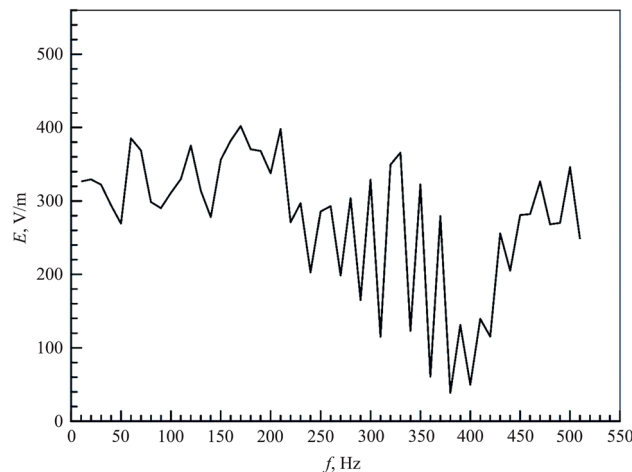


Fig. 6. Shielding of the electric field of ultralow frequency by means of a metal-polymer material

The above spectrum shows that the electric field of ultralow frequency is guaranteed to be reduced twice by a metal-polymer material (Fig. 4, *a*).

Shielding factors in protection against ultrahigh-frequency electromagnetic field by means of a metal-polymer material were similarly determined (Table 2).

Table 2

Shielding of the ultrahigh-frequency electromagnetic field by a metal-polymer material

<i>n</i>	$S_f, \mu\text{W}/\text{cm}^2$	$S_s, \mu\text{W}/\text{cm}^2$	K_s
1	200–210	35–39	5.7
2	200–210	15–19	11.2

The above results can also be considered satisfactory. The maximum permissible level of the electromagnetic field in mobile communication never reaches $10 \mu\text{W}/\text{cm}^2$. However, the obtained materials may be used to protect personnel serving radio engineering facilities such as civil aviation airfields and shielding individual radio equipment items. The effectiveness of two layers was studied because the equivalent depth of field penetration is critical for high-frequency electromagnetic fields. The practical doubling of the shielding factor in a two-layer material indicates that no shielding jump occurs for this material at the selected frequency.

6. Discussion of the results obtained in the study of protective properties of composite materials and determining ways of their improvement

Analysis of the study results shows that the developed procedure makes it possible to consume magnetic fluid no more than $35 \text{ g}/\text{m}^2$ (the previous result was $45\text{--}50 \text{ g}/\text{m}^2$) [14]. In this case, the shielding factors with respect to the magnetic field of industrial frequency increased 2.5 times for a single-layer material in comparison with the previous results [14], Table 3. The same applies to the electric field. The shielding factors of the electromagnetic field of ultrahigh-frequency were 5.7–11.2 (one and two layers). The above results required an adequate interpretation. This was realized by determining the weight content of the shielding substance in the material. The same linen fabric served as a base both for this protective material and that described in [14]. Besides, the same substance was used to remove the process fluid from materials. The number of ferromagnetic particles in both materials in the final form was determined by weighing. A sample was made using the technology described in [14] and the weight difference between the sample used in [14] and the sample described in the present paper was determined by weighing. It was found that the actual residue of ferromagnetic particles was $1.5\text{--}1.6 \text{ g}/\text{m}^2$ in the material described in [14] and $2.9\text{--}3.0 \text{ g}/\text{m}^2$ in the obtained material, that is, almost twice as much. Quantity of ferromagnetic nanoparticles irreversibly implanted into the fabric fibers increases under the effect of applied magnetic treatment. This explains the increase in shielding factors.

It should be noted that the shielding factors obtained for the metal-polymer material treated with ultrasound and applied on a textile base (0.5–1.0 mm thick) by rolling corresponded to the shielding factors for at least a 5 mm thick met-

al-textile material having the same content (20 %) of iron ore powder [15]. However, the latter material has poor processability in practical applications (high thickness and low flexibility). The higher shielding factor of the metal-polymer material can be explained by increased dispersity of the shielding substance and isotropy of the initial metal-polymer mixture. Dry iron ore concentrate does not contain surfactants, so its individual particles stick together and ordinary mechanical mixing does not ensure their even distribution in the latex base. Under the impact of powerful ultrasonic radiation suitable even for hardening of metal products, dispersity of the shielding substance grows ensuring its even distribution in the polymer. The use of iron ore concentrate as a shielding substance instead of iron ore powder [15] is an additional factor in raising the shielding factors as it contains 15–20 % more ferromagnetic components in the metal-polymer material.

In general, as the study results show, the metal-textile and metal-polymer materials developed for shielding electromagnetic fields can be considered wide-range materials.

However, the study results have left a series of non-solved issues. Frequency shifts of industrial frequency harmonics of the magnetic field and smoothing of fixed frequency peaks are not clear. A change in nature of the shielded electric field, that is, a change in the prevailing maximum amplitudes, needs to be explained. These issues should advisably be considered based on ratios of the continuous media electrodynamics.

The limitation of the performed study consists in that it was based entirely on experimental data. To design magnetic and electromagnetic shields, practitioners need to be able to pre-evaluate the shield performance. To obtain the shield wall thickness, it is necessary to consider the equivalent depth of field penetration into the shield thickness, δ . It is known from electrodynamics of continuous media that

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}},$$

where f is the field frequency, μ is the absolute magnetic permeability of the material, σ is the specific electrical conductivity of the material.

Equivalent penetration depth is the depth distance from the shield surface at which the field is 2.7 times smaller. The actual depth of penetration depends on the required degree of field reduction. For example, when the field is reduced by 10 times, the actual depth of field penetration is 2.3δ . Taking into consideration that the innovative materials have magnetic and electrophysical data that are not tabular, initial data should be obtained experimentally. The specific conductivity of materials is easily determined by measuring its reciprocal, that is, resistivity. This is done using the standard double bridge method. Magnetic permeability can be determined from a series of experiments with measuring shielding factors of materials having different concentrations of the shielding substance.

The following ratio in terms of the shielding factor when protecting against a magnetic field of an industrial frequency by means of a cylindrical shield was obtained in [15]:

$$K_s = \frac{\mu_{eff} (b^2 - a^2)}{4b^2},$$

where K_s is the shielding factor; a is the inner radius of the cylindrical magnetic shield; b is its outer radius and μ_{eff} is the effective magnetic conductivity of the material.

Based on the data obtained, one can evaluate parameters of the shields of required efficiency.

The study of the dependence of the quality of the metal-polymer mixture on time and frequency of ultrasonic treatment is a promising task. This will make it possible to get mixtures of maximum dispersity and homogeneity.

Another promising task consists in the optimization of the shielding factors of materials relative to electric, magnetic, and electromagnetic fields of different sources. For example, when organizing shielding of the most common magnetic fields of industrial frequency, it is necessary to ensure the stable operation of mobile communication means. It is known that when the level of the base station signal is below 0.15–0.20 $\mu\text{W}/\text{cm}^2$, the radiation intensity of mobile phones dramatically grows which is harmful to users. Therefore, radiation of ultra-high frequency has a lower limit in mobile communication. The natural geomagnetic field also has a lower limit reduction of which more than twice is prohibited in production conditions [18]. Considering that the horizontal component of the geomagnetic field is the predominant component, optimization of protective properties of shielding materials primarily concerns the protective materials for lining walls of rooms and buildings.

7. Conclusions

1. The technology of fabrication of a metal-textile material for shielding electromagnetic fields was developed. It is based on the influence of a constant magnetic field of high heterogeneity from two magnetic conductors on a textile

material impregnated with a magnetic fluid containing ferromagnetic nanoparticles. This has made it possible to reduce magnetic fluid consumption from 45–50 g/m^2 to 35 g/m^2 compared to its counterparts and increase the number of shielding particles implanted into fabric fibers from 1.5–1.6 g/m^2 to 2.9–3.0 g/m^2 .

2. The technology of manufacturing metal-polymeric material has been developed. It differs from its counterparts in pre-treatment of a mixture of iron ore concentrate and liquid polymer by ultrasonic radiation at a frequency of 23 kHz and amplitude of 45–50 μm . This has enabled an increase in the dispersity of the iron ore substance by mechanical action and ensured uniform distribution of particles in the polymer by intensive ultrasonic mixing.

3. The study of protective properties of a single-layer textile material has shown that the guaranteed shielding factor in protection against the magnetic component of the electromagnetic field of industrial frequency and its harmonics amounted to 6. The shielding factor of the electrical component was 1.5. The shielding factor in protection against an electromagnetic field of ultrahigh-frequency (2.45 GHz) was 3.6. Such values indicate the suitability of the studied materials for the manufacture of personal protective means.

4. Studies of protective properties of the metal-polymer material have shown that the guaranteed shielding factor for the magnetic component of the electromagnetic field of industrial frequency and its harmonics is 3. The shielding factor for the electrical component is 2. The shielding factor for the electromagnetic field of ultra-high frequency (2.45 GHz) is 5.7. Such protective properties indicate the possibility of using the material as a means of collective protection, for example in facing surfaces of large areas.

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