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REGULATION OF LUBRICANT FILTRATION IN MACHINE ELEMENTS USING NANOMAGNETIC METHODS

Introduction. *The current state of filtering technology has been defined by the growing requirements for the purity of technical fluids, the enhanced durability of filter elements, and the advances of modern nanotechnology, particularly with respect to magnetic properties.*

Problem Statement. *The incorporation of nanomagnetic components based on iron oxides has had the potential to fundamentally transform the structure and functional parameters of porous materials used in filter devices. However, no technology has yet enabled the adjustment of these parameters under the influence of a magnetic field.*

Materials and Methods. *The materials employed are porous structures based on polyurethane foams saturated with nanocomposites of divalent and trivalent iron oxides. Experimental methods have included measurements of magnetic induction and the throughput capacity of porous elements, while theoretical methods have involved the analysis of magnetic forces and the application of hydrodynamic equations for channel flows.*

Results. *Porous filter materials infused with magnetic nanocomponents consisting of mixed divalent and trivalent ferric oxides have demonstrated structural changes under the influence of a magnetic field. The proposed system of electromagnetic control for filters filled with magnetic nanocomposites has allowed the adjustment of their structural parameters. When the magnetic field induction has been varied from 0 to 0.2×10^{-3} T, the filter bandwidth increases 1.7–1.9 times, corresponding to a change in the average pore diameter by a factor of 1.24–1.17. This principle has enabled both the increase of filter throughput as clogging occurs and the adjustment of pore sizes to selectively retain harmful components of predetermined dimensions.*

Conclusions. *The study has confirmed the feasibility of regulating the structural parameters of porous filtering materials by incorporating magnetic nanocomponents. Electromagnetic control has made it possible to achieve adjustable filter capacity tailored to specific operational requirements.*

Keywords: liquid purification, nanomaterials, porosity, filter elements.

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Several modern technologies require the purification of technical liquids. These requirements have been determined both by environmental regulations [1] and by the need to ensure the reliability and durability of equipment [2]. Recent advances in the purification of technical fluids in heavy hydrostatic bearings have opened new prospects for improving accuracy and productivity [3]. Key issues related to lubricant contamination, cleaning, and filtration methods that mitigate negative consequences have been addressed in prior research [4].

The purity of lubricants has proven decisive in numerous processes, particularly in stamping technologies [5]. Machining operations such as turning and grinding, which are performed under increasingly stringent environmental and accuracy requirements, have required the use of highly purified technical liquids [6]. Modern machine drives have required continuous filtration and cleaning of lubricating fluids [7, 8].

Advances in filtration methods have also been necessary for electric drives and machines [9, 10], as well as in industries associated with fuel and technical fluid production [11]. The main analytical approaches for determining purification and filtration parameters of technical liquids have been presented in prior studies [12], while diffusion–convective statistical models of filtration have been examined in [13].

The feasibility of creating porous structures for the filtration of technical liquids has been demonstrated in [14]. Further, [15] has reported attempts to develop specialized porous structures for filtration and purification using 3D printing methods.

The primary purpose of filters and filter elements has been to improve the quality of liquids for technological processes, environmental protection, and human health. The principal quality indicators of liquids during filtration have been specified in [16]. Research has established the relationship between filter structure and liquid quality [17]. At the same time, the complexity of filter and liquid quality should be considered from a systemic perspective [18].

The purification of technical fluids has been closely associated with the characteristics of the filters themselves. The preparation of filter devices for different environments depends on the porosity of filter materials. While prior research has provided data on the porous structures of filters [19], the possibility of adjusting porosity has not been sufficiently addressed.

The authors of [20] have expanded the set of indicators for assessing filter efficiency by introducing pore size distribution factors and fluid permeability parameters related to pore geometry. Although the importance of this factor has been demonstrated, practical recommendations for its implementation have not been provided.

Research [21] has examined liquid transport in porous media during the filtration process and has determined the influence of channel geometry on filtration performance. These studies have confirmed the significant impact of porosity parameters on the efficiency of filtration. At the same time, practical methods for ensuring the desired pore characteristics have not been sufficiently investigated.

Porous materials with the ability to form predetermined structures have been described in [22]; however, these structures remain static during operation. Adjustable structures, in contrast, have the potential to significantly enhance material performance.

The feasibility of analytical research on porous media has been substantiated in [23], while [24] has identified the influence of pore structure on the mechanical characteristics of materials. Modern nanotechnologies have created substantial opportunities for the design of porous materials [25]. Nanocomponents, in particular, have enabled the controlled formation of porous structures with tailored properties [26].

A number of studies have highlighted the promising applications of magnetic nanomaterials [27]. These materials have provided new opportunities for the retention of harmful metallic substances [28, 29]. Moreover, when incorporated into porous structures, they have generated forces capable of deforming and modifying the medium,

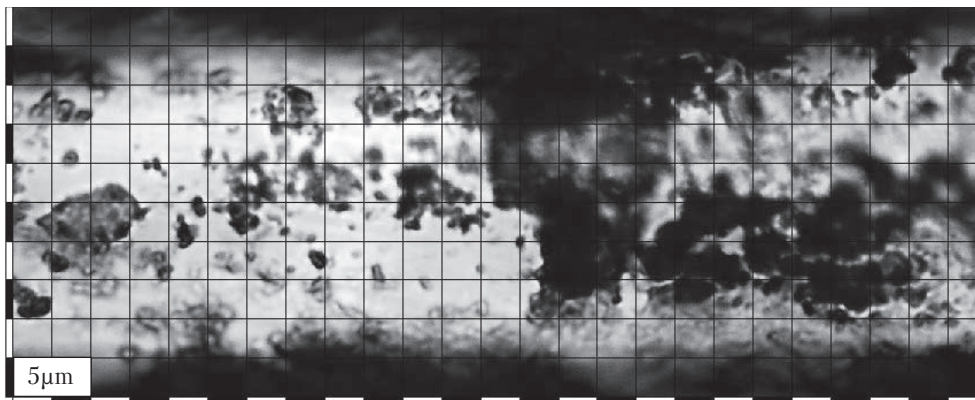


Fig. 1. Components of iron oxides on the pore surface

thereby offering a pathway toward adjustable filtration properties.

Based on the review of the main sources, it can be concluded that the development of porous filters with a controlled structure remains highly relevant. The potential for achieving such effects through magnetic nanotechnologies has been recognized, yet this issue has not been sufficiently addressed in prior research, which underscores the feasibility and necessity of further investigations in this direction.

Nanocomponents based on a mixture of divalent and trivalent iron have been synthesized by combining FeSO_4 and FeCl_3 solutions. The controlled addition of NH_4OH ensures the formation of magnetic components with nanoscale dimensions. The synthesis technology of FeO and Fe_2O_3 nanomixtures has been described in detail in [30, 31].

Porous and foamed materials with incorporated nanocomponents have demonstrated a pronounced structural organization [32]. The geometry of the pores can be defined at the production stage [33], while a specific concentration of nanocomponents ensures the formation of open structures [34]. Although rapid prototyping methods can also be used to produce open structures [34], magnetic technologies have provided higher productivity while maintaining structural quality. Such properties are particularly relevant for filtration applications, as magnetic methods enable the adjustment of pore size to achieve the required filtration performance.

The microscopic examination has shown that the internal pore surfaces appear coated with iron oxide components (Fig. 1).

The determination of the distribution of visible sizes has demonstrated the clear expediency of continuing the curve toward nanosizes (Fig. 2).

At the same time, it is possible to take into account the presence of the limitation $d > 0$. That is, the size of the particles shall have clear values.

The number of nanosized particles is determined by the area under the graph (zone 1). This is approximately 35% of the total number of particles.

The nanosize of the obtained structures is confirmed by studies using electron microscopy (Fig. 3).

The porous material has been produced by mixing polyurethane with azodicarbamide with the molecular formula $\text{C}_2\text{H}_4\text{O}_2\text{N}_4$. Magnetic powder based on a mixture of divalent and trivalent iron oxides is added to the mixture. As a result of the chemical reaction, a porous material has been obtained. The porosity parameters depend on the content of magnetic components.

Nanoparticles get into the irregularities of the porous structure and provide their magnetic properties. The experiments have confirmed the attraction of these materials to magnets.

Placement of a magnetic porous material within an annular magnetic field generates a distributed load on each porous element, leading to either tensile or compressive deformation (Fig. 4).

In the course of the experiment, the induction of the magnetic field changes from 0 to 0.1 mT by adjusting the current in the electromagnet. The change in size is determined by the tangential method while measuring the flow of liquid moving throughout the porous medium.

The deformation of the porous element can be determined in the model of the loaded cylinder [36, 37]:

$$u = \frac{p(1+\nu)d}{E} \frac{d}{2},$$

where E is the modulus of elasticity of a monolithic material without pores; ν is Poisson's ratio; d is the average pore diameter; p is the pressure inside the pore.

Given sufficiently small values of the modulus of elasticity, the deformations can reach values comparable to the pore sizes. On the other hand, this deformation is related to the initial d_0 and the final pore diameter d : $u = d - d_0$.

Then the current diameter of the pore under the action of internal loads, given the direction of pressure, is equal to:

$$d = \frac{d_0}{1 \pm \frac{p(1+\nu)}{2E}}.$$

In the presence of a magnetic field, ferromagnetic materials experience a force that is governed by the magnetic field induction B . The force distributed over the area is proportional to the square of the magnetic induction:

$$p = k \cdot \frac{B^2}{2\mu_0},$$

where μ_0 is the magnetic permeability.

For this case, the real force will depend on the structure and distribution of nanoparticles and cannot be theoretically recognized.

The pore diameter is also difficult to measure continuously.

It should be noted that changing the pore diameter also changes the filter capacity. We will de-

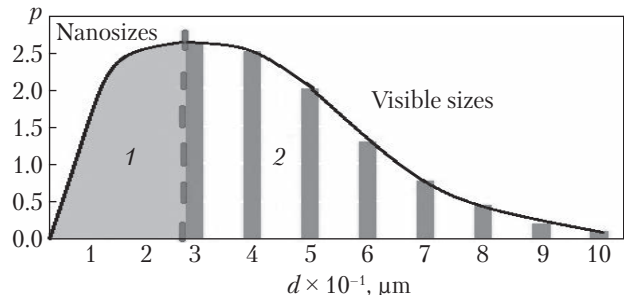


Fig. 2. Distribution of iron oxide particles by size 1 – nanosizes; 2 – visible sizes; p is the probability density

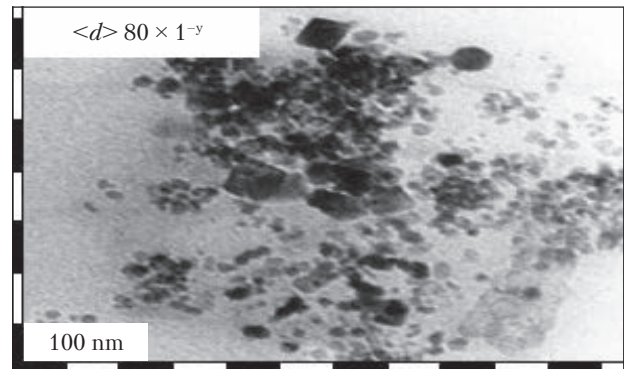


Fig. 3. Image of iron oxide structures in an electron microscope

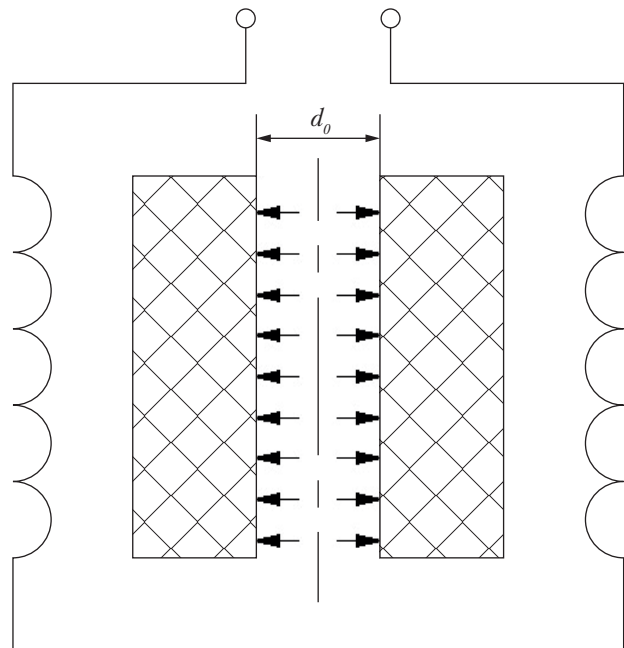


Fig. 4. Loading of the porous element by magnetic forces

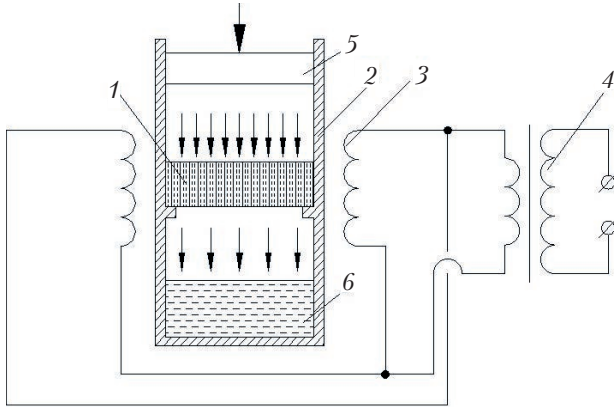


Fig. 5. Determination of the bandwidth dependence of the filter with magnetic regulation

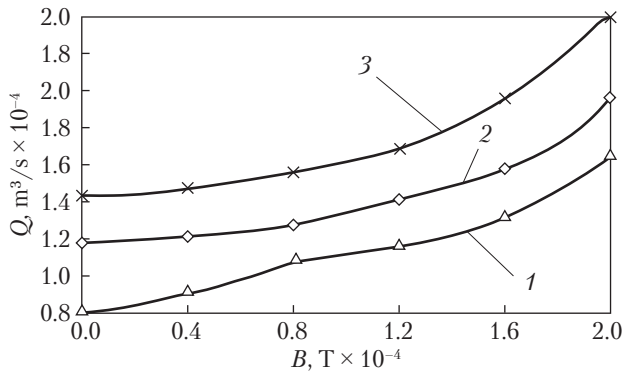


Fig. 6. Dependence of liquid flow on magnetic field induction: 1 – Δ*p* = 1 Pa; 2 – Δ*p* = 2 Pa; 3 – Δ*p* = 3 Pa

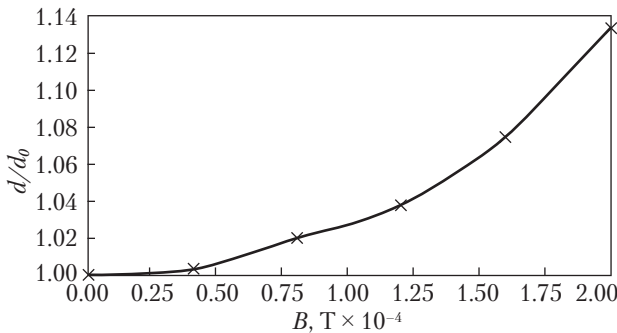


Fig. 7. Change in the average diameter of the pores in the magnetic field

fine this value as the flow rate of the liquid to be filtered depending on the pressure.

Small speeds of fluid movement inside the pores determine the laminar flow regime that is described by the Poiseuille equation [38, 39]:

$$\Delta p = \frac{32 \cdot \eta \cdot h \cdot Q}{\pi \cdot d^4},$$

where η is the dynamic viscosity of the liquid passing through the filter; h is the length of the pore, which is approximately equal to the thickness of the filter; Q is the volume flow of liquid; Δp is the pressure drop.

Given the value of the pressure created by the magnetic field, and the change in the pore diameter due to the action of this pressure, it is possible to write down the expression for the change in the flow rate of the liquid passing through the filter:

$$Q = \frac{\pi \cdot \Delta p}{32 \cdot \eta \cdot h} \left(\frac{d_0}{1 \pm \frac{k \cdot B^2}{2\mu_0} \frac{1+\nu}{E}} \right)^4.$$

Thus, the magnetic field can affect the bandwidth of the filter.

To verify this fact, the porous filter element 1 is saturated with magnetic particles of a mixture of divalent and trivalent iron (Fig. 5). This element is placed in the tubular chamber 2 that, in turn, is placed in the cavity of the ring electromagnet 3. The voltage and inductance of the magnetic field are adjusted using an autotransformer 4. The pressure in the tubular element is created by the piston 5 and measured by a manometer. Liquid consumption is determined by the amount of liquid 6 passing through the filter per unit of time.

The autotransformer regulates the voltage to 220 volts. At the same time, the magnetic induction can reach 5–6 mT.

The hydraulic oil used for the experiments is SAE J300 APR97 0W-30 with a viscosity of 9.3 cSt. The fluid flow rate through the filter is determined by the volume of fluid that flows freely under its own weight per unit time. Figure 6 shows the dependence of the fluid flow on the magnetic field induction at different pressure values. The graph

demonstrates the ability to adjust the bandwidth of the filter by electromagnetic means.

The experiments have confirmed an increase in the liquid flow under the action of a magnetic field, as a result of an increase in the cross-sections of channels for the passage of liquid. With the use of data on the change in the filter's ability to pass liquid, it is possible to determine the change in the average diameter of the pores about the initial diameter.

$$d/d_0 = \sqrt[4]{\frac{Q}{Q_0}}$$

The expected change in the average diameter of the pores depending on the magnetic induction, taking into account the experimental data, is shown in Fig. 7.

The research results confirm the ability of the obtained porous materials to change the geometric parameters of the pores under the conditions of the magnetic field that affects the parameters of the filter devices, their throughput, and cleaning purity.

The paper solves the problem of creating porous systems with adjustable filtration parameters. A porous structure with magnetic properties is

created based on a nanocomposite mixture of oxides of divalent and trivalent iron. Under conditions of location in an annular magnetic field, the parameters of the porous structure change, and the throughput of the filtering device changes accordingly. An increase in magnetic field induction from 0 to 0.2 mT results in a 1.7–1.9-fold increase in the filter bandwidth, which corresponds to a 1.24–1.17-fold change in the average pore diameter.

The ability to adjust the size of the pores for the passage of liquid during the operation of the filtration creates new opportunities for their functioning.

In particular, it is possible to create conditions for cleaning unwanted terms with a given geometry. Taking into account the magnetic properties of the obtained filter media, they additionally receive opportunities for the retention of harmful metal particles.

In case of contamination of such filter devices, their lifetime can be extended by adjusting the cross-sections of the channels for cleaning. In the case of dynamic, in particular, cyclic changes in the magnetic field, such systems can acquire the ability to self-clean. Such tasks can be the direction of further research.

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РЕГУЛЮВАННЯ ФІЛЬТРАЦІЇ МАСТИЛЬНИХ МАТЕРІАЛІВ ЕЛЕМЕНТІВ МАШИН НАНОМАГНІТНИМИ ЗАСОБАМИ

Вступ. Сучасний стан фільтрувальної техніки визначається вимогами до чистоти очищення технічних рідин, збільшення довговічності фільтрувальних елементів, можливостями сучасних нанотехнологій з урахуванням магнітних властивостей.

Проблематика. Впровадження наномагнітних складових на основі оксидів заліза може якісно змінити структуру і параметри пористих матеріалів, що використовуються у фільтрувальних пристроях. Технології зміни цих параметрів в умовах дії магнітного поля не існує.

Матеріали й методи. Використано пористі матеріали на основі пінополіуретанів, які насичуються наноскладовими оксидів двовалентного і тривалентного заліза. Застосовано експериментальні методи вимірювання магнітної індукції та пропускної спроможності пористого елемента, теоретичні методи визначення залежностей сил, що виникають у магнітному полі, а також рівняння гідродинаміки в каналах.

Результати. Пористі фільтрувальні матеріали, наповнені магнітними наноскладовими на основі суміші оксидів двовалентного і тривалентного заліза, в умовах дії магнітного поля змінюють свою структуру. Запропонована система управління параметрами фільтра, наповненого магнітними наноскладовими з електромагнітним контролем, дозволяє регулювати структурні характеристики фільтрувального пристрою. При зміні індукції магнітного поля з 0 до $0,2 \times 10^{-3}$ Тл зміна пропускної спроможності фільтрів підвищується в 1,7–1,9 рази при зміні середнього діаметру пор в 1,24–1,17 рази. Запропонований принцип дозволяє збільшувати пропускну спроможність фільтра при його забрудненні, а також регулювати розмір порожнин для утримання шкідливих компонентів заданого розміру.

Висновки. Дослідження довело реальну спроможність регулювати структурні параметри фільтрувальних пористих матеріалів з додаванням магнітних наноскладових. Електромагнітне керування дозволяє створювати задану пропускну спроможність фільтрувальних елементів.

Ключові слова: очищення рідин, наноматеріали, пористість, фільтрувальні елементи.