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MAGNETOPHORETIC MOTION OF MICRON-SIZED MAGNETIC PARTICLES IN THE WORKING GAP OF A MAGNETIC FLUID SEAL

The operational experience of bearing units in technological equipment has been analysed. The use of magnetic fluid seals to enhance the reliability and failure-free operation of equipment has been justified. A method for expanding the application range of seals by adding micron-sized magnetic particles to the working magnetic fluid, in accordance with Ukrainian Patent No. 106420, has been proposed. The distribution of magnetic induction in the active zone of the seal with an increased gap (0.8 mm) has been calculated for two cases—with and without a defect on the shaft surface. A regime where micron-sized magnetic particles are additionally introduced into the working magnetic fluid has been considered. The non-uniform distribution of the field and the vector quantity of the magnetic force acting on microscopic particles in the magnetic fluid has been demonstrated. The distribution of the velocity of these particles under the influence of this force in the active zone of the seal, both with and without a defect on the shaft, has been obtained through calculations. It has been shown that these particles concentrate in areas with non-uniform fields—in the angular zones of the teeth of the magnetic system and near the defect on the shaft. The characteristic transition time for particles with diameters of dp = 0.1; 1 and 10 µm is 630, 6.3, and 0.063 minutes, respectively.

1. INTRODUCTION

The safe operation of technological equipment in industrial enterprises is primarily determined by its accident-free performance and reliability [1, 2]. Statistical data indicate that for many types of equipment (electric motors, reduction drives, pumps, fans, etc.), the failure rate is most often determined by the reliability of bearing assemblies. According to literature data, up to 90% of emergency bearing unit failures are directly or indirectly caused by

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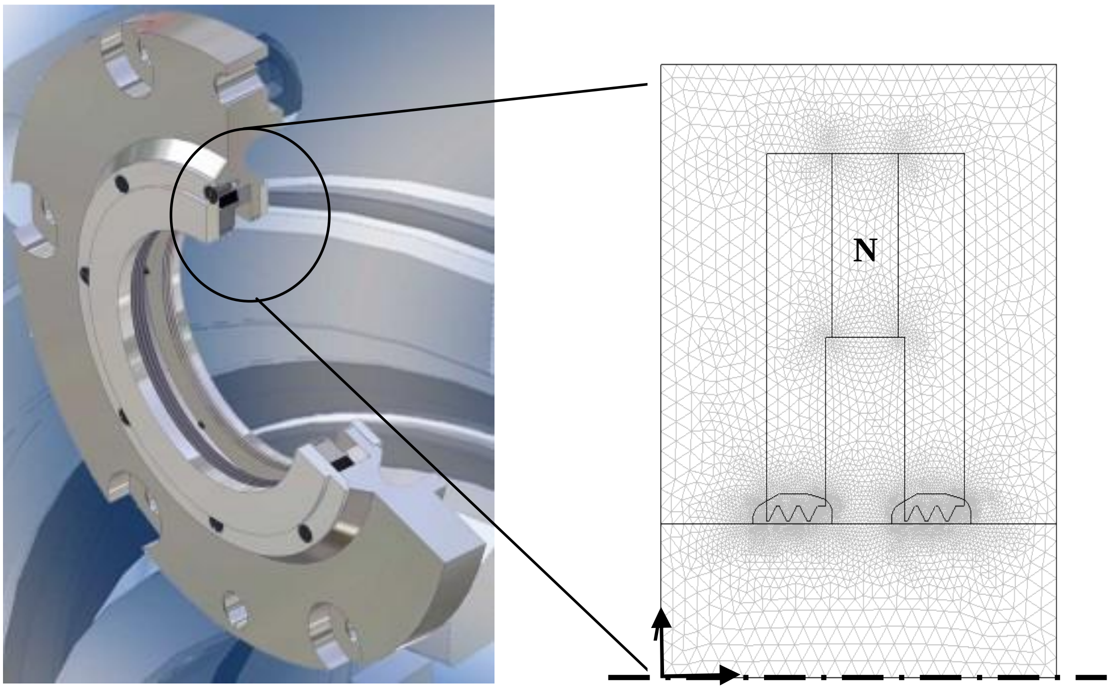
unsatisfactory seal performance [3]. Most bearings fail due to contamination from the surrounding environment [4]. Operational experience with bearing units shows that a significant amount of dust, foreign particles (including abrasive and aggressive ones), moisture, water mist, etc., penetrate them, leading to premature wear and subsequent destruction of the bearing itself, and then the entire unit as a whole [5]. The key requirement for seals is to ensure complete hermeticity. The application of known types of seals often does not solve the specified technical problems.

2. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Magnetic fluid seals (MFS) for rotating shafts surpass all known types of seals in terms of hermeticity and represent a new independent class of technical devices with permanent magnets that use magnetic fluid [6, 7]. The principle of MFS operation is based on the interaction of the magnetic fluid with the magnetic field of the seal's magnetic system, which ensures sealing of the internal area of the device relative to the external area in the presence of a rotating shaft. A typical design of a cylindrical MFS is shown in Fig. 1 and contains a magnetic system with a permanent magnet magnetized in the axial direction. Inside the magnetic system is a rotating shaft (not shown in Fig. 1a), and in the gap under the poles, which have a toothed structure to obtain a sharply inhomogeneous magnetic field, there is a magnetic fluid retained by magnetic forces, ensuring sealing of the internal medium at a certain pressure differential in the axial direction. The gap size is usually 0.20–0.25 mm.



a) b)

Fig. 1. General view of a typical seal design. a) – computational domain of the active zone of the MFS; b) – finite element mesh

At the same time, analysis of operating conditions and the state of technological installations shows that, in practice, this parameter should be increased to at least 0.5–0.8 mm. This is due to the wear of equipment, for which shaft runout and misalignment values significantly increase, as well as the harsh operating conditions and large shaft diameters of applied technical devices (for example, for double-row spherical roller bearings with a diameter of 200–225 mm, the gap size is 0.22–0.29 mm, which already exceeds the optimal working gap in MFS) [8].

The main difficulty in experimental research on the interrelated magnetic, hydrodynamic, electrical, mechanical, and thermal processes in MFS is due to the small size of the working gap, which significantly complicates or makes many physical measurements impossible.

Studying the fundamental patterns of magnetic field distribution and the nature of magnetic fluid flow in the active zone of the seal is an important scientific and practical task aimed at creating new MFS designs with extremely high characteristics. When solving this problem, it is advisable to use modern computer modelling methods along with physical modelling methods.

Computer modelling presents an alternative and, in many cases, the only possible research method, which can successfully complement and, in some cases, replace labor-intensive and expensive scientific experiments. Numerical experiments make it possible to obtain new results that outpace experimental results and provide a diverse and multifaceted understanding of the studied object [9,10].

In recent years, many mathematical studies of MFS have been conducted. Most studies are limited to calculating the distribution of magnetic field lines [11,12]. This approach does not account for most hydrodynamic processes occurring in the MFS gap but allows optimization of the seal's magnetic system using the maximum magnetic induction gradient in the working gap as a criterion [13].

The only way to obtain a complete understanding of the multitude of interacting physical processes in MFS is multiphysics numerical modelling.

Currently, few works have been conducted in this direction. The general approach to solving weakly coupled multiphysics modelling problems is similar across different authors [14–16]. The boundaries of the magnetic fluid in the seal gap are defined based on the equal induction lines obtained from numerical calculations of the magnetic field. Then, using the finite element method, hydrodynamic processes in this fluid volume are studied during shaft rotation.

The operation of magnetic fluid seals with increased working gaps leads to a sharp decrease in the magnetic field induction in the gap.

To compensate for the negative influence of this factor, and considering the presence of shaft defects (such as eccentricity) or surface defects (cavities or pits), micron-sized magnetic particles can be added to the magnetic fluid in the seal gap [17].

In fact, this results in a magnetorheological fluid without the need to ensure its stability. It is known that strong rheological effects are observed over a wide range of shear rates, and these suspensions are unstable to particle sedimentation. The thermodynamically unstable fractions are primarily composed of micron-sized particles. These particles can also aggregate into clusters [18, 19].

A magnetic powder with micron-sized particles in the magnetic fluid will settle in areas of the strongest magnetic field, i.e., at the peaks of annular teeth and valleys between them, occupying part of the working gap and reducing its size. At the same time, due to their higher magnetic permeability compared to the magnetic fluid, ferromagnetic micron-sized particles will further increase induction in the working gap.

The goal of this work is computer multiphysics modelling and investigation of the spatial distribution in the active region of a rotating shaft seal of the magnetic field, magnetic forces acting on micron-sized magnetic particles, as well as the velocity of magnetophoretic motion of particles under the action of these forces. In this work, the numerical finite element method implemented in the Comsol software package [20] is used.

3. CALCULATION OF THE MAGNETIC FIELD IN THE ACTIVE ZONE OF THE SEAL

The studied seal is characterized by axial symmetry, hence the field problem can be solved in a two-dimensional formulation in a cylindrical coordinate system in the plane $r0z$. The computational domain for the analysis of the magnetic field is shown in Fig. 1 b and contains regions with three types of magnetic materials: permanent magnets magnetized in the axial direction, ferromagnetic material of the poles of the magnetic system and the rotating shaft, as well as the region occupied by the magnetic fluid. The magnetization characteristics of these materials will be discussed later.

The field problem is considered as magnetostatic and is solved in an axisymmetric formulation in a cylindrical coordinate system in the $r0z$ plane for the vector magnetic potential A, which has a single φ -component, i.e.,$A = (0, A_0, 0)$.
From the system of Maxwell's differential equations for a stationary magnetic field

$$\nabla \times H = 0, B = \nabla \times A, \nabla \cdot A = 0 \tag{1}$$

and the equation of state of the magnetic material, written in the general case as

$$B = \mu_0 \mu_r H + B_r \tag{2}$$

we obtain the following differential equation for the vector potential

$$\nabla \times [(\mu_0 \mu_r)^{-1} \nabla \times A - (\mu_0 \mu_r)^{-1} B_r] = 0 \tag{3}$$

Here H is the magnetic field strength, B is the magnetic induction, B_r is the residual induction characterizing the permanent magnet and specified in the region occupied by this magnet, μ_0 is the magnetic permeability of vacuum, $\mu_r(|B|)$ is the relative value of magnetic permeability (scalar quantity) for the magnetic material, depending on the modulus of the magnetic induction vector.

The permanent magnet of the magnetic fluid seal is made of NdFeB material grade 38SH, characterized by a residual induction of $B_r = 1.26\ T$ and a coercive force of $H_s =$

950 kA/m. Hence, for the equation of state of the magnet from expression (2) after substituting these values, we obtain for the region of the permanent magnet $\mu_r = 1.06$.

For the magnetic fluid in a magnetic field $H > 200\ kA/m$, the magnetic permeability was taken as $\mu_r = 2$ The magnetic material of the poles of the magnetic system and the rotating shaft was characterized by a nonlinear magnetization curve taken from the Comsol software package database.

As boundary conditions, the symmetry condition on the axis of rotation of the shaft and the magnetic insulation condition $B \cdot n = 0$ on the side and upper surfaces were used. For the numerical solution of the partial differential equation (3) with the specified boundary conditions, the finite element method implemented in the Comsol software package was used.

4. CALCULATION OF THE MAGNITUDE OF THE MAGNETIC FORCE ACTING ON MAGNETIC PARTICLES

Consider a magnetic suspension diluted to such an extent that the magnetic particles in it can be considered non-interacting with each other. In a non-uniform constant magnetic field B_0 , each magnetic particle with a magnetic moment m is acted upon by a magnetic force determined based on the following expression [21]:

$$F_m = (m \cdot \nabla)B_0 \tag{4}$$

The calculation of the magnitude of the magnetic moment m depends on the type of magnetic particles—whether they are multi-domain or single-domain. The micron-sized particles considered in this article, made of carbonyl iron, are multi-domain, and their magnetic moment is equal to $m = V_p M$, where V_p is the particle volume; M is the magnetization of the particle material. For a spherical particle, the material of which is characterized by a relative value of magnetic permeability μ_r, the magnitude of magnetization is calculated as [18]

$$M = \frac{3(\mu_r - 1)B_0}{\mu_r + 2\mu_0} \tag{5}$$

Taking this equality into account, the expression for the magnetic force (5) can be written as

$$F_m = \frac{3(\mu_r - 1)}{\mu_r + 2} V_p \nabla \frac{|B_0|^2}{2\mu_0} \tag{6}$$

5. MAGNETIC FORCE FUNCTION

Expression (6) for the magnetic force acting on particles in a non-uniform magnetic field can be transformed into the form

$$F_m = \frac{3(\mu_r - 1)}{\mu_r + 2} V_p G_B \tag{7}$$

Where:

$$G_B = \nabla \frac{|B_0|^2}{2\mu_0} \tag{8}$$

Here G_B is a vector quantity depending on the spatial position of the field point and determining the degree of non-uniformity of the magnetic field. Let's call it the magnetic force function of the magnetic field [22].

The magnetic force function G_B can be considered as a characteristic of the magnetic system (seal) creating a non-uniform magnetic field in its active zone. Knowing the value and direction of the vector function G_B at each point, using expression (8), the magnitude of the magnetic force acting on the magnetic particles can be calculated.

When analysing the velocity of particle motion, the following assumptions are used: 1) the particles have a spherical shape and 2) the motion of the particles occurs in a steady-state regime under the action of only magnetic forces $F_m$distributed in space. In this case, the motion of the particles obeys Stokes' law, and the magnitude of their velocity can be determined from the following expression [23]:

$$V = \mu_p F_m \tag{9}$$

Where $\mu_p = 1/(3\pi\eta d_p)$ is the mobility of the particle, η is the dynamic viscosity of the fluid, and d_p is the diameter of the spherical particle.

6. ANALYSIS OF CALCULATION RESULTS

The calculations were carried out with the following initial data: shaft diameter — 100 mm, seal gap—0.8 mm, diameter of magnetic particles added to the working magnetic fluid, $d_p = 0.1\mu m\ 1\mu m\ \ 10\mu m$, $\eta = 43{,}3 Pa \cdot s$, magnetic permeability of particles $\mu_r = 100$, magnetic permeability of the magnetic fluid was taken as $\mu = 2$. The calculations were performed for two cases—in the absence and presence of a defect on the shaft surface.

The distribution of magnetic field lines (isolines $A\varphi r$) and magnetic induction (in color) in the active zone of the seal is shown in Fig. 2a. Fig. 2 also shows the distribution of the value $|B_0|^2/(2\mu_0)$ (Fig. 2b) and the vector of the force function G_B (Fig. 2c) in the absence of a defect on the shaft.

As can be seen from these figures, the presence of a tooth structure on the surface of the poles creates a sharply non-uniform field and, accordingly, a force distribution in the active zone.

As a defect on the shaft, a groove of size 0.5×0.5 mm was specified, located on the entire surface of the shaft. The distribution of the magnetic field and magnetic force in the presence of such a defect is shown in Fig. 3. It can be seen that near the defect, the magnetic field is non-uniform, which leads to the emergence of a magnetic force F_m acting on the microparticles.

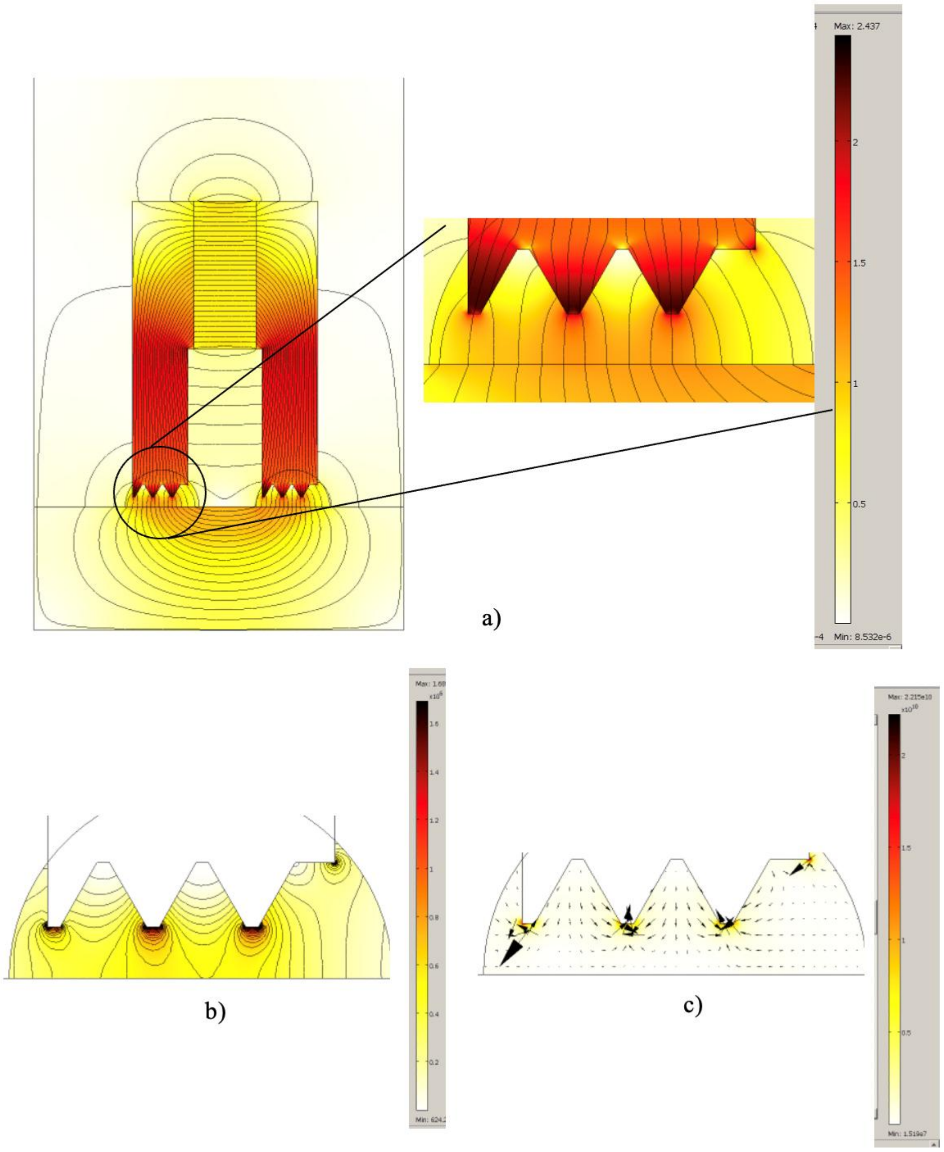


Fig. 2. Distribution of fields in the active zone of the seal in the absence of a defect on the shaft.
a) – distribution of the magnetic field;
b) – distribution of the value $|B_0|^2/(2\mu_0)$;
c) – distribution of the vector of the magnetic force function.

Figure 4 shows the distribution of the velocity of motion of microscopic particles of various sizes in the active zone of the seal without a defect on the shaft, and Fig. 5—in the presence of a defect. From the analysis of these data, it can be concluded that after some characteristic time of the transient process, the particles will concentrate in regions with sharply non-uniform magnetic fields, i.e., they will concentrate in the angular zones of the teeth of the magnetic circuit and in the zone of the defect.

To estimate the magnitude of this characteristic time, we will use the concept of the average particle velocity $\langle V \rangle$ —the average value of the velocity modulus (8) over the region of the magnetic fluid. In this case, the estimated value of the characteristic time of the transient process will be $\tau = \delta / \langle V \rangle$, where $\delta = 0.8$ mm is the gap size.

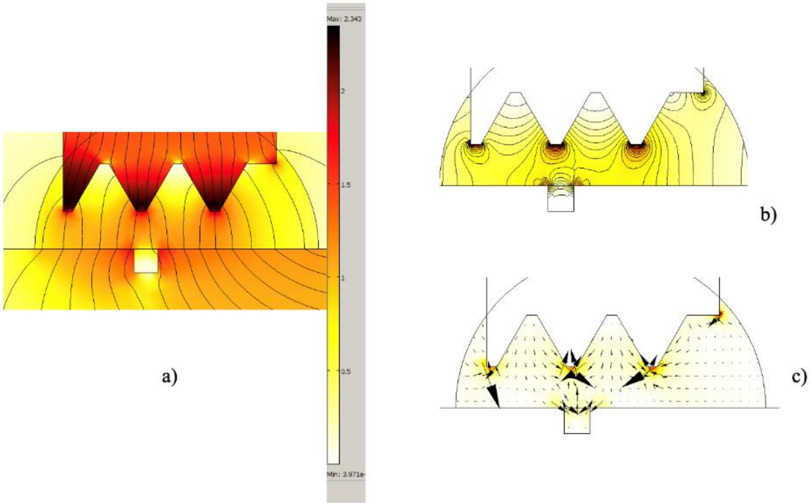


Fig. 3. Distribution of fields in the active zone of the seal with a defect on the shaft.
a) – distribution of the magnetic field;
b) – distribution of the value $|B_0|^2/(2\mu_0)$;
c) – distribution of the vector of the magnetic force function.

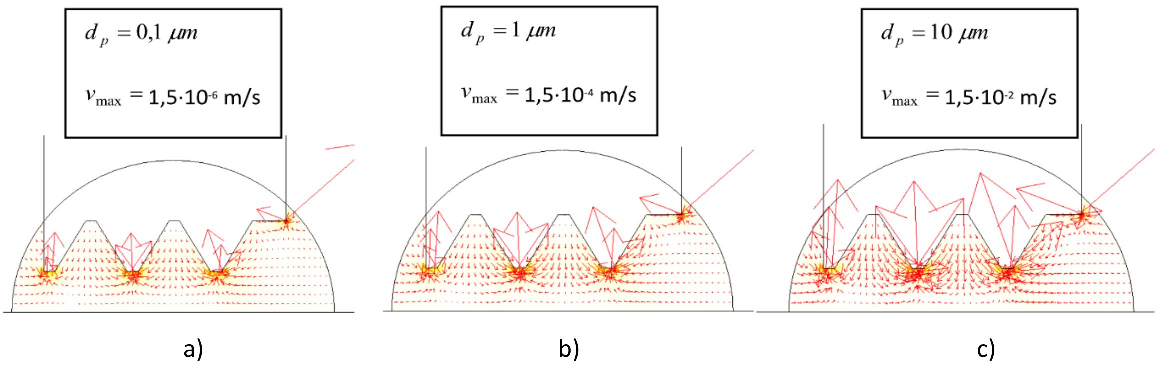


Fig. 4. Distribution in the active zone of the seal of the velocity vector of magnetic particles of different diameters: a) d_p= 0.1 µm; b) d_p = 1 µm; c) d_p = 10 µm.

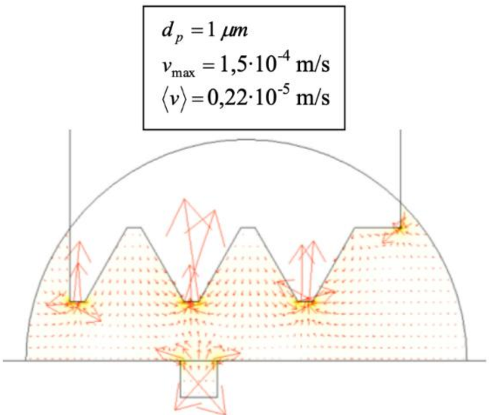


Fig. 5. Distribution in the active zone of the seal of the velocity vector of magnetic particles with a diameter of d_p = 1 µm in the presence of a defect on the shaft.

For particles of different diameters $d_p = 0.1\mu m, 1\mu m\ and\ 10\mu m$, the value of this time will be $\tau = 630min; 6.3min; 0.063\ min$, respectively. Thus, particles of size 1 µm will be localized in the non-uniformity zones shown in Fig. 2 and 3 in approximately 1 minute. This result has been experimentally confirmed [24].

7. CONCLUSION

A finite element calculation of the magnetic induction distribution in the active zone of a seal with an increased gap (0.8 mm) was performed using Comsol software for two cases: 1) when the rotating shaft is smooth and 2) when the shaft has a defect. For the first time, the regime in which additional micron-sized magnetic particles are introduced into the working magnetic fluid was analytically examined, in accordance with Ukrainian Patent No. 106420. The distribution of zones characterized by maximum local inhomogeneity of this field, determining the magnitude and direction of magnetic force acting on microscopic particles in the magnetic fluid, was shown.

The calculated distribution of magnetic force acting on microparticles of various diameters (0.1–10 µm) and the velocity of these particles under this force were obtained. It was shown that these particles concentrate in zones with inhomogeneous fields—at the angular zones of the magnetic system teeth and near the shaft defect, with the characteristic transition time for particles of $d_p = 0.1; 1\ and\ 10\ \mu m$ being 630, 6.3, and 0.063 minutes, respectively. The addition of micron-sized particles to the working gap of the seal allows for an increase of up to three times in the gap size while maintaining operational reliability.

The performed calculation demonstrated the feasibility of applying the technology according to Ukrainian Patent No. 106420. The implementation of MFS with increased gaps in technological equipment proved the adequacy of the developed mathematical model.

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