Investigation of the orientation of floccules in magnetic sump during cleaning of cooling lubricants

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Abstract. The article deals with the problem of cleaning cooling lubricants involved in technological processes of parts machining. As a result of cutting, drilling, grinding, cooling lubricants are contaminated with extraneous impurities. The most dangerous for the quality of products and equipment are magnetic particles of various sizes. One of the cleaning methods is a magnetic sump, which will reduce the mass-dimensional parameters of the system on retention of a high degree of purification. An analysis of existing designs is made and it is shown how the configuration of the magnetic field affects the kinetics of the motion of impurities in cooling lubricants. Experimental dependencies of the deposition rate for different orientations of floccules formed as a result of the effect of a magnetic field on particles are found. The coefficient of drag of the floccules is found from the number of particles. It is proved that the use of only the shape factor and the equivalent diameter is not enough for calculations.

1. Introduction
When cutting, extruding, rolling, stamping, drilling parts, etc. cooling lubricants are often used, which divert heat from the working tool and the workpiece and lubricate the rubbing parts. In general, the use of cooling lubricants allows increasing the intensity of technological processes, labor productivity, and equipment productivity, and improving the quality of products. During operation, the cooling lubricants are contaminated with swarf, hard dust, extraneous oils or microorganisms. Pollution leads not only to a decrease in the efficiency and quality of materials processing and, accordingly, to frequent replacement, but also cause equipment breakdown.

2. Objectives of work
There are various ways to clean viscous media from extraneous impurities: settling tanks, sumps, hydro cyclones, separators. Sumps designed for cleaning cooling lubricants from mechanical impurities have found wide application in various sectors of the national economy due to the simplicity of the designs and their operation, reliability of work, and low material and energy costs. They are most often used as the first stage of purification from large extraneous impurities [1-3]. Due to the fact that particles possessing electrical properties are often contained in impurities, electric fields are used to improve the efficiency of purification [2]. Despite the fact that these devices have been used for a long time, many theoretical and experimental questions related to the use of electric fields have not been investigated so far. The objective of the work is to analyze the effect of the
magnetic field for reducing the size of the sumps as a consequence of increasing the extraction efficiency of magnetic impurities and the effect of floccules’ orientation on the deposition process.

3. Information analysis of researches and publications
The use of a magnetic field for the purification of cooling lubricants is most effective when the amount of magnetic particles allows them to be forced into coagulation. The main force effecting the particles in the sump is gravitational. Except it, in the presence of a field, magnetic attractions and coagulations affect the particles [1]:

\[ F_M = \mu_0 \chi V H \text{grad} H \]  

(1)

where \( \mu_0 = \text{const} = 4\pi \times 10^{-7} \) - magnetic constant, H/m; \( \chi \) - magnetic susceptibility; \( V \) - volume of the particle, m\(^3\); \( H, \text{grad} H \) - the intensity of the magnetic field and its gradient, A/m and A/m\(^2\), respectively.

However, magnetic forces not only attract magnetic particles to zones with the greatest field strength, but also serve to coagulate them. Under the effect of magnetic (Coulomb) forces, the particles grow, forming floccules of an acicular structure:

\[ F_F = \frac{4\pi M_1 M_2}{\mu_0 \mu r^2} \]  

(2)

where \( M_1, M_2 \) - the "magnetic masses" of the particles, m\(^2\) kg/s\(^2\) A; \( \mu \) - the magnetic permeability of the medium in which the particles are located; \( r \) - the distance between the particles, m.

4. Theoretical part
The magnetic field inside the working chamber increases not only the cleaning efficiency, but also reduces the mass-dimensional parameters, because the coagulated particles have a greater weight, and accordingly, they need less time to sediment. Thus, the volume of the sump and the residence time of the cooling lubricants in it decrease [4]. In figure 1, two sumps are shown: one is ordinary; the other is with a magnetic field source located at the bottom of the working chamber.

As we can see, the particles are attracted to the pole (areas with the greatest intensity), thereby reducing the distance that requires deposition to the bottom of the sump. The other two particles coagulated, which significantly reduced the distance traveled by the particle. Summarizing these two factors, we can say that the use of a magnetic field in a continuous flow sump reduces its length by \( \Delta L \) while maintaining the degree of purification.
There are many designs of magnetic sumps [4-6], but three basic ones can be distinguished, shown in figure 2.

![Diagram of magnetic sump designs](image)

**Figure 2.** Basic designs of magnetic sumps: 
a) sump with electromagnetic coagulator; b) sedimentation tank-coagulator; c) precipitation tank (1 – working chamber, 2 – slurry, 3 – screw for discharge of sludge, 4 – electromagnetic coagulator, 5 – coil, 6 – baffle, 7 – ferromagnetic core)

The first type uses magnetic fields for precoagulation of the particles at the inlet. The coagulated particles are deposited under gravity to the bottom, where they are removed from the working chamber by means of various devices (in this case by means of a screw). This design is characterized by a minimum consumption of electricity, but at the same time, it has defects. The main disadvantage of a sump with an electromagnetic coagulator is that the destruction of the floccule can occur in the working chamber or under the effect of the mixing of the liquid, or in the case where the mechanical impurities belong to soft magnetic materials.

The second type differs from the previous one in that coagulation of the particles does not take place at the inlet, but in the working chamber, thereby preventing the floccules from particle decay. In addition, the coil is wound in such a way that the strength of the magnetic field increases with the approach to the bottom of the sump. Thereby not only gravity, but also magnetic force will effect on the particle. Baffle serves to ensure that the flow of cooling lubricant passes through the entire working chamber; otherwise the effect of the magnetic field on the mechanical impurities will be minimal. The disadvantages of this type of sumps are that large material and energy costs for the electromagnetic system. So this type is used extremely rarely, despite the high degree of purification.

The process of particle coagulation in a magnetic precipitation tank takes place directly in the working chamber. The coagulated particles settle at the poles of the electromagnetic system under the effect of gravity and magnetic forces. Advantage of a precipitation tank is that it also captures soft magnetic impurities. This type of magnetic sumps has become the most widespread because it provides high purification efficiency at relatively low material and energy costs. However, this design of magnetic sumps does not have a convenient slurry collector and discharge of slurry can be made either through the lid of the collector or through the sidewall.

Magnetic sumps often have baffles and non-magnetic nozzles [1, 7, 8] in order to let the entire contaminated stream pass by a magnetic field with high strength.

Calculation of pre coagulation units is rather complicated, the formed floccules have an unequal number of particles, and therefore the application of the Stoke’s law, which is used in calculating the process of gravity separation (clarification), is incorrect, since it is applicable only to spherical particles [9]. A similar situation exists in the calculation of other magnetic clarifiers, so we have to
use the criteria for performance evaluation of the magnetic field on the process of purifying of technical fluids, among which a special place is occupied by the cooling lubricants [10].

A formula for clarifying liquids in clarifiers, in which there are mechanical impurities (for the Stoke’s law application) is well-known.

\[
\frac{dn}{dt} = \frac{nU_0}{h}
\]

(3)

for \( \tau(0)=0, n(0)=n_0, h=\text{const}, U_0=\text{const} \),

where \( n_0, n \) - initial and current value of particles in a clarifier, units; \( h \) – height of clarifier, m; \( U_0 \) - the particle deposition rate, m/s.

In the case of high polydispersity of particles, \( U_0 \) is calculated for each fraction (for each particle size) separately. Thus, additional theoretical and experimental studies are necessary to determine the velocity of floccules formed under the effect of a magnetic field.

5. Experimental technique

The results of an experimental study of the deposition of floccules, which were formed after the effect of a magnetic field on magnetic particles are given below. The scheme of experimental unit and the results of the research are shown in figure 3.

![Experimental unit](image)

**Figure 3.** a) the scheme of unit for research of the hydraulic resistance to the motion of particles for different orientations in a viscous medium; b) the dependence of the rate of deposition of floccules with horizontal and vertical orientation.

Experimental conditions: spherical particles (\( d=1 \text{mm} \)), medium-glycerin, permanent magnet for orientation of floccules during deposition, thermometer, stopwatch. The motion of single, double, built particles, etc. has been monitored. The permanent magnet moved simultaneously with the deposition of bodies at a distance of 150 mm from the flask, so the magnetic field had no effect on the horizontal and vertical movement of the particles. Their deposition passed only under the gravity. Each body was deposited repeatedly (from 7 to 12 times) in horizontal and vertical positions.

6. Results and discussion

Analysis of the experiment showed that the difference in precipitation rates increases with the increase in the number of particles in the floccule. A further increase in the number of particles leads to a stabilization of the difference, which is quite understandable physically due to the equalization of the drag coefficient.

The gravity was counteracted by the medium's resistance force, which is calculated by the following formula [11]:

\[
F = \frac{1}{2} \rho C_D Av^2
\]
\[ F_d = \lambda S \rho \frac{U^2}{2} \quad (4) \]

where \( \lambda \) - the coefficient of medium resistance; \( S \) – the cross section of the particle, \( m^2 \); \( \rho \) – the density of the medium, \( kg/m^3 \); \( U \) – the velocity of the particle, \( m/s \).

The resistance force of the medium for particles of spherical shape is calculated by the Stoke’s formula [12]:

\[ F_d = 3\pi \eta d U \quad (5) \]

where \( \eta \) – the dynamic viscosity of the medium, \( Pa\cdot s \); \( d \) – the diameter of the spherical particle, \( m \).

Despite the fact that the equivalent diameter and the shape factor of the floccule for different orientations are the same, the deposition rates differ from each other, so bringing the particles to an equivalent sphere and finding the shape factor is meaningless.

The specified numerical values of speed and deposition depending on the number of particles in the floccule - vertically oriented particles deposit faster than horizontally oriented ones.

Based on formula (4), the highest deposition rate should be observed with a vertical orientation of particle, because the cross section of the floccule will be minimal (see table 1). However, the resistance of the medium to the lateral surface of the floccule is not taken into account (this is especially noticeable in the vertically oriented particle). This makes the prediction of the deposition rate from the cross section incorrect. Experimental data confirm fully the last statement.

**Table 1.** The values of the cross section of the floccule with its different orientations and equivalent diameter

| Orientation | Value       |
|-------------|-------------|
| Vertical    | \( \pi d^2/4 \) |
| Horizontal  | \( n\pi d^2/4 \) |
| Equivalent diameter | \( n\pi^{2/3}d^2/4 \) |

where \( d \) – the diameter of one particle in the floccule, \( m \); \( n \) – the number of particles in the floccule, unit.

Let’s represent the results in the form of a sign model, finding it by the rate of deposition of the floccules \( U_F \):

\[ U_F = U_0 f (n_F) \quad (6) \]

where \( U_0 \) – the deposition rate of a particle of spherical shape, \( m/s \); \( n_F \) – the number of particles in the floccule, units

\[ n_F = l_F / d_F \quad (7) \]

where \( l_F, d_F \) – length and diameter of the floccule, respectively, \( m \); \( f(n_F) \) – the functional dependency, which is found from the experiment.

\[ U_{FV} = U_0 \left( 0.455 \cdot \exp(-0.263 \cdot n_F) + 0.644 \right) \quad (8) \]

\[ U_{FG} = U_0 \left( 0.782 \cdot \exp(-0.389 \cdot n_F) + 0.462 \right) \quad (9) \]

Coefficient of determination \( (R^2) \) for the deposition rate of floccules with horizontal orientation is 0.996, with vertical one - 0.998.

Let’s represent the results in the form of a sign model, having found it in terms of the coefficient of aerodynamic resistance \( \lambda_F \):

\[ \lambda_F = \lambda_0 f (n_F) \quad (10) \]

Generally, it can be found on the basis of the equation of the resistance and gravitational forces:

\[ \lambda_F = \frac{2Mg}{SU^2} \quad (11) \]

where \( M = m_i \cdot n_F \) – mass of floccule, \( kg \).
For vertical orientation, the dependency will be as follows:

$$\lambda_{F} = \lambda_{0} \cdot (2.227 \cdot \exp(-0.952 \cdot n_{F}) + 0.139)$$  \hspace{1cm} (12)

Coefficient of determination ($R^2$) for the coefficient of aerodynamic resistance is 0.998. Graphically, the dependency is shown in figure 4. The values of $\lambda_{F}$ for a horizontal orientation will be independent of the number of particles in the floccule.

![Figure 4. Dependency $\lambda = f(n_{F}) = f(l_{F} / d_{F})$ with the vertical orientation of particles.](image-url)

It is advisable to use the results in engineering practice for the calculation of magnetic sumps and for mathematical modeling of the kinematics of magnetic coagulation processes and particle deposition.

7. Conclusion
The article deals with the problem of cleaning cooling lubricants from magnetic impurities in magnetic sumps. The analysis of existing designs is made and the basic design versions of purifying devices of gravitational type are represented. Experimental dependencies of the deposition rate and the drag coefficient on the number of particles in the floccule are found. It is proved that the use of only the shape factor and the equivalent diameter is not enough for calculations. The results are recommended to be used in the calculation of magnetic sumps.

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