Simulation of graphene-containing viscous fluid motion in the gap between static and rotating discs

V Pershin1, Z Alhilo2, A Baranov1, N Memetov1 and E Tugolukov1

1Department of Technique and Technology of Production of Nanoproducts, Tambov State Technical University, 1 Leningradskaya Street, Tambov 392000, Russian Federation
2University of Kufa, Kufa, P.O. Box (21), Najaf Governorate, Iraq

E-mail: pershin.home@mail.ru

Abstract. The motion of a graph-containing viscous fluid between stationary and rotating disks is considered. The initial differential equations of motion for the elementary volume of a liquid are compiled and the initial conditions are determined. Assuming that the flow in the gap is a Couette flow, an analytical solution has been obtained to change the radial and angular coordinates of the elementary volume with time. With the use of the mathematical package Maple, characteristic trajectories of the movement of elementary volumes of fluid in the gap between a fixed and rotating disk with different consumption characteristics and geometry are obtained. Calculated speed, time of stay and the path traveled by an elementary volume, depending on the initial coordinate of the thickness of the gap.

1. Introduction
Since the first mechanical device, lubrication has been an important element for moving parts used in machines, mechanical tools and vehicles. The main functional purpose of lubricants is to reduce the coefficient of friction between surfaces moving relative to each other and to reduce their wear [1].

Greases consist of a liquid base (dispersion medium), a solid thickener (dispersed phase) and various additives or additives. To improve performance, additives of various functional purposes and solid additives are added to the composition of lubricants.

Thus, lubricants are complex multi-component systems, the main properties of which are determined by the properties of the dispersion medium, the dispersed phase, additives and additives. As a dispersion medium of lubricants, various lubricating oils and liquids are used. Initially, nanomaterials, in particular graphite, were used only as dry lubricants in very harsh operating conditions of friction pairs.

In recent years, numerous studies have shown that it is possible to control the size, shape and surface properties of nanoparticles; therefore, nanoparticles in colloidal systems offer great opportunities in controlling the properties of plastic lubricants [2-5]. The addition of nanoparticles to lubricating oils and greases significantly reduces interfacial friction and increases the load-carrying capacity of parts, which is considered a great potential as lubricating additives [6-9]. In our opinion, when creating plastic and environmentally friendly lubricants, graphite derivatives such as graphene and graphene are very promising materials. This assumption is based on the fact that the addition of 0.1 mass.% graphene in greases “Solidol-Zh” and “Litol-24” reduce the coefficient of sliding friction by 1.5-2 times, reduce the diameter of the wear spot by 50%, increase the bulky index by almost
2.9 times, and the carrying capacity by 3.8 times [10, 11]. One of the main problems of modifying plastic greases with graphene is the uniform distribution of graphene particles throughout the lubricant. Disk devices using the energy of shear deformations in the gap between the rotating and fixed disk have broad prospects for dispersing and homogenizing nanoparticles in a liquid base.

Therefore, this paper addresses the issue of modeling the movement of a viscous graphene-containing fluid in a small gap between fixed and rotating disks. The solution to this problem is necessary for the transition from laboratory to industrial installations.

2. Simulation object and problem statement

The object of the simulation is an installation for the homogenization of a grease modified with few layer or multilayer graphene. The installation consists of a cylindrical body with a flat bottom, inside which the disk is coaxially located. The rotation of the disk is driven by an adjustable speed drive. In the center of the bottom there is a branch pipe, into which a plastic grease, previously mixed with graphene, is fed under pressure. During processing, the lubricant passes in the gap between the bottom (fixed disk) and the rotating disk. As the moving speed varies along the height of the gap, practically, from zero, in close proximity to the bottom, to the peripheral speed of the disk, some lubricant layers shift relative to others, and the process of redistribution of graphene particles in the lubricant or homogenization takes place. When designing industrial plants, it is necessary to know the regime and geometrical parameters, which ensure not only the specified performance, but also the required quality of mixing or homogenization. These parameters can be calculated using a mathematical model of the mixing process, for which, first of all, it is necessary to know the parameters of the movement of elementary volumes in the gap between the fixed and rotating disks.

The formulation of the simulation problem can be formulated as follows: find the velocity distribution of a viscous fluid in a stationary mode in the gap between the fixed and rotating disks, as a function of three coordinates along the radius, polar angle and thickness of the gap.

The distribution of velocities allows not only to proceed to the modeling of the process of mixing graphene structures with a viscous base, but also to determine the geometrical and regime parameters of the installation to ensure the required motion regime.

3. Mathematical model of the process

In figure 1 shows a schematic diagram of the installation and a geometric interpretation of the movement of a viscous fluid in the gap between the disks.

![Geometric interpretation of movement in the gap between the disks](image)

**Figure 1.** Geometric interpretation of movement in the gap between the disks: front view with a cut (a), top view (b).

The radial velocity component from the flow equation for a radius \( r(\tau) \):

\[
\omega \cdot \frac{V}{2 \cdot \pi \cdot r(\tau) \cdot h},
\]

where \( V \) is the volumetric flow rate.

The tangential component of the velocity at a radius \( r(\tau) \) in the gap with the \( x \) coordinate (Figure 1):
$$w_i = \frac{\omega \cdot r(\tau) \cdot x}{h}. \quad (2)$$

Considering that

$$w_i = \frac{dr(\tau)}{d\tau} \quad (3)$$

and

$$w_i = r(\tau) \frac{d\varphi(\tau)}{d\tau} \quad (4)$$

to find the trajectory of an elementary volume, it is required to solve differential equations given in the following form:

$$\frac{dr(\tau)}{d\tau} = \frac{V}{2 \pi r(\tau) h}, \quad (5)$$

$$r(\tau) \frac{d\varphi(\tau)}{d\tau} = \frac{\omega \cdot r(\tau) \cdot x}{h}. \quad (6)$$

with the following initial conditions: $r(0)=r_0$, $\varphi(0)=\varphi_0$.

The solution is as follows:

$$r(\tau) = \frac{\sqrt{\pi \cdot h \cdot (V \cdot \tau + r_0^2 \cdot \pi \cdot h)}}{\pi \cdot h} \quad (7)$$

$$\varphi(\tau) = \varphi_0 + \frac{\omega \cdot x \cdot \tau}{h}. \quad (8)$$

Using solutions (7) and (8), it is easy to obtain characteristic trajectories of particles and elemental fluid volumes in the gap between the fixed and rotating disk with different flow characteristics and geometry. In addition, it is possible to calculate the residence time of the particle in the gap and the path traveled by the particle between the disks.

With the use of the mathematical package Maple, characteristic trajectories of the movement of elementary volumes of fluid in the gap between a fixed and rotating disk with different consumption characteristics and geometry are obtained. Calculated speed, time of stay and the path traveled by an elementary volume, depending on the initial coordinate of the thickness of the gap.

4. Results and discussion

Figure 2 shows the characteristic trajectories of the fluid elementary volume motion at different distances from a fixed disk.

The trajectory shown in figure 2a is calculated with the following parameters: $V = 0.1 \cdot 10^{-6} \text{ m}^3/\text{s}$; $\omega = 52.36 \text{ rad/s}$ (500 rpm); $R = 0.03 \text{ m}$; $r_0 = 0.005 \text{ m}$; $\varphi_0 = 0 \text{ rad}$; $h = 0.0001 \text{ m}$; $x = 0.00005 \text{ m}$.

When calculating the trajectory shown in figure 2b, one parameter $x = 0.000005 \text{ m}$ was changed. The length of the trajectory shown in figure 2a is equal 1.473 m, and on figure 3b – 0.52 m, with the same residence time between disks equal to 2.748 s.

The difference in the shapes and lengths of the presented trajectories confirm the presence of shear phenomena along the height of the gap. It is the shift of one elemental volume relative to another that ensures the redistribution of graphene structures over the volume of a viscous fluid.

Experimental studies in a laboratory setup with a disk diameter of 60 mm at speeds of rotation from 300 to 1500 rpm showed satisfactory convergence between the calculated and experimental values.
Figure 2. The trajectory of the fluid elementary volume motion between the disks, obtained using the mathematical package Maple.

Besides, the motion of a viscous fluid in a small gap between the fixed and rotating discs was simulated herein through the computational fluid dynamics method using the package FlowVision (TESIS, Russia). For this, a three-dimensional model describing the “fluid domain” was imported into the program. Besides, the parameters corresponding to figure 2 were set up. Using the laminar fluid model and setting the boundary conditions at the inlet and outlet \( V = 0.1 \times 10^{-6} \text{ m}^3/\text{s} \) and wall boundary condition on stationary and rotating wall (disks), the velocity and pressure fields were calculated, and the visualization of the elementary volume trajectories was performed. From figure 3, it is clear that the step between the loops decreases with increasing distance from the axis of the movable disk rotation, like in figure 2.

Figure 3. Trajectory of the fluid elementary volume motion between the disks obtained using the package FlowVision.

5. Conclusion

A mathematical model of the pressure motion of a graphene containing viscous fluid in the gap between the stationary and rotating discs has been developed. With the use of the mathematical
package Maple, characteristic trajectories of the movement of elementary volumes of fluid in the gap between a fixed and rotating disk with different consumption characteristics and geometry are obtained.

A similar view of the trajectories of the elementary volume motion was obtained by computational fluid dynamics using the package FlowVision (TESIS, Russia).

Calculated speed, time of stay and the path traveled by an elementary volume, depending on the initial coordinate of the thickness of the gap. The transition from a mathematical model to a computer model makes it possible to simulate changes in the viscosity of a fluid entering the gap between the disks, which are caused by changes in the concentrations of graphite in the initial suspension. Since these changes are probabilistic in nature, an analytical decision is impossible. Using a computer model allows you to simulate these changes.

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