Journal of Applied Mechanics and Technical Physics, Vol. 49, No. 4, pp. 610–613, 2008

MODELING OF THE HYDRODYNAMICS OF A FACILITY FOR REMOVING MECHANICAL IMPURITIES FROM OIL

I. Yu. Khasanov,[1] **I. A. Kaliev,**[2] **M. F. Mugafarov,**[3]
G. S. Sabitova,[2] **N. Kh. Faizullin,**[1] **and G. I. Khasanova**[2]

UDC 621.6.03

The separation of a viscous fluid flow by means of a device operating on the centrifugal principle was modeled. Parameters of the device with a specified separation size were obtained in a series of numerical experiments.

Key words: *viscous fluid flow, screw channel, finite-element method, device with a specified separation size.*

Introduction. The requirements on the quality of the composition of transported oil and oil products have become more and more stringent. Sand, clay, scale, rust, and other mechanical impurities present in flow considerably complicate the operation of technological equipment, resulting in its premature wear. Impurity can be localized in a certain region for the purpose of its subsequent removal due to the action of centrifugal forces, which requires flow swirling. As is known, swirling flows are used to activate heat and mass transfer and to remove impurities from gases and liquids. However, existing facilities operating on the centrifugal principle (separators, centrifuges, etc.) are power consuming and have a low through capacity. In this context, designing an effective commercial flow cleaning device is an important problem.

Formulation of the Problem. Descriptions of a device designed to separate various mechanical impurities from oil flow are given in [1–4]. In this device, the fluid flows in a channel formed by the turns of a fixed screw and an outer cylindrical surface. The action of centrifugal forces leads to flow separation with the solid particles displaced to the near-wall region, from which they are then removed. Unlike in screw conveyor and bowl centrifuges (see, for example, [5]) in this the device, the screw is fixed, which saves power and considerably increases the service life of the device.

A diagram of the screw device is shown in Fig. 1. In the settling section there are coaxially located cutting plates, which have dampers made of an elastic material and distributed along the screw surface. The plates are fixed rigidly on a mud tank. The tank is mounted on movable bearings and could slide in a guide and be removed from the device through the end gate. The plates are open at the bottom. There is a window for removal of mechanical impurities into the mud tank. The device operates as follows. The fluid flow to be cleaned passes through the inlet pipe and falls onto the screw turns. The swirling flow is subjected to separation in the field of centrifugal forces. Impurities enter the near-wall layer, which is then separated by the frontal ends of the plates of the settling section. The contaminated flow, being incident on the damper surface, moves along the plate surface down into the window and is collected in the mud tank. Once a blocking pressure is reached in the chamber, the device is switched-off and washed, after which it is ready for further operation.

The flow is described using the complete steady-state system of Navier–Stokes equations. Difference methods for solving the equations of hydrodynamics for simple flows are described in many papers (see, for example, [6]). However, the complex flow dynamics in screw channels has been studied insufficiently. Using certain assumptions

[1]Shéryk Research-and-Production Center, Salavat 453266; sherik@basnet.ru. [2]Sterlitamak State Pedagogical Academy, Sterlitamak 453103; kalievia@mail.ru; sabitovags@mail.ru. [3]Department of the Ufa State Aviation Technical University, Ishimbai 453200; Mugafarov_MF@mail.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 49, No. 4, pp. 108–112, July–August, 2008. Original article submitted June 28, 2007.

 0021-8944/08/4904-0610

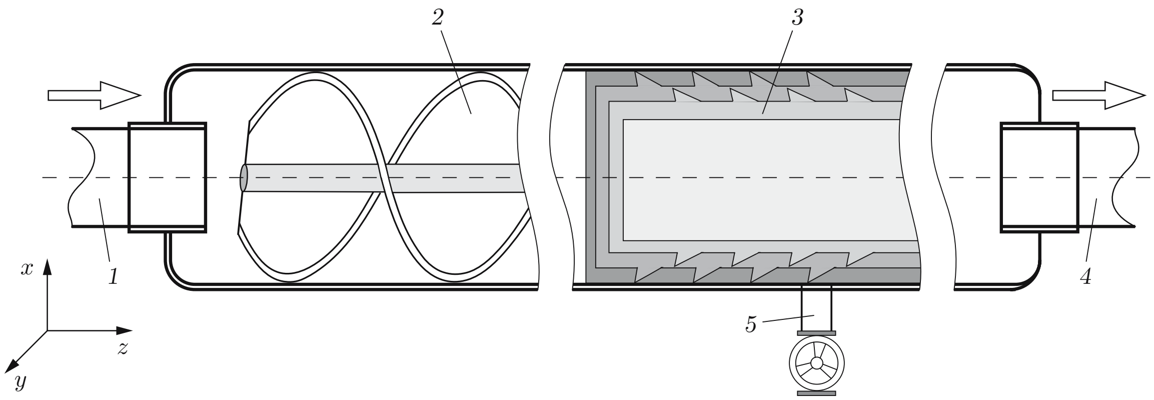

Fig. 1. Diagram of the screw devices: 1) inlet branch pipe; 2) screw; 3) settling section; 4) outlet pipe; 5) drain valve.

on the flow structure, Vainshtein et al. [7] and Shkoropad [8] obtained approximate solutions of the problem that describe flow properties. Fainerman [9] obtained expressions for the flow velocity and the pressure distribution in the form of series in modified Bessel and Hankel functions for the case of negligibly small circulation.

We introduce three-dimensional Cartesian coordinates, with the filter axis coincident with the Oz axis, and the coordinate origin at the frontal edge of the screw. To describe the flow, we represent the system of steady-state Navier–Stokes equations and the continuity equation in vector form

$$-\nabla\cdot[\mu(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{\mathrm{t}})]+\rho_l(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}+\nabla p=\boldsymbol{F},$$

$$\nabla\cdot\boldsymbol{u}=0.$$

Here $\boldsymbol{u}=(u,v,w)$ is the velocity vector, p is the pressure, ρ_l is the fluid density, μ is the dynamic viscosity of the fluid, $\boldsymbol{F}$ is the gravity, and $\nabla=(\partial/\partial x,\partial/\partial y,\partial/\partial z)$ is the Hamiltonian.

In the initial cross section $z=z_0$, we specify the velocity $\boldsymbol{u}_0=(u_0,v_0,w_0)$ in the form of a Poiseuille profile:

$$u_0=0,\qquad v_0=0,\qquad w_0=u_{\max}(1-(x^2+y^2)/R^2).$$

According to the Stokes law, the total stress tensor T can be expressed in terms of the strain rate tensor:

$$T=-pI+\mu(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{\mathrm{t}})$$

(I the unit matrix). At the outlet section $z=z_{\max}$, we specify the stress tensor on the outward normal vectors $\boldsymbol{n}$:

$$T\boldsymbol{n}=-p_0\boldsymbol{n}.$$

On the remaining boundaries of the region (the surface of the screw and the wall of the device), the no-slip condition is specified:

$$\boldsymbol{u}=0.$$

In the present work, we determine the dependence of the separation size of solid particles (critical particle size) on the geometry of the screw facility, the flow parameters at the inlet and the total flow velocity at the outlet. The goal of the calculations is as follows. By varying the screw step h and the numbers of turns n, it is necessary to obtain the value of the angular flow velocity at the outlet that ensures the specified separation size d. In this case, all particles of diameter larger than d are settled, which considerably increases the wear resistance of units of main pipelines. The calculations were performed for the horizontal and vertical arrangements of the device.

The problem was solved using the finite-element method with an adaptive grid. As a first step, the computation region is broken up into elementary pyramids (Fig. 2). The grid refinement depends on the geometry, in particular, on the screw, the grid is finer, and on the pipe walls, it is coarser. This method of constructing the grid provides high-accuracy and high-speed calculations. In the calculations, we used grids containing 18,000 to 120,000 elements.

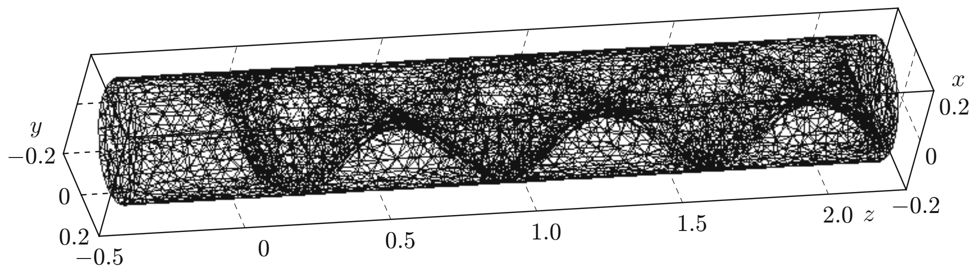

Fig. 2. Computation region.

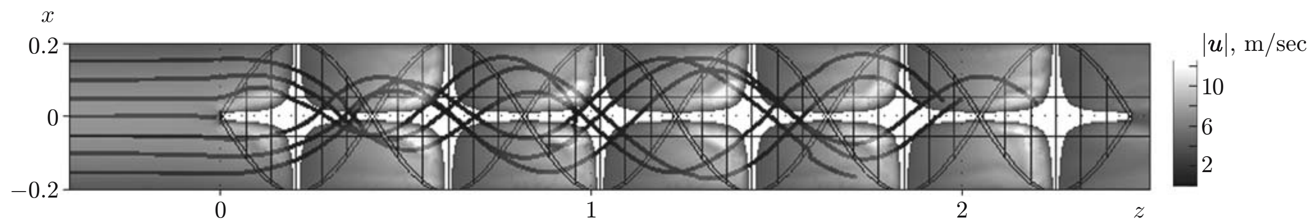

Fig. 3. Streamlines and distribution of the total flow velocity in the axial section ($|\boldsymbol{u}|_{\min} = 2.161 \cdot 10^{-16}$ m/sec and $|\boldsymbol{u}|_{\max} = 12.891$ m/sec).

Next, the problem is discretized, resulting in an algebraic system containing about 10^6 unknowns. This system is solved using an iterative sweep method. As a result, we obtain the components of the velocity vector and pressure at the vertices of the elementary pyramids. In the final stage, the discrete solution obtained is interpolated to the entire computation region. The streamlines and the distribution of the total flow velocity in the axial section are presented in Fig. 3.

Below we give calculation results for the following parameters of the device: outer radius $R = 0.205$ m, inner radius $r = 0.01$ m, screw step $h = 0.41$ m, number of turns $n = 6$, length of the screw part $L = 2.46$ m, maximum velocity at the inlet $u_{\max} = 5$ m/sec, pressure $p_0 = 1$ atm, density of the fluid (oil) $\rho_l = 865$ kg/m^3, dynamic viscosity of the fluid $\mu = 0.017$ N$\cdot$ sec/m^2, density of solid particles $\rho_s = 1115.85$ kg/m^3, and $\boldsymbol{F} = (0, 0, \rho_l g)$, which corresponds to the vertical arrangement of the device.

To determine the angular flow velocity, we introduce the vorticity of the velocity vector field:

$$\operatorname{rot} \boldsymbol{u} = \Big(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}, \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}, \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\Big).$$

The doubled third component of the obtained vector field is equal to the angular velocity ω.

Integration of the calculated value of the third component w of the velocity vector $\boldsymbol{u}$ over the given section yields the volumetric discharge $Q = 0.33$ m^3/sec. The average integrated value of the modulus of the third components of the vorticity vector $\operatorname{rot} \boldsymbol{u}$ is equal to $\omega/2 = 35.82$ sec^{-1}.

To determine the separation size, we use the results of [10], in which theory of sedimentation processes in screw settling centrifuges is constructed under some simplifying assumptions. The separation size is calculated by the formula [10]

$$d^2 = \frac{18\mu Q(\ln R - \ln r)}{\pi(\rho_s - \rho_l)\omega^2(R^2 - r^2)L}.$$

Substitution of the calculation results and values of the parameters of the device into the formula yields $d = 0.527$ mm.

Table 1 gives calculated separation sizes for various arrangements of the screw device with various screw steps and angle of inclination α. The values of the parameters not presented in Table 1 are given above. Among the results, the optimal one is apparently version 2 with the vertical arrangement of the device. For this version, Table 2 gives calculated the separation sizes for various numbers of screw turns (from one to six).

The calculation results show that the least size of the settled particles ($d \approx 0.5$ mm) is reached for the vertical arrangement of the device with $\alpha = 45°$, $L = 1.64$ m, and $n = 4$.

TABLE 1

Calculation version	h, m	α, deg	L, m	Arrangement of device	d, mm
1	0.710	30	4.260	Vertical	0.725
2				Horizontal	0.985
3	0.410	45	2.460	Vertical	0.527
4				Horizontal	0.902
5	0.236	60	1.416		3.018
6				Horizontal	4.508

TABLE 2

n	L, m	d, mm
1	0.41	1.812
2	0.82	0.948
3	1.23	0.740
4	1.64	0.506
5	2.05	0.519
6	2.46	0.527

Thus, modeling was performed of viscous incompressible fluid flow in a screw channel. The results were used to calculate the separation size. In a series of numerical experiments, parameters of the screw device were obtained that ensure a separation size $d = 0.5$ mm.

REFERENCES

1. I. Yu. Khasanov, N. Kh. Faizullin, and I. M. Gimaletdinov, "Flow filter for removing mechanical impurities from fluids," Russian Federation Patent No. 2263531, MPK B 01 D 29/11, Publ. 11.10.2005, Bull. No. 31.
2. I. Yu. Khasanov, N. Kh. Faizullin, "Mud filter," Russian Federation Patent No. 2293596 B 01 D 35/02, Publ. 2.20.2007, Bull. No. 5.
3. N. Kh. Faizullin, V. I. Rogozin, I. Yu. Khasanov, and M. M. Gareev, "Increasing the performance of oil equipment," in: *Problems and Methods of Ensuring the Reliability and Safety of Transport Systems for Oil, Oil Products, and Gas*, Proc. 6th Congress of Oil and Gas Operators of Russia, Inst. of Transport Problems of Power Resources, Ufa (2005), p. 127.
4. N. Kh. Faizullin, I. Yu. Khasanov, M. F. Mugafarov, and I. A. Kaliev, "Filter for removing mechanical impurities from fluids operating on the centrifugal principle," in: *Proc. Conf. Oil and Gas Processing and Petrochemistry*, Inst. of Chem. Oil Processing, Ufa (2006), pp. 302–303.
5. P. A. Fischer, "New type of water separator could help fill multiple oilfield needs," *World Oil Magazine*, Vol. 226.12 (2005).
6. D. Potter, *Computational Physics*, Wiley, New York (1973).
7. I. I. Vainshtein, E. M. Gol'din, I. A. Fainerman, and D. E. Shkoropad, "On the hydrodynamics of settling screw centrifuges," in: *Theoretical Foundations of Chemical Technology*, **19**, No. 1, 80–85 (1985).
8. D. E. Shkoropad and O. P. Novikov, *Centrifuges and Separators for Chemical Production* [in Russian], Khimiya, Moscow (1987).
9. I. A. Fainerman, *Calculation and Designing of Screw Centrifuges* [in Russian], Mashinostroenie, Moscow (1981).
10. D. E. Shkoropad, *Centrifuges for Chemical Production*, Mashinostroenie, Moscow (1975).