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Analysis of the Influence of Mode Parameters Cylindroconical Hydrocyclone for Separation of Viscoplastic Mediums Pressure Flotation

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ABSTRACT

A mathematical model for the separation of inhomogeneous liquid systems in a field of centrifugal forces is adapted to the process of purification of viscoplastic liquids in a cylindrical-conical hydrocyclone by pressure flotation. The model takes into account the action of inertial forces, Coriolis and the added mass of fluid. The system of partial differential equations describing the flotation process is reduced to a system of ordinary differential equations and solved by a numerical method taking into account the geometry of the working space of a cylindrical-conical hydrocyclone. Based on the developed mathematical model, the influence of the separation factor on the residual concentration of solid phase particles was analyzed at different values of the body cone angle and plasticity number. A physical substantiation of the obtained results is given. The results obtained can be used in calculating equipment for separating viscoplastic media in hydrocyclones by pressure flotation.

Keywords: viscoplastic liquid; yield stress; pressure flotation; cylindrical-conical hydrocyclone; plasticity number; separation factor; nonlinearity index; consistency index; residual concentration.

1. Introduction

Hydrocyclones, characterized by their simplicity of design, reliability and high efficiency of separation processes, can be used to carry out highly efficient separation processes in a centrifugal field.

Settling tanks and separators used in purification and enrichment processes do not provide high clarification rates and occupy significant production areas. Due to the fact that the centrifugal field provides a higher intensity of separation processes compared to gravity, it is advisable to use hydrocyclones and carry out the process of pressure flotation of impurities in them. The highest intensity of the centrifugal field is provided by a cylindrical-conical hydrocyclone operating in a film flow mode, therefore, the implementation of the pressure flotation process in this apparatus is advisable for many technological processes.

Work[1] emphasizes that hydrocyclones are traditionally used quite widely at mining and processing enterprises, but for water treatment - unjustifiably little due to the fact that small particles released in water treatment processes are not completely separated in hydrocyclones. The flotation process in a field of centrifugal forces, which makes it possible to significantly reduce the boundary grain of separation, in this case will significantly expand the scope of hydrocyclones.

Experiments on the separation of a water-oil emulsion and a three-component

system “water - motor oil - quartz sand” in a hydrocyclone-flotator[2] showed that, over the entire studied range of concentrations and input pressures, the hydrocyclone-flotator provides a higher efficiency of solid phase collection than a conventional hydrocyclone.

Work[3] shows that the extraction of suspended particles from wastewater pressure flotation, carried out in the field of centrifugal forces in a hydrocyclone, contributes to significant intensification of the process and achievement almost complete removal of solid phase particles due to the separation of particles of the finest fractions from wastewater. To achieve more efficient cleaning, a method for calculating separation processes in hydrocyclone flotators is proposed based on the equation of radial motion of a particle associated with an air bubble.

It was established in[4] that during turbulent flow of a viscous fluid in a field of centrifugal forces, gas bubbles are unstable formations and can be destroyed. Therefore, devices operating in film flow mode provide the most favorable conditions for carrying out the flotation process in the field of centrifugal forces.

The authors of [5] proposed to introduce dispersed gas directly into the inlet pipe of the hydrocyclone without taking into account the fact that solid phase particles serve as centers for the formation of gas bubbles during pressure flotation, which significantly increases the intensity of the formation of flotation complexes.

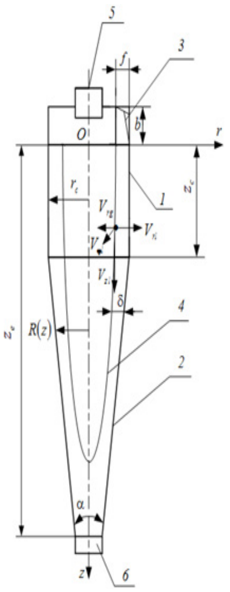
In[6], based on the results of numerical modeling, an analysis of the influence of the design parameters of a cylindrical-conical hydrocyclone on the hydrodynamics of a non-Newtonian fluid was carried out. The influence of the cone angle of the conical part of the hydrocyclone body and the separation factor on the attenuation of the circumferential velocity component in the direction of the hydrocyclone axis and the thickness of the liquid film has been established.

A description of separation processes in a cylindrical-conical hydrocyclone with a freely formed surface of a viscoplastic liquid phase based on the solution of complete rheodynamic equations has not yet been carried out and is of significant theoretical and applied interest.

The purpose of the work is to study the influence of the separation factor at different values of the cone angle of the apparatus body and the plastic properties of the medium on the separation indicators when implementing the purification process by pressure flotation in a cylindrical-conical hydrocyclone.

2. Mathematical Model of The Separation Process Viscoplastic Media by Pressure Flotation In A Hydrocyclone

The flow diagram of the separated medium in a cylindrical-conical hydrocyclone is shown in Fig. 1. The hydrocyclone consists of a cylindrical chamber.



Rice. 1 Scheme for separating a viscoplastic medium pressure flotation in a hydrocyclone;

1 - cylindrical chamber;

2 - conical part of the body;

3 - inlet pipe;

4 - rotating liquid film with a free surface;

5 - upper outlet pipe;

6 - lower drain pipe;

1, and a conical part 2 with a taper angle. Into the cylindrical chamber 1 through the inlet pipe 3, installed in its upper part, tangentially. The suspension, previously saturated with gas, is supplied at elevated pressure (up to 0.8 MPa). The suspension entering the hydrocyclone flows down along the walls of the apparatus body, possessing circumferential, axial and radial velocity components, forming a rotating film with a free surface 4. When the pressure decreases to atmospheric, a supersaturation of the dissolved gas is created and the suspension "boils". Particles of the solid phase, under the influence of centrifugal force, move towards the wall of the hydrocyclone body, and gas bubbles, under the influence of the buoyant centripetal force of Archimedes, move towards them to the surface of the film. When particles of the solid phase collide with gas bubbles, flotation complexes are formed, carrying the particles of the solid phase to the surface of the film into a foam layer, which is removed through the upper outlet pipe 5. In addition, the particles of the solid phase serve as direct centers for the formation of gas bubbles released when the pressure decreases, which leads to a significant increase in the kinetic coefficient of pressure flotation. The clarified suspension is removed from the apparatus through the lower drain pipe 6.

The mathematical formulation of the problem is made under the following assumptions: when a suspension enters the hydrocyclone, the pressure in the suspension drops and monodisperse gas bubbles are released, uniformly distributed throughout the entire volume, the concentration of which at the entrance to the hydrocyclone is c_{go}; there is no coalescence of gas bubbles; for a film flow of a suspension with a non-Newtonian dispersion medium with a high effective viscosity, the flow regime is laminar and the regime of sedimentation of solid phase particles and the rise of gas bubbles is laminar[8].

The most common case in hydrocyclone flotation practice is when one particle is extracted by several bubbles in a field of centrifugal forces. In this case, the concentration of gas bubbles significantly exceeds the concentration of solid phase particles with $c_g > c_h$ and can be assumed with c_g =const throughout the entire volume of the suspension film in the hydrocyclone.

We believe that the rheological properties of a viscoplastic separated medium for the case of a three-dimensional flow can be characterized by the Herschel – Bulkley equation [7], which, when written in the components of the strain rate tensor, taking into account the von Mises plasticity condition, has the form

$$\tau_{ij} = \left(\frac{\tau_0}{A} + kA^{n-1} \right) \gamma_{ij}, \qquad (1)$$

$$A = \sqrt{2\left(\frac{\partial V_r}{\partial r}\right)^2 + 2\left(\frac{V_r}{r}\right)^2 + 2\left(\frac{\partial V_z}{\partial z}\right)^2 + \left(\frac{\partial V_\varphi}{\partial r} - \frac{V_\varphi}{r}\right)^2 + \left(\frac{\partial V_\varphi}{\partial z}\right)^2 + \left(\frac{\partial V_z}{\partial r} + \frac{\partial V_r}{\partial z}\right)^2}$$

where τ_{ij} are the components of the stress tensor, Pa; τ_0 – ultimate shear stress, Pa; γ_{ij} – components of the strain rate tensor, c^{-1} ; A – intensity of strain rates, c^{-1} ; n – indicator of nonlinearity of the flow curve; k – consistency index, Па·c^n ; z – radial and axial coordinates, m; φ– circumferential coordinate, rad.

The Herschel–Bulkley equation allows one to simulate the rheodynamics of many non-Newtonian media in industrial settings.

To mathematically model the concentration field when separating a suspension from a viscoplastic dispersion medium by pressure flotation in a cylindrical-conical hydrocyclone, we use the differential equation of convective diffusion in cylindrical coordinates, which, taking into account the flow of solid phase particles due to binding into complexes and flotation by gas bubbles when the molecular diffusion coefficient is zero, can be written for solid phase particles and gas bubbles as follows

$$div(\overline{V}_h c_h) = -J_h \,, \qquad (2)$$
$$div(\overline{V}_g c_g) = -J_g \,,$$

where $\overline{V}_h$ is the velocity vector of solid phase particles; $\overline{V}_g$ – velocity vector of gas bubbles; c_h – concentration of solid phase particles, кг/м³; c_g – concentration of gas bubbles, кг/м³; J_h, J_g – drain of solid phase particles and gas bubbles due to flotation.

Taking into account the accepted assumptions, the second equation of system (2) can be eliminated and system (1) is reduced to one equation, the flow of solid phase particles J_h due to flotation in which, according to[9], has a form similar to the kinetic equation of a first-order chemical reaction

$$div(\overline{V}_h \tilde{n}_h) = -K c_g c_h \,, \quad (3)$$

where K is the kinetic flotation constant, c^{-1} .

At $c_g = 0$, there is no flow of particles due to flotation and equation (3) describes the process of dividing the suspension by separation in the field of centrifugal forces.

The flotation rate constant K was determined by the formula obtained in[10] on the basis that the probability of collision of particles and bubbles is similar to the probability of collision of molecules in the molecular kinetic theory of gases.

After transformations, equation (3) takes the form:

$$V_h \frac{\partial c_h}{\partial r} + V_h \frac{\partial c_h}{\partial z} = -c_h \left\{ K c_g + \frac{1}{r} \frac{\partial [r(V_h - V_t)]}{\partial r} \right\} \quad (4)$$

where is the axial coordinate, м; $V_{rh}(r, z)$ – radial component of the velocity of solid phase particles, м/с; $V_{rh}(r, z)$ – axial component of the velocity of solid phase particles, м/с.

When developing a model for separating a suspension in a hydrocyclone by pressure flotation, we took into account the inertial forces acting on a solid phase particle in the radial direction, which are significant during the flotation of large particles and a significant difference in the densities of the solid phase particles and the dispersion medium. Under the condition that the centrifugal force of Archimedes, the drag force and the Coriolis force act on the particle of the solid phase, the equation of motion of the particle of the solid phase in projections on the axis has the form:

$$V_{rh} \frac{\partial V_{rh}}{\partial r} + V_{zh} \frac{\partial V_{rh}}{\partial z} = \frac{V_{\varphi h}^2}{r}\left(1 - \frac{\rho_l}{\rho_h}\right) - \frac{3}{4} \frac{K_{fr} \rho_l (V_{rh} - V_{rl}) |V_{rh} - V_{rl}|}{\rho_h d_h \Phi}$$
$$V_{rh} \frac{\partial V_{\varphi h}}{\partial r} + V_{zh} \frac{\partial V_{\varphi h}}{\partial z} = \frac{V_{\varphi h} V_{rh}}{r} - \frac{3}{4} \frac{K_{f\varphi} \rho_l (V_{\varphi h} - V_{\varphi l}) |V_{\varphi h} - V_{\varphi l}|}{\rho_h d_h \Phi} \qquad (5)$$

where $K_{fr}, K_{f\phi}$ are the coefficients of resistance to particle motion in the radial and circumferential directions; $V_{\varphi h}(r,z)$ – circumferential component of the velocity of particles of the solid phase, м/с; $V_{rl}(r,z)$ – radial component of the velocity of the dispersion medium, м/с; $V_{\phi l}(r,z)$ – circumferential component of the velocity of the dispersion medium, м/с; d_h – diameter of solid phase particles, м; φ – circumferential coordinate, degrees; Φ – correction factor taking into account the constraint of sedimentation of solid phase particles.

The drag coefficients for radial and circumferential motion of the particle were determined according to[11]. In this case, the consistency index k was calculated as the effective viscosity of the pseudoplastic fluid according to the rheological equation (1), taking into account the presence of a limiting shear stress in the separated medium .

The coefficient taking into account the constraint of particle sedimentation was calculated using the formula of V.I. Sokolov[12].

3. Numerical Modeling

Equation (4), together with the equation of motion of a particle of the solid phase (5), taking into account the forces of inertia, Coriolis and the added mass of the liquid, was solved according to the method described in[13].

In accordance with the method of characteristics, the system of partial differential equations, given by equation (3) and the equation of motion of a solid phase particle taking into account the flow of particles due to flotation, is reduced to an equivalent system of ordinary differential equations, one of which specifies the trajectory of a solid phase particle, and the rest are the concentration of particles on trajectories, taking into account runoff due to flotation.

The calculation on each trajectory was carried out to a radial coordinate value equal to the dimensionless radius of the hydrocyclone body $R_k(Z)$, which in the case of a cylindrical-conical hydrocyclone is a piecewise linear function Z, determined from the relation

$$R_k(Z) = 1 \; (Z < Z_s), \quad (4)$$

$$R_k(Z) = 1 - (Z - Z_c)\, tg(\alpha/2) \; (Z > Z_c),$$

where $R_k(Z) = r_k(z)/r_c$ -is the dimensionless radius of the hydrocyclone body; $Z = z/r_c$ – dimensionless axial coordinate; r_c –radius of the cylindrical chamber of the hydrocyclone, m.

The resulting system of differential equations with a boundary condition specifying the volume fraction of solid phase particles C_0 at the entrance to the hydrocyclone was solved together with the equations of motion of solid phase particles[13] using the fourth order Runge-Kutta method with a fixed step. Due to the fact that the rate of change of the axial coordinate as the trajectory approaches the wall is many times greater than the rate of change of the radial coordinate, this system of equations belongs to the class of rigid systems and requires a very large number of steps for its solution. The integration interval from the lower boundary of the inlet pipe of the hydrocyclone to the outlet of the conical part of the body was divided into $M = 3.10^5$ steps along the Z axis and the resulting system of differential equations was numerically integrated using a program written in Compaq Visual Fortran. The solution error of the system was estimated by doubling the number of steps and did not exceed $1 \cdot 10^{-5}$.

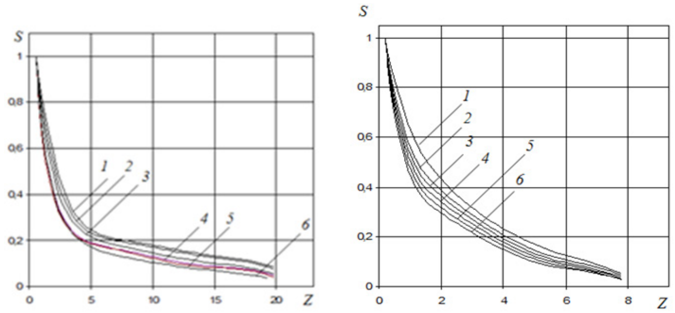
The flow of a viscoplastic fluid in a hydrocyclone is characterized[6] by the centrifugal Froude number Fr (separation factor), the modified Reynolds number Re_n, the plasticity number Pl, equal to the ratio of the ultimate shear stress to the inertia force[13], the nonlinearity index of the flow curve n, and also a hydrocyclone design parameter Q, characterizing the ratio of the cross-sectional area of the inlet pipe of the hydrocyclone to the horizontal cross-sectional area of the apparatus body.

To assess the quality of the separation process, we used the dimensionless residual concentration of solid phase particles S (the ratio of the volume fraction of particles not extracted from the suspension in a given section of the film to the volume fraction of particles in the inlet pipe of the hydrocyclone), which was determined according to the method described in[13].

3. Discussion of Results

The simulation results are shown in Fig. 2, 3.

In Fig. 2, a and b, the distribution curves of the residual concentration of solid phase particles S along the axis of a cylindrical-conical hydrocyclone are shown at values Pl=0,0085, Re_n=4· 10^3, Q=0,02, α = 5°; n=0,7, d_h=2·10^{-5} м, d_g=3·10^{-5} м. On the curves you can highlight a section of rapid decline



Rice 2: Distribution of the residual concentration of solid phase particles S along the axis of the cylindrical hydrocyclone at Pl = 0.0085, Re_n = 4·10 ^{3},

Q= 0.02; n = 0.7 ; d_h=2·10 $^{-5}$ m; d_g = 3·10 $^{-5}$ m:

a –α = 5°; б – α = 15°;

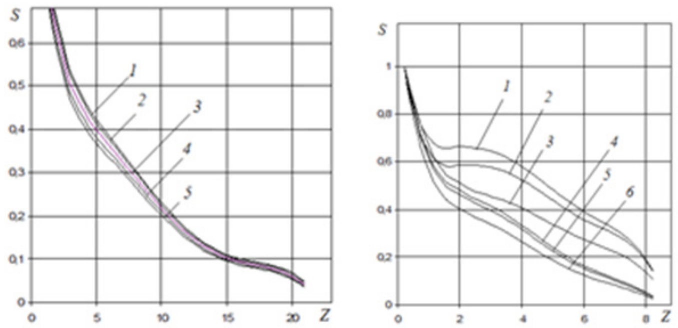
1 – Fr= 40; 2 – Fr= 60; 3 – Fr= 70; 4 – Fr= 80; 5 – Fr= 90; 6 – Fr= 95

Residual concentration S(up to Z = 2.5–3.0), corresponding to the area of the most intense attenuation of the circumferential component of the flow velocity. This section has a slightly greater extent than for a cylindrical hydrocyclone (up to Z=2,0–2,5)[13], which is explained by an increase in the thickness of the liquid film and a decrease in intensity attenuation of the circumferential velocity component. From the analysis of the data shown in Fig. 2, but it follows that the residual concentration of S in the outlet section of the hydrocyclone decreases with increasing number Fr (separation factor) more intensively than in a cylindrical hydrocyclone[13], which can be explained by a more significant increase in the thickness of the liquid film in the conical part of the body and path, passing through the liquid by particles of the solid phase and gas bubbles, which leads to an increase in the number of collisions and the number of flotation complexes formed.

In Figure 2 a and b shows the distribution curves of the residual concentration of solid phase particles S along the axis of a cylindrical-conical hydrocyclone, at the same parameter values as in Fig. 2, a, for the taper angle of the conical part of the body α = 15°. From a comparison of the data shown in Fig. 2, a and b, it follows that in the initial section of the flow (up to Z = 5.0) the residual concentration S in the outlet section of the hydrocyclone decreases at α = 5° more intensively due to less attenuation of the circumferential component of the flow velocity $V_{\varphi l}$ in the direction of the hydrocyclone axis[6], which causes an increase in the radial components of the velocity of solid phase particles V_{rh} and gas bubbles V_{rg}, and the kinetic flotation coefficient K, and a corresponding increase the number of collisions of particles with gas bubbles and a decrease in the residual concentration of S. However, at the outlet of the hydrocyclone, the residual concentration S of solid phase particles is lower at α = 15° due to more intense swirl of the flow at the outlet of the hydrocyclone.

In Fig. 3, a and b, the same dependences are shown as in Fig. 2, for the value Pl= 0.085. From a comparison of the data shown in Fig. 2, a and fig. 3, and it follows that for values of the cone angle α = 5° an increase in the plasticity number Pl and a corresponding increase in the ultimate shear stress lead to a decrease in the residual concentration of S in the outlet section of the hydrocyclone, since an increase leads to an increase in the anomaly the non-Newtonian properties of the dispersion medium and the corresponding decrease in the intensity of the attenuation of the circumferential velocity component

Dispersion medium Vφl in the direction of the hydrocyclone axis, as well as to an increase in the fullness of its radial distribution[6]. This also leads to a decrease in the residual concentration of S due to an increase in the centrifugal force acting on particles of the solid phase and the centripetal force acting on gas bubbles, which causes an increase in the speed of their oncoming movement and a corresponding increase in the kinetic flotation coefficient K.



A B

Rice 3: Distribution of residual concentration of solid phase particles S along the axis of the cylindrical hydrocyclone at Pl=0,085, Re_n=4·103, Q=0,02; n=0,7; d_h=2·10^{-5} м; d_g=3·10^{-5} м:

a –α = 5°; 1 – Fr=60; 2 – Fr=70; 3 – Fr=80; 4 – Fr=90; 5 – Fr=100;

б –α = 15°; 1– Fr=30; 2 – Fr=40; 3 – Fr=45; 4 – Fr=55; 5 – Fr=60; 6 – Fr=80

From the comparison of Fig. 3, b from fig. 3, a and fig. 2, b it follows that at α = 15° and Pl = 0.085, a decrease in the residual concentration of solid phase particles can be achieved only at high values of the separation factor (Fr = 50 – 80), since at lower values of the Fr *number*, an increase in the thickness of the film of the separated suspension in the lower zone of the conical part of the apparatus body at α = 15° compared to the case α = 5° leads to a decrease in the efficiency of the flotation process.

At α = 15° and Pl = 0.085, the influence of the Fr number on the residual concentration of solid phase particles is the most significant.

4. Conclusion

Thus, using the developed mathematical model, adapted to the process of separating suspensions with a viscoplastic dispersion medium by pressure flotation in a cylindrical-conical hydrocyclone, the influence of the body cone angle and the plastic properties of the separated medium on the residual concentration of solid phase particles at the outlet of the hydrocyclone was established. The results obtained are a theoretical basis for creating a methodology for engineering calculations of cylindrical-conical hydrocyclones - flotators for separating viscoplastic media and can be used to control the flotation process in the field of centrifugal forces.

5. References

1. Basharov MM, Sergeeva OA. Design and calculation of hydrocyclones. Westfalika 2012.
2. Dikov VA, Sukhanov DE. Study of the possibility of using hydrocyclones for centrifugal flotation enrichment of potassium-containing ores. Engineering Bulletin of the Don 2013;4(27):23-26.
3. Karataev OR, Shamsutdinova ZR. Modeling of separation processes in hydrocyclone flotators. Bulletin of the Technological University 2015;18(16):117-119.
4. Lagutkin MG, Klimov AP. Behavior of gas bubbles in a hydrocyclone. Theoretical foundations of chemical technology 1993;27(5):468-472.
5. Kutepov AM, Lagutkin MG, Pavlovsky GV, Mushtaev VI. Separation of dispersed systems in hydrocyclones with additional input of dispersed gas. Theoret. basics of chemistry technol 1999;33(5):571-577.
6. Yablonsky VO, Ryabchuk GV. Flow of a rheologically complex suspension in a cylindrical-conical hydrocyclone. Theoret. basics of chemistry technol 2005;39(4):355 - 361.
7. Robert AC, Fernández-Nieto ED, Reina NG. Vigneaux P. Viscoplastic Free-Surface Flows: The Herschel-Bulkley Case. Seventh International Conference on Computational Fluid Dynamics 2012:1-15.
8. Dyakowski T, Hornung G. Williams RA Simulation of non-newtonian flow in a hydrocyclone. Chem. Eng. Res. Des. A 1994;72(4):520-523.
9. Deryagin BV, Dukhin SS, Rulev NN. Microflotation: Water purification, enrichment. M.: Chemistry 1986:112.
10. Tyabin NV, Dakhina GL, Golovanchikov AB, Mamakov AA. Calculation of ideal displacement devices for separating thin suspensions with electrolytic gases. Theoret. basics of chemistry technol 1979;880 - 884.
11. Acharya A, Mashelkar RA, Ulbrecht J. Flow of inelastic and viscoelastic fluids past a sphere. Rheologica Acta 1976;15(9):454-463.
12. Sokolov VI, Centrifugation VI. Sokolov. Moscow: Chemistry.1976:408.
13. Yablonsky VO. Modeling the influence of the rheological properties of a viscoplastic medium on the performance of flotation cleaning in a cylindrical hydrocyclone. Energy and resource saving: industry and transport 2022;2(40):18-26.