Improvement of disc stack centrifuge design to increase efficiency of formation fluid separation

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Abstract. It should be noted that numerous theoretical studies on flow hydromechanics in the centrifugal field have not been sufficiently used in designing separators with a high productivity index. This is caused by the extreme complexity of the flow conditions of the separated liquid in the intra-rotor space. Therefore, experimental studies of intra-rotor flows have now gained great importance. The obtained results of studies carried out on a real product at a pressure and flow rate corresponding to production conditions made it possible to create and manufacture an industrial sample of the assembly. The authors use experimental data to calculate similar hydrocyclones meant for operation with other mixtures.

1. Introduction
It should be noted that numerous theoretical studies on flow hydromechanics in the centrifugal field have not been sufficiently used in designing separators with a high productivity index. This is caused by the extreme complexity of the flow conditions of the separated liquid in the intra-rotor space. Therefore, experimental studies of intra-rotor flows have now gained great importance. Thus, it was experimentally shown [1, 2] that when the separation process intensifies, it is not possible to examine the operation of individual rotor parts separately, and the operation should be considered of a system including a plate stack, a mud space, centrate channels and a discharge unit.

2. Results and discussion
The use of hydrocyclones in various technological processes for the separation of heterogeneous disperse systems allows keeping energy consumption down, reducing cost and improving product quality. In various industries, separable suspensions in many cases represent non-Newtonian media, which effective viscosity decreases with the increase of the deformation rate intensity. Such suspensions are separated in the production of protein-vitamin concentrates (paprin, gaprin, meprin), suspensions of biomass, glaze and SiC3, as well as in the sewage water treatment from oil, fats and other substances. The lack of an adequate model for the separation of non-Newtonian suspensions in a hydrocyclone has thus far been a major obstacle to the creation of a general methodology for the design of such assemblies.

It is known that the hydraulic resistance in cylindrical straight-flow hydrocyclones is significantly lower than in cylindrical conical devices, therefore, for the separation of non-Newtonian suspensions with significant effective viscosity it is advisable to use cylindrical straight-flow hydrocyclones that discharge separation products through a lower drain thus preventing large pressure drops in the device.

The hardware of the process determines the type of technological production and physicochemical properties of separated mixtures. A large number of design solutions are known for devices designed to separate heterogeneous mixtures by using the centrifugal force field and its properties during high-speed phases.
The practice of using hydrocyclones is reflected in special technical literature [1-4], especially the operation of cylindrical-conical hydrocyclones is studied in detail. It was found that the separation process mainly takes place in the external flow [1, 2, 5].

There are two points of view on the mechanism for flow formation in hydrocyclones: 1st – transition of liquid from downward to upward flow occurs along the entire height of the cylindrical conical hydrocyclone [1, 2]; 2nd – the main part of the liquid phase to the upward flow comes from the lower part of the device [2, 3].

A recognized fact is the presence of closed circulation vortices between the rotating flows of the liquid phase and the central gas-air column [2, 3]. The theoretical assumptions of researchers only state the difference between the ideas about the role of these factors and the place of the internal flow formation. The choice of the centrifugal separation process in the cyclone and hydrocyclone type devices depends on the solution of this issue.

The processes of flow formation in a hydrocylcone and jet separation determine the initial parameters of introduced suspension jet. The suspension entering the hydrocyclone body tangentially or at some angle already has a formed jet profile (h x b or dax) and retains it as it moves towards the lower discharge orifice. The separation process takes place in a swirling jet as it moves in the hydrocyclone, and the efficiency of this process depends on the factors determining the stability of the jet flow structure.

The results of the study [6] can be used for the theoretical justification of these statements, in which the stability of the cylindrical flow is considered from the points of instability: longitudinal Poiseuille flow and azimuthal Couette flow. The study of flow stability in cylindrical channels implies that it is enough to consider the stability relative to each individual spiral harmonic of displacement in cylindrical coordinates r, \( \varphi \), z.

One of the most effective methods of separating non-Newtonian suspensions with a finely dispersed solid phase is pressure flotation [1, 2] carried out when introducing a pre-aerated suspension into a hydrocyclone at increased pressure. The suspension entering the hydrocyclone, rotating, flows down its walls at a speed, which components include circumferential \( v_\varphi \), axial \( v_z \) and radial \( v_r \). When pressure drops, air bubbles are released from the suspension, which form flotation complexes with solid phase particles extracted by centrifugal forces on the film surface, into the foam.

Based on the solution of the radial motion equation of the “particle-bubble” complex the works [3, 4] propose a method of calculating separation indices for a hydrocyclone flotation unit. However, the developed calculation methods do not take into account the hydrodynamics of the swirling film of the suspension with a free surface flowing along the walls of the hydrocyclone, which leads to significant deviations from real values. To calculate the separation process in the hydrocyclone, reliable data are needed on the nature of the flow in the device, for which it is necessary to obtain complete equations of suspension thermodynamics.

The modeling of film flow hydrodynamics of non-Newtonian suspension in cylindrical direct-flow hydrocyclone using complete equations of thermodynamics was performed in works [5, 6]. Ostwald de Ville’s power rheological equation was used to describe the rheological properties of the suspension. The dependencies of suspension film thickness on axial coordinate, as well as the field of velocity and pressure components distribution in the device were obtained at different values determining similarity criteria and rheological properties of the medium. For further use of the obtained results, the calculated data were approximated with analytical expressions in the entire range of changes in the rheological properties of the suspension and similarity criteria characterizing the flow.

In separating fine suspensions in a hydrocyclone by pressure flotation, the equations of continuity of solid phase particle flows and gas bubbles were used for mathematical modeling of the concentration field, which can be written as follows:

\[
\text{div}(\overline{v}_h c_h) = -J_h;
\]

\[
\text{div}(\overline{v}_g c_g) = -J_g,
\]

where \( \overline{v}_h, \overline{v}_g \) – velocity vectors of solid phase particles and gas bubbles; \( c_h, c_g \) – volume fractions of solid phase particles and gas bubbles in the suspension; \( J_h = B_h c_h, J_g = B_g c_g \) – volumetric runoff intensities of particles and bubbles determined according to work [7]. \( c^1; B_h, B_g \) – kinetic constants of pressure flotation, \( c^1 \). Indices: h – solid phase particles; g – gas bubbles.

The most common case in flotation processes is when one particle is extracted by several bubbles in the centrifugal force field. Moreover, the volume fraction of gas bubbles significantly exceeds the volume fraction of solid phase particles in the suspension, i.e. \( c_g > c_h \), and it can be assumed that \( c_g = \text{const} \). For this case...
case, the second equation of the system of equations (1) can be excluded, and reduced to one equation.

Since the radial velocity components of solid phase particles and gas bubbles differ from the radial velocity component of the continuous flow of the dispersion medium, and the radial velocity component of the liquid is neglected due to its low content, we will have the following:

\[
\text{div } \vec{v}_h \left( \frac{1}{r} \frac{\partial (rv_h)}{\partial r} \right);
\]

\[
\text{div } \vec{v}_g \left( \frac{1}{r} \frac{\partial (rv_g)}{\partial r} \right).
\]

Since the pressure flotation is most effective with a slight difference in the densities of the solid phase particles and the dispersion medium, it can be assumed with a sufficient degree of accuracy that in the axial direction the solid phase particles move without inertia, i.e. the axial velocities of the solid phase particles and the dispersion medium coincide \( v_{zh} = v_{zl} \) (index \( l \) – dispersion medium).

Previously, it was shown \[3, 4\] that unevenness of nutrition entails a decrease in the performance index sometimes by 2 times or more. Nutritional unevenness has been studied several times and methods of reducing it have been proposed \[5\]. The influence of unevenness in the height of the stack should be taken into account both when increasing the number of plates and when manufacturing them, taking into account the need to accurately observe the selected gap between them.

Thus, it can be concluded that the increase in the productivity of separators by increasing their size has come close to the limit and the use of available reserves in this direction obviously involves the need to overcome large and unjustified difficulties. Further development of this direction is irrational.

There is still a way to intensify the separation process by equalizing the distribution of intra-stack flows and intra-rotor, to eliminate the flotation effect and destruction of the dispersed phase, to improve the stacks, to adapt the mode of operation of the separators depending on changes in the properties of the separated liquid.

Various types of hydrocyclones are used in oil industry to separate the formation fluid and for waste water treatment. Typically, the hydrocyclone is a cylindrical body which is conical at the discharge unit, with a tangential liquid phase inlet and a central drain pipe.

In general, the profile of the tangential velocities of the liquid varies according to the following law

\[
\vartheta_p r^n = \text{const}
\]

(1)

where \( \vartheta_p \) – tangential velocity in the wall area, m/s; \( r \) – hydrocyclone radius, m; \( n \) – power coefficient.

According to various authors, the power coefficient \( n \) varies from \(-1\) to \(+1\). The tangential velocity in the hydrocyclone is influenced by its geometric parameters, the conicity of the body and the withdrawal of the condensed fraction.

When cleaning highly paraffinic formation fluid in industrial conditions, crusts are forming in the hydrocyclone periodically clogging the discharge hole. The propose of the device is to ensure the best hydrodynamic conditions of the formation fluid separation in the hydrocyclone and to prevent discharge hole clogging (Fig. 1), containing only the cylindrical part of the housing \[6, 7\]. The discharge hole is formed due to placement of conical displacer of the hydrocyclone lower part. Hydraulic cyclone housing has a tangential choke for formation drain pipe, fluid inlet, baffle rings, condensed fraction choke, conical displacer, and units for manual or automatic opening of the discharge hole. The conical displacer ensures the maintenance of optimal hydrodynamic conditions along the entire length \( L \) of the device. The displacer conicity affects the tangential velocities distribution profile of the liquid in the wall region allowing the specific flow rate along the section and velocity profile along the radius of the device to be kept constant.
3. Experiment

Figure 2 shows the results of obtaining data during the hydrocyclones operation. The study examines displacers with a taper angle of 25, 35, 43, 45 and 50°, with one and two baffle rings and smooth ones. The outer rings diameter of was 1.2-1.8. It was found in the experiments that hydrocyclones work better with two baffle rings with the 1.45-1.5 diameter. The optimum distance is 0.7-0.8 of the average diameter. The best taper angle of the γ displacer is 35-43°.

The optimal hydrocyclones performance was obtained with the solid particles content in the initial formation fluid not more than 3 g/l.

Mathematical processing of experimental results made it possible to obtain data on the change of tangential velocity of liquid phase in the device, which are consistent with results given in works [8, 9]. Tangential velocity of the liquid in the wall area can be determined by formula [10]:

\[ \frac{\theta_{\text{ex}}}{\theta_{\text{in}}} = 3.1 \left( \frac{d_{\text{ex}}}{D} \right)^{0.32}, \]  

where \( \theta_{\text{ex}} \) – rate of suspension at the inlet to the hydrocyclone, m/s; \( d_{\text{ex}} \) – equivalent diameter of the inlet rectangular nozzle, m; \( D \) – hydrocyclone diameter, m.

To solve the partial differential equation of the first order (2), the characteristic method was used allowing reducing the partial differential equation to an equivalent system of ordinary differential equations, one of which determines the trajectory of particle movement in the suspension, depending on the place of entry of the particle into the device; i.e. the direction of the characteristic is set, and the other determines the values of the function, i.e. relative volume fractions of solid particles on the characteristic. The system of ordinary differential equations was solved using the Runge-Kutt method with a fixed pitch. When dividing the calculation interval according to the radius of the hydrocyclone by fifty steps, the maximum calculation error was 0.026%, which fully provides the necessary accuracy for calculating the concentration field.

Based on the results of simulation of the velocity and pressure fields in the flow of the non-Newtonian suspension in the hydrocyclone obtained in works [5, 6], and their subsequent approximation, the concentration field of solid phase particles was simulated during separation of the suspension in the hydrocyclone by pressure flotation. The simulation consisted in a numerical solution of the differential equation system characteristic method obtained from equation (2) under boundary condition (1) for different values of the determining criteria of similarity and rheological properties of the suspension when they change in a wide range. The suspension flow in the hydrocyclone was characterized by a centrifugal Froude number \( Fr \) (separation factor), an analogue of the Reynolds criterion for power-law liquids \( Re_\text{in} \), a dimensionless flow...
rate $\bar{Q}$, as well as an indicator of the nonlinearity of the flow curve $n$ [5, 6], which can be calculated using the following formulas: $Fr = \frac{u_0^2}{gR}$, $Re_n = \frac{\rho R u_0^2}{k}$; $\bar{Q} = Q/(nR^2u_0) = ab/(nR^2)$, where $\rho$ – suspension density, kg/m$^3$; $a$ – axial size of the feed pipe, m; $g$ – gravity acceleration, m/s$^2$.

It is necessary to use integral performance indicators of the device to assess the influence of the determining similarity criteria on the performance of the hydrocyclone. The most important of these indicators is the recovery degree of the solid phase particles, which characterizes the solid phase particles proportion extracted from the suspension in a given film section. It is determined by the formula

$$S = 1 - \frac{2\bar{a} \int_{-\bar{b}}^{\bar{b}} c_h \phi_0(\bar{r}, \bar{z}) d\bar{r}}{\bar{a} \int_{-\bar{b}}^{\bar{b}} c_{h0} \phi_0(\bar{r}, \bar{z}) d\bar{r}}$$

(3)

where $\bar{a}$ – dimensionless axial size of the feed pipe; $\bar{b}$ – radial size of the flow zone in which the volume fraction of solid phase particles in the suspension is different from zero, m; $\phi_0(\bar{r}, \bar{z})$ – distribution of the dimensionless circumferential component of the flow rate when the suspension enters the hydrocyclone.

Calculations of the degree of recovery in different sections of the suspension film by the height of the hydrocyclone working zone were carried out using formula (6) and the Maple 6 computer algebra package. As a result, graphs of changes in the degree of extraction depending on the axial coordinate $\bar{z}$ were obtained. To obtain the distribution of the relative volume fraction of solid phase particles in each section of the film, an approximation of the distribution of the volume fraction of solid phase particles by polynomial was made with subsequent numerical integration of functions according to formula (6) within the specified limits.

**Fig. 2.** Dependence of solid particles content in a drain $C$ on the flow rate of suspensions $V$.

**4. Conclusion**

The research was carried out on a real product at a pressure and flow rate corresponding to production conditions. The obtained results allow us to design and manufacture an industrial sample of the device. It is possible to use experimental data for calculating similar hydrocyclones for operation with other mixtures.
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