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Authors:

Alexandr Repko, Milan Sága, Boris Sentyakov, Vladislav Sviatskii

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Article

Development and Testing of a Block Hydrocyclone

Alexandr Repko [1,*], Milan Sága [2], Boris Sentyakov [1] and Vladislav Sviatskii [1]

[1] Technology of Mechanical Engineering and Instrument Making, Votkinsk Branch of Kalashnikov Izhevsk State Technical University, 427430 Votkinsk, Russia; sentyakov@inbox.ru (B.S.); svlad-2000@yandex.ru (V.S.)
[2] Department of Applied Mechanics, Faculty of Mechanical Engineering, University of Žilina, 01026 Žilina, Slovakia; milan.saga@uniza.fstroj.sk
* Correspondence: aleksrepko@gmail.com

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Abstract: The study aimed to theoretically substantiate the efficiency of liquid purification and obtain corroborating experimental data for a hydrocyclone, consisting of several blocks. Mathematical models of the process of hydrodynamic fluid filtration were developed with the use of screw swirlers. The obtained mathematical models characterize all the main processes of fluid movement in various zones of the functioning of the hydrocyclone. Formulas for calculating the structures of hydrocyclone blocks are included. A block for swirling the flow of the liquid to be cleaned has been made in the form of a three-way screw. For the first time, wear-resistant and high-strength plastic ZEDEX ZX-324 has been used as a material. An experimental study was conducted and the change in the Reynolds number and the coefficient of fluid consumption was shown, using different constructions of the three-way screw. The research results confirmed the correctness and sufficiency of mathematical models for the development and production of block hydrocyclones.

Keywords: block hydrocyclone; filter; screw swirler; swirl unit; filtration unit; flow hydrodynamics

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1. Introduction

The production process of oil is accompanied by the need to supplement large amounts of water or special fluids under high pressure to underground wells. Such liquids must be cleaned first of mechanical impurities. To solve this problem, hydrocyclone devices for cleaning liquids of mechanical impurities are of great interest. Hydrocyclones are preferred units for sizing or desliming large slurry volumes cheaply and because they occupy very little floor space or headroom. They operate most effectively when fed at an even flow rate and pulp density and are used individually or in clusters to obtain desired total capacities at required splits [1]. The ability of a hydrocyclone to meet required solids/liquid separation needs is governed by the design variables of the equipment itself [2]. These variables include cone diameter, overall body length, as well as the dimensions of the feed, apex, and vortex openings [3–5]. A major drawback of hydrocyclones is that during upsets in flow or pressure drop, the rotary motion in the cone may be interrupted, possibly causing solids to carry over into the overflow liquid. Other drawbacks are wear problems, large pressure drops, and limited ability to handle surges in flow. Some manufacturers offer replaceable liners to handle wear problems [6–9]. Replaceable liners are made of stainless steel. They have a complex shape, large mass, and are expensive to manufacture. An urgent task is to simplify the design of the replaceable liner and use modern materials for individual parts, for example, wear-resistant plastics.

In hydrocyclones, it is necessary to ensure the presence of an optimal flow swirling zone; a liquid purification zone with maximum trapping of impurities with subsequent disposal; and a purified liquid supply zone with minimal friction losses and resistance at the outlet of the device.

The presence of three hydrocyclone zones, different in purpose and design, associated with the conditions of a continuous flow of liquid with mechanical impurities, creates a complex system that requires the development of mathematical models of the hydrodynamics of the filtration process to ensure quality and geometric characteristics [10–12].

For a hydrocyclone consisting of several blocks, it is necessary to theoretically justify the optimum hydrodynamics of fluid flow in all zones and experimentally determine the variables needed to correct the formulas.

Mathematical models and experimental data should make it possible to calculate or design individual hydrocyclone blocks, as well as to take into account their relative position and design. The hydrodynamics of the liquid filtration process in a hydrocyclone must be predictable.

2. Materials and Methods

Analytical and experimental research methods were used to solve the problem posed in this work [13,14]. The mathematical model of the fluid filtration process was built based on the well-known equations of hydrodynamics: the equations of fluid motion through pipelines, the continuity equation of the fluid flow, the laws of motion of swirling fluid flows. and the Bernoulli equation [15]. For the experimental study of the flow swirling and fluid filtration units, a special experimental setup was made. The working fluid was water at a temperature of 20 °C. The coefficients of the flow rate of each element and the flow regimes of the liquid were determined according to the Reynolds criterion. The unit for swirling the fluid flow was a screw with three complex-shaped channels that was produced using modern CAD/CAM/CNC technologies [16,17]. The studies used ANSYS Fluent software. Research methodology using this program included developing a mathematical model, accepting boundary conditions, performing calculations, and analyzing the results [18,19].

2.1. Mathematical Models

Oil production processes use water, which supplies formations under high pressure. Water is taken from wells and open reservoirs of large areas. Water intakes supply water through filtration units, where water is purified from solid impurities, sand, fine gravel, and clay inclusions, in centrifugal filters located along the flow in the pipes. The mathematical models of the hydrodynamics of the filtration process developed in this project considered the special block design of the hydrocyclone filter. The design of the filter provides a unit for swirling the liquid flow in the form of a three-way screw and a filtration unit with holes to remove dirt particles. The blocks were manufactured and installed separately, and their design and geometric dimensions depend on several parameters: the size and material of the particles of mechanical impurities, the value of the specified separation coefficient, and the required flow rate and fluid pressure. The design and operation of the blocks mutually influence each other to ensure minimum friction and resistance losses. Figure 1 shows the design of a block hydrocyclone developed by the authors.

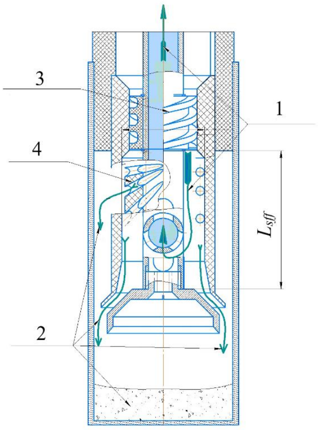

Figure 1. Functional diagram of the relative position and operation of the fluid flow swirl unit (screw) and the filtering device.

L_{sff}—length of swirling fluid flow, mm;
1—the direction of fluid movement;
2—the direction of movement and location of particles of mechanical impurities in the sump;
3—fluid flow swirling unit (auger);
4—filtration unit.

Various devices, e.g., tangential channels, helical and straight blades, spirals, and screws with helical channels, can provide rotational movement of the liquid. In our work, the object of the research was a screw with several screw channels. A typical auger layout is shown in Figure 2.

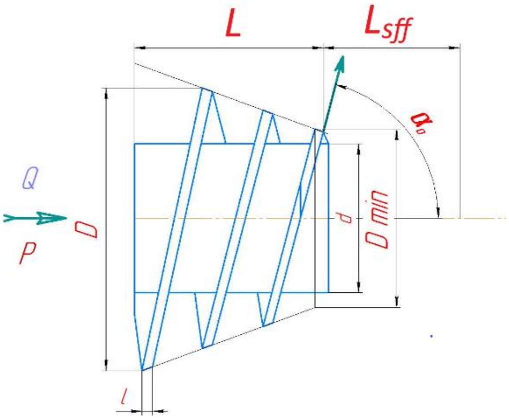

Figure 2. Schematic of a screw with screw channels.

In the manufacture of hydrocyclones, the cylindrical billet of the screw is changed to the shape of a cone with the diameters of the initial and final parts D and D_{min}, respectively, and L is the length of the turnover of the spiral of the screw channel along the axis of the screw (Figure 2).

Then, the length of the screw channel of the screw decreases and for the correctness of the calculation results in (1.1) instead of D it is necessary to use $\frac{D+D_{min}}{2}$.

There can be one to several screw channels. The length of the spiral of each screw channel, L_{sc}, according to the diagram, can be determined in a simplified way:

$$L_{sc} = \sqrt{\pi^2 D^2 + L^2} \tag{1}$$

Then, the angle of inclination of the screw channel of the screw to the axis of the hydrocyclone α_0 will be equal to:

$$\alpha_0 = \sin^{-1}\frac{\pi D}{L} \tag{2}$$

The pressure loss in the channels between the spirals, $h_{\omega\kappa}$, will primarily depend on the modes of water movement.

So, for the laminar regime (Darcy's formula) [20–22].

$$h_{\omega\kappa} = \frac{32 V_k \nu L_{sc}}{q d_k^2} \tag{3}$$

For turbulent conditions (Konakov's formula) [20–22].

$$h_{\omega\kappa} = \frac{L_{sc}}{d_k\left(1.8\log\frac{V_k d_k}{\nu} - 1.5\right)^2}\frac{V_k^2}{2g} \tag{4}$$

Equation (4) is for each channel, i.e., if there are K_{sc} channels, then the total pressure loss in the flow will be K_{sc} times greater. Usually, the main indicators of the entire water supply device is the flow rate Q (total) and then the pressure. We find the cross-section of the channels by the formula:

$$S_k = \frac{\pi^2}{4K_{sc}}\left(D^2 - d^2\right) - \frac{l(D-d)}{2} \tag{5}$$

D—maximum screw diameter, mm;
l—wall thickness between the screw channels of the screw, mm;
d—screw base diameter, mm.

From the equation of continuity:

$$Q = V_{fl}\frac{\pi D^2}{4} = K_{sc}V_kS_k \tag{6}$$

We get:

$$V_k = \frac{Q}{K_{sc}S_k} \tag{7}$$

Q—total flow rate, m^3/s;
V_{fl}—flow velocity, m/s;
K_{sc}—number of channels;
S_k—cross-sectional area of screw channels, mm^2;
V_k –flow velocity at the outlet of the screw channel, m/s.

The presented mathematical model (Formulas (1)–(7)) not only describes the hydrodynamics of flows in the screw swirler but also allows you to determine the geometric dimensions of the screw and its screw channels to reduce pressure losses and obtain the required fluid flow rate at the outlet of the device.

Since the fluid flow rate at the outlet of the helical channel, V_k, is directed at an angle, α_0, to the axis of the flow, we can decompose it into axial and torque components.

Following the design characteristics of the hydrocyclone, the contaminated liquid, after swirling the flow with a screw, is poured in the form of small-volume streams into the filtration unit. The filtration unit is a pipe with holes for removal of mechanical impurities from the liquid. In a short time, the liquid fills the entire cavity of the filtration unit, therefore, according to the flow continuity theorem, the flow rate, Q, will remain constant. Only the pressure will change.

The twisting component, V_{tc}, creates a vortex motion of water in the pipe and V_{ac} translation.

$$\left.\begin{array}{l} V_{tc} = V_k \sin\alpha_0 \\ V_{ac} = V_k \cos\alpha_0 \end{array}\right\} \tag{8}$$

Centrifugal forces act on the particles of impurities located in the volume of the liquid flowing through the pipe and deposit these impurities on the walls. The attenuation of the velocity, V_{tc}, along the length of the pipeline is small because its losses occur on the pipe walls, and they are always covered with a thin boundary layer of the liquid, and the coefficient of friction against this layer is insignificant. The speed of a forward movement of water, V_{ac}, decreases significantly. It is necessary to determine if fluid flow in the hydrocyclone is laminar (3) or turbulent (4).

Naturally, for a screw with several channels, you need to substitute in the formulas:

When determining losses, instead of losses in one channel, $h_{\omega\kappa}$, use the loss of the entire flow in the sum of the channels, $K_{sc}h_{\omega\kappa}$;

When determining the geometry of the arrangement of devices for capturing particles of impurities in a liquid, instead of L_{sc} (the length of the spiral of each screw channel), it is necessary to put in the formula for the length of the swirling liquid flow, L_{sff};

When determining the area of the supply channels, instead of the diameter of the screw channel, d_k, use the sum of the diameters of the screw channels of the screw, D_k.

The amount of impurities deposited is constant in any cross-section per unit time of one revolution of the vortex of water in the pipe. However, due to the decrease in the fluid flow rate due to pressure losses along the length, the outlet openings for impurities can be positioned along the pipe with a step, separating the volumes of the liquid to be cleaned with the same amount of impurities (Figure 3)

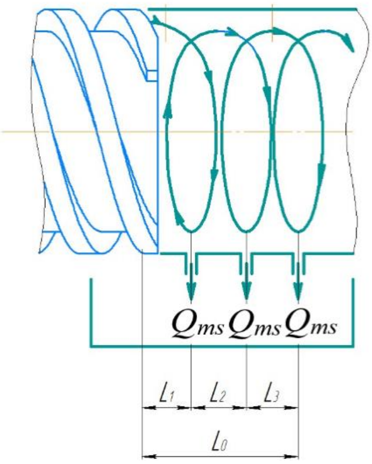

Figure 3. The layout of the outlets for the collection (disposal) of particles of mechanical impurities.

Let us designate the flow rate of the separated particles of mechanical impurities through the outlet openings in the liquid filtration unit as Q_{ms}.

The main task is to select the value of Q_{ms} so that the sum of all losses compensates for or is equal to the loss of flow from the pressure loss along the length of the turnover of the spiral of the screw channel along the screw axis L (Figure 2) and the pressure losses along the length or height (depending on the horizontal or vertical design) of the devices for disposal (removal) of particles of mechanical impurities L_0 (Figure 3). Then, the theory of fluid flow continuity is not violated and the values V_{tc} and V_{ac} are constant. In other words:

$$Q_{\sum\ \Delta h} = Q_{\Delta hf} + NQ_{ms} \tag{9}$$

$Q_{\sum\ \Delta h}$—liquid flow rate taking into account the sum of all losses, m^3/s;
$Q_{\Delta hf}$—liquid flow rate taking into account the friction loss, m^3/s;
N—number of holes.

The diameter of the holes for Q_{ms} should be selected according to the real pressure in the sector between the holes according to the Bernoulli equation [20–22].

$$Q^0_{ms} = \mu\sqrt{2g\left(\frac{P}{\rho g} - K_{sc}h_{\omega k} - h^0_{fl}\right)} \tag{10}$$

$\mu = \nu\rho$—dynamic viscosity index, Pa·s;
P—pipe inlet pressure, Pa;
ρ—density of a liquid contaminated with particles of mechanical impurities, Kg/m^3;
h^0_{fl}—losses along the length L_1, or L_1, L_3 of the flow from the flow exit from the screw swirler to the first, second, etc. the outlet for disposal (removal) of particles of mechanical impurities.

From (10) it can be seen that the pressure in the pipe falls, and, therefore, the flow velocity at the inlet to the screw swirler should fall, otherwise the law of fluid continuity will be violated. To increase the flow rate, the inlet pressure must be increased by:

$$\left(K_{sc}h_{\omega k} + h^0_{fl}\right)\rho g = P_{max} \tag{11}$$

The deposition rate of a particle with a diameter d_{ms} and a density ρ_{ms} will have the form:

$$V_{ms} = \frac{d^2_{ms}(\rho_{ms} - \rho)\omega^2 r_{lms}}{18\ \mu g} \tag{12}$$

It is clear (since r_{lms} is the radius of the particle from the axis of rotation) that this velocity is not constant in magnitude. Due to the insignificance of the value of the pipe diameter, we will assume that it grows linearly from zero to $V_{ms\ max}$.

The minimum size (diameter) of a particle that can overcome the resistance of the current environment is calculated as follows:

$$d_{ms\ min} = \frac{40.5}{n}\sqrt{\frac{\mu V_{ms}}{(\rho_{ms} - \rho)r_{lms}}} \tag{13}$$

In the case of $d_{ms\ min} = d_{ms}$, we assume that the sand admixtures are uniform, then $r_{lms} = r_{lms\ min}$, i.e., at this radius, sand is not removed, the fluid flow passes through the center polluted by speed $\frac{V_{ms\ max}}{2}$, and the ring from $r_{lms\ min}$ to $r_{ms} = \frac{D}{2}$ is cleared completely, but at different speeds, and the maximum speed will be:

$$V_{ms\ max} = \frac{d^2_{ms}(\rho_{ms} - \rho)\omega^2 \frac{D}{2}}{18\mu g} \tag{14}$$

The amount of cleaning is determined by the ratio of the volumes of the contaminated and treated liquid, namely $\frac{\frac{\pi D^2}{4}L_{sff}}{\pi r^2_{ms\ max}L_{sff}} = \frac{D^2}{4r^2_{ms\ max}}$. The degree of liquid purification from solid impurities η_{fl} is equal to:

$$\eta_{fl} = \frac{r^2_{ms\ max}}{4D^2}\cdot 100\% \tag{15}$$

From Bernoulli's law, the speed of fluid flow along the length of the flow due to friction losses decreases in proportion to the change in $\sqrt{P}$, where P is the pressure in the pipe.

Having determined the Reynolds number characterizing the mode of water flow through the screw, we correct the design of the liquid filtration unit. For laminar mode, P changes linearly from P to P_{min}.

Therefore, it is possible to arrange the outlet openings for the collection (disposal) of particles of mechanical impurities so that equality of the flow rate and the velocities of the liquid will be ensured. To do this, it is necessary to place the holes on the boundaries of the plot sections with the same area S_1; S_2; S_3 (Figure 4):

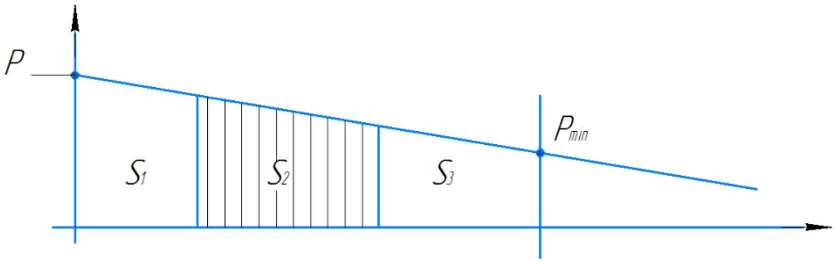

Figure 4. The layout of 3 holes for collection (disposal) of particles of mechanical impurities, depending on the decrease in pressure.

Hole diameters are calculated using the formula:

$$d = \sqrt{\frac{4Q_{ms}}{\pi}} \tag{16}$$

Thus, Formulas (1)–(16) fully describe the mutual dependencies of the process of cleaning a contaminated liquid by a block-type hydrocyclone using a screw swirler and a filtration unit: the flow rate and pressure of the liquid, the number and length of screw channels, the location and diameters of the outlets for the disposal (removal) of particles of mechanical impurities, diameters of the inner surface of the filtration unit, and the screw swirler.

These are all variable values, the threshold values of which must be assigned to increase the degree of liquid purification from mechanical impurities. If the degree of cleaning is determined by the customer, then the geometric characteristics of the hydrocyclone filter must be determined.

2.2. *Area of Research*

To confirm the correctness of the developed mathematical models and to determine the variables that are necessary for correcting the formulas, experimental studies of the flow passage through the blocks of swirling and filtration of the liquid were carried out.

A schematic diagram of the experimental setup for research is shown in Figure 5. The installation is a screw, 2, installed with interference in a cylindrical tubular body, 1, along the axis of which a tubular element, 3, is located. The body, 1, is installed in a sleeve, 4, with a transparent pipe, 5, and is fixed in the lower part of the vessel, 6, filled with water at a temperature of 20 °C. In the lower part of the installation, there is a measuring container, 7, for receiving the water flowing out of the swirling unit. To ensure the required corrosion resistance of the hydrocyclone, steel 1.7034—EN 10083-3 was used for the body parts; tubular element, 3, is made of steel X6CrNiTi18-10—1.4541.

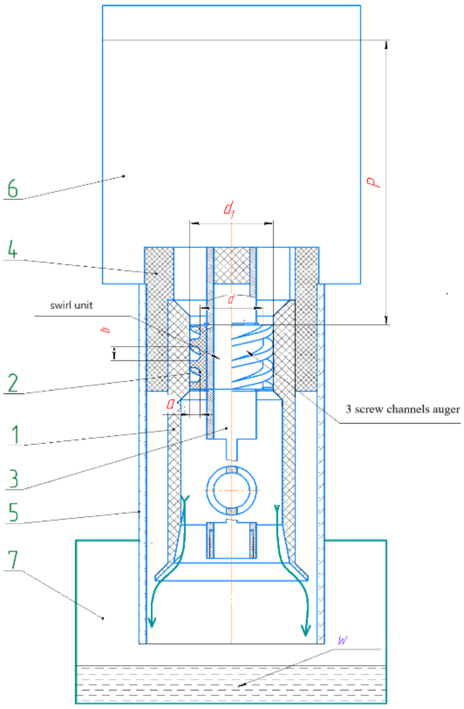

Figure 5. Diagram of the experimental setup for studying the swirling block of the flow of the liquid being cleaned.

The main task of the experimental study of the unit for swirling the flow of the liquid to be cleaned was to determine its flow coefficient and the flow regime of the liquid. For this purpose, to eliminate the influence of extraneous factors, the tubular element, 3, was plugged and the walls of the body, 1, were made smooth, without holes.

In the course of the experiments, water under constant hydrostatic pressure, P, flowed out over time, t, through the swirling unit into the measuring vessel, 7. In this case, the actual water flow rate, Q, was calculated as a quotient by dividing the volume, W, of the outflowed liquid by time, t.

The swirler (Figure 6) was a round piece with an outer surface made in the form of a 3-lead spiral; the outer diameter was 22 mm. The inner diameter of the liquid filtration unit for impurities was 14 mm. The progressive plastic ZEDEX ZX-324 was used as a material for the manufacture of the swirler. It has high wear resistance, the polymer reinforcement with carbon fiber increases strength by 1.5 times and reduces the effect of alternating temperature and physical loads, and the surface wettability indicator provides low resistance to liquid outflow, which in turn ensures high production efficiency.

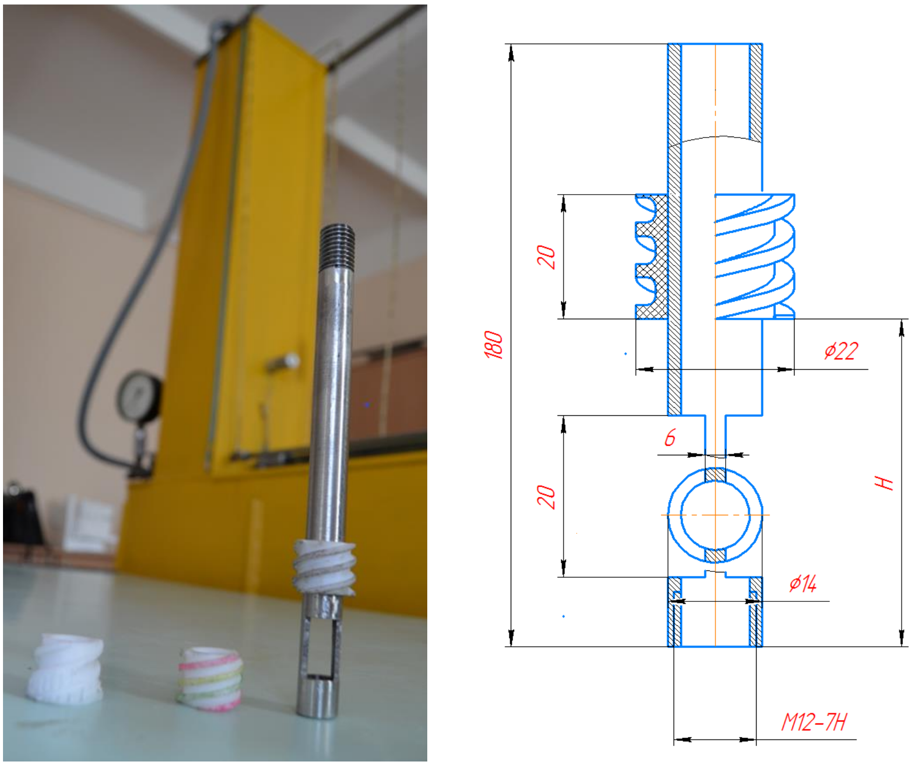

Figure 6. General view and diagram of the manufactured fluid flow swirling unit.

To determine the flow rate of the swirling unit and the outflow mode, the known [22,23] calculated dependences were used.

The flow rate of water, Q, through the channels of the screw when it flows out under constant hydrostatic pressure is as follows:

$$Q = \mu_{fl} S_k (2gP)^{0.5} \tag{17}$$

μ_{fl}—coefficient showing the flow rate of fluid through the swirl unit;
S_k—total cross-sectional area of the screw channels, $m^2 \cdot 10^{-3}$;
$g = 9.8$ m/s^2;
P—hydrostatic pressure (head), m.

Average water velocity:

$$V_k = \frac{Q}{S_k} \tag{18}$$

Reynolds number characterizing the mode of water flow through the swirling unit:

$$Re = \frac{2S_k^{0.5}V_k}{\pi\nu} \tag{19}$$

where ν =10^{-6} m^2/s, i.e., the kinematic viscosity of water at 20 °C.

3. Results and Discussion

The results of the experimental study of the two variants of a swirling unit having in its design three-way screws with different channel cross-sectional areas and different channel spacings when water flows through it at a temperature of 20 °C under the pressure of $P = 0.21$ m are presented in Table 1.

Table 1. Swirling unit research results.

№ Test	Area of the Screw Channels, S_k, $m^2 \cdot 10^{-3}$	Liquid Flow Time, t, s	Volume Liquid, W, $m^3 \cdot 10^{-3}$	Flow Rate, Q, $m^3/s \cdot 10^{-3}$	Water Velocity, V_k, m/s	Reynolds Number, Re	Coefficient Flow Rate, μ_{fl}
The pitch of screw channels of swirler 15 mm							
1	0.0172	237	4.8	0.0170	0.98	4590	0.487
2	0.0172	76	1.35	0.0177	1.029	4819	0.507
3	0.0172	71	1.2	0.0169	0.983	4604	0.484
4	0.0172	62	1.1	0.0177	1.029	4819	0.507
5	0.0172	61	1.075	0.0176	1.023	4791	0.504
6	0.0172	61.5	1.12	0.0172	1.000	4683	0.493
7	0.0172	76	1.35	0.0177	1.029	4819	0.507
Average values						4732	0.498
The pitch of screw channels of swirler 22 mm							
8	0.027	62	2.1	0.0339	1.250	7325	0.619
9	0.027	63	2.175	0.0345	1.277	7483	0.623
10	0.027	61	2.05	0.0336	1.244	7289	0.616
Average values						7365	0.619

Analyzing the results presented in Table 1, we can conclude that with an increase in the total cross-sectional area of the screw channels from $0.0172 \cdot 10^{-3}$ m^2 to $0.027 \cdot 10^{-3}$ m^2 with a simultaneous increase in the pitch of their location from 15 to 22 mm, under the hydrostatic pressure P = 0.21 m (0.00205 MPa), the average Reynolds number increases from 4732 to 7365, and the average coefficient flow rate increases from 0.498 to 0.619.

The maximum deviation of the flow coefficient values obtained in the indicated groups of experiments from the average values is from 0.6 to 2.2%, which makes it possible to ensure good repeatability of the results, and the accuracy is sufficient for engineering calculations. To ensure flow swirling and liquid purification, the Reynolds number must be at least 3000, and the coefficient flow rate must be 0.35. Consequently, a hydrocyclone filter made by the developed mathematical models is operational even at minimum values of hydrostatic pressure. To ensure the required length of the swirling fluid flow, taking into account the obtained Reynolds number, the formulas presented in the article allow calculating a new design of a 3-entry screw. This, in turn, determines the location of the holes for collecting particles of mechanical impurities while ensuring the equality of the flow rate and fluid flow rates in the filtration unit.

4. Conclusions

The results of the study make it possible to take into account the mutual influence of the flow rate and pressure of the liquid, the number and length of screw channels, the location and diameters of the holes for collecting particles of mechanical impurities, and the diameters of the inner surface of the filtration unit and the screw swirler [24,25]. Studies have shown that hydrocyclone blocks can be made of materials of various properties, e.g., metals and plastics, which improve performance, reduce weight, and allow the use of advanced materias processing technologies that reduce the cost of the product. Mathematical models, supplemented by experimental data, take into account the type and size of particles of mechanical impurities, which is necessary for the design and manufacture of hydrocyclones with a given degree of fluid purification for a particular well or reservoir. It is also possible to use the developed block hydrocyclone with predetermined separation characteristics to separate only certain materials from the liquid, for example, in the extraction of minerals. The proposed formulas allow for calculating the optimal overall dimensions of the hydrocyclone to ensure the maximum compactness of the ground filtration unit. In the case of using a good block hydrocyclone, the maximum efficiency of liquid filtration will be ensured. The applied designs allow for a simple and quick replacement of blocks and improve the maintainability and durability of the hydrocyclone.

Analysis of the results showed that with an increase in the total cross-sectional area of the screw channels and an increase in the spacing of the channels' location, both the average Reynolds number and the average flow coefficient will increase:

The values of the increase of the Reynolds number and the flow coefficient are as follows:

- the average Reynolds number from 4732 to 7365 and
- average flow coefficient from 0.498 to 0.619.

The results of the study must be taken into account for developing designs for block hydrocyclones of increased efficiency and maintainability.

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