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ON THE IMPROVING THE CLASSIFICATION CHARACTERISTICS IN A HYDROCYCLONE THROUGH WATER INJECTION

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In hydrocyclones, the particle separation efficiency is limited by the suspended fine particles, which are discharged with the coarse product in the underflow. It is well known that injecting water in the conical part of the cyclone reduces the fine particle fraction in the underflow. This paper presents a mathematical model that simulates the water injection in the conical part of apparatus. The model accounts for the fluid flow and the particle motion. The model includes: the turbulent particle diffusion and particle settling. Particle interactions, due to hindered settling caused by increased density and viscosity of the suspension, and fine particle entrainment by settling coarse particles are also included in the model. Water injection in the conical part of the hydrocyclone is performed in an experiment to reduce fine particle discharge in the underflow. This added water transports the fine particles of the sediment to the center, where they are directed to the overflow.

The investigation of the influence of additional water injection in a classifier on the particle separation process characteristics has been performed on the basis of numerical modelling. It has been shown that the increase in water injection velocity leads to the increase of both the cut size and the minimal value of separation curve.

Keywords: water injection, fluid flow, particle motion, turbulent particle diffusion, particle settling.

Introduction

Instead of its great advantages, the conventional (normal design) hydrocyclone still have some limitations which makes it not able to fulfill all the industry applications. These limitations may be due to the following reasons:

a) the cut size lies outside the desired region,

b) fine particles fractions are not adequately captured by the classification

c) the sharpness of separation of the solid material is not high enough.

This can be explained with relative high turbulence in the apparatus which leads to enhancement of the diffusion of small fractions in the whole volume of hydrocyclone. As a result, the portion of fine material which misreported through the underflow discharge is proportional to the amount of water flow through the apex.

Progress in hydro - classification during the last 50^{th} years led to the development of a number of technical improvements in the construction of hydrocyclone contributing to the advancement of the desired characteristics [1, 2]. One of the most effective methods of adjusting the characteristics of hydrocyclone is the injection of water in the region of the high concentration solid phase (near the underflow opening). This technique has repeatedly reflected in the literature [1 -10], and still currently on the way of its development.

The simplest theoretical point of view on the mechanism of injection impact on the classification performance can be concluded to the imagination of washout the particles from the wall, where the zone filled with concentrated solid material is exist. It is assumed that the velocity of the injecting water which carries the particles in the direction from the wall towards the kernel flow is higher, at least for particulate fines, than their own sedimentation rate to the wall. Accordingly, the fine particles will be mostly moved together with the mean flow to the overflow.

The aim of the present work is, based on [10], to develop a simple mechanical-mathematical model which could give a clear indication of the impact injection mechanism for the classification process. This also will be an opportunity, at least in the first approximation to predict the dependence of the basic characteristics of the classification on the amount of the injected water and the influence of a number of parameters that characterize the hydrocyclone (hydrocyclone diameter, overflow and underflow openings diameters) and technological parameters (pressure, properties of processed suspension) on classification characteristics.

The simulation results were examined and compared with the experimental data obtained from the experiments which carried out through the present work using 50 mm water injection hydrocyclone.

The formulation of the model

By drafting the model, we consciously neglect some details of the complex hydrodynamics in a hydrocyclone, focusing on the following main factors which determine the classification process in a hydrocyclone:

- the movement of particles under the influence of the mass (centrifuge) forces to the wall,
- the diffusion of particles through turbulent diffusion caused by gradient of concentration of solid material (usually from the wall),
- the flow of water injection.

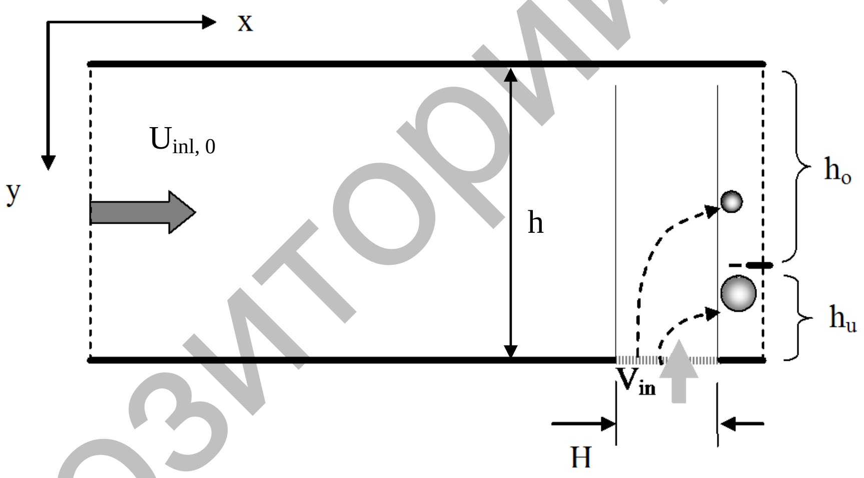


Fig. 1. The simplified schematic of a classifier (hydrocyclone)

As can be shown in Fig. 1, a classifier in form of a tube [11-13] of length L and height h, where the suspension flows from the left to the right at a constant velocity $U_{inl,0}$ will be considered. At the exit there are two discharges underflow (coarse) and overflow (fine). The particles in the suspension are subjected to the action of the centrifugal force along the *y*-axis and to the turbulent diffusion. Thus, the particles in the classifier move from left to right and settle in the vertical direction.

At the range of the length H immediately before the expiration of suspension the injection is made transverse to the main flow of water in such a way as to remove (mostly smaller) particles from the wall. This injection should be sufficient to "transfer" fine particles in the discharge upper section. But the injection should be quite weak, so that larger particles still were withdrawn through the bottom hole. We will consider that $\frac{d_j^2}{\nu} \Big/ \frac{d_j}{\left|V_{in} - V_{s,j}\right|}$ <<1 (particles are non inertial).

The equation for determining the particle concentration of each fraction will be written in the form of the system of equation, which describes the evolution of the volume concentration of the j-th size fraction (particles with diameter d_j) in the apparatus:

$$\frac{\partial\, U_{inl}(x)\, c_j}{\partial x} + \frac{\partial}{\partial y}\left[\left(V_{s,j} + V_{in}\right) c_j - D\frac{\partial c_j}{\partial y}\right] = 0\,, \tag{1}$$

The boundary conditions are:

$$\left(V_{s,j} + V_{in}\right) c_j - D\frac{\partial c_j}{\partial y} = 0 \text{ for } y = h\,, \tag{2}$$

$$V_{s,j} c_j - D\frac{\partial c_j}{\partial y} = 0 \text{ if } y = 0\,.$$

The condition in the entry is:

$$c_j\big|_{x=0} = c_{j,0}\,. \tag{3}$$

The model of jet injection

As a part of a simplified model an injection can be presented in the form of jet, flowed on a wall. In a simplified form the component of injection velocity along the jet will be described by a linear function of the coordinates across the main currents in the apparatus:

$$V_{in}(y) = \begin{cases} 0, \ 0 < x \le L - H, \\ \left(-\frac{y}{h}\right) V_{in,0}, \ L - H < x \le L \end{cases}, \tag{4}$$

The component of the velocity along the axis of the device is restored, based on the volume conservation equation:

$$\frac{U_{inl}(x)}{U_{inl,0}} = \begin{cases} 1, \ \ 0 < x \le L - H \\ 1 + \frac{V_{in,0}}{U_{inl,0}}\left(\frac{x - (L - H)}{h}\right), \ L - H < x \le L \end{cases} \tag{5}$$

Modeling of Particle Sedimentation in a Polydisperse Suspension

Experimental and theoretical results on settling of dense suspensions were developed by many investigators [2], whose studies were focused on the settling behavior of polydisperse suspensions. It has been observed that the settling velocity of the fine particles increases in the presence of coarser fractions. This phenomenon has been explained by different model considerations. Herewith, the results [14] on the settling of the dense suspensions are used.

In polydisperse suspensions, the most important effects which act on the settling particle are as follows:

1.Increasing the "effective" density and the viscosity of the fluid.

2. Counter flow of the displaced fluid caused by settling particles.

3. Entrainment of fine particles in the boundary layer range of coarse settling particles.

The complete equation for the settling velocity of j-fraction particles is summarized [14] as follows:

$$V_{S,j} = \frac{V_{H,j}}{d_j^2}\left[d_j^2 + g(c_V)f_E(d_j) - c_V\sum_{i=1}^{n}\left(d_i^2 + g(c_V)f_E(d_j)\right)\frac{c_j}{c_V}\Delta d_j\right]. \qquad (6)$$

In Eq. (6) the first term describes the hindered particle settling velocity due to the modification of the effective viscosity and density of the suspension where, the second term is responsible for an increasing of the settling velocity due to the entrainment of the fine particles by coarser ones and the third term considers a decreasing of settling velocity because of the counter flow of displaced liquid. From Eq. (6) it can be concluded that in a polydisperse suspension, the settling velocity of a particle depends not only on the total solids concentration c_V but also on the particle size distribution.

Here, $V_{H,j} = V_{St,j}(1-c_V)(1-c_V/0.6)^{1.5}$ is the function, which considered the hindering of the settling due to altering of viscosity and density, $g(c_V) = 4.0 \cdot c_V^{2/3}\exp\left[-\left(\frac{c_V}{0.2}\right)^3\right]$ - the correction function from experiments, $f_E(d_j) = \left(\sum_{i>j}\Delta m_i d_i^6\right)^{1/3}$ - the entraining function, $\Delta m_i = \frac{c_i}{c_V}$ - relative volume ratio of particles of j-th fraction, c_V - the total volume concentration of solid phase, β - parameter , which characterizes the size of particle, which can entrain the finest particles, $V_{St,j} = b\frac{gd_j^2}{18\mu_L}(\rho_p - \rho_L)$- sedimentation rate after the Stokes rate, b - centrifugal Number (ratio of the centrifugal acceleration to the g - gravitational one) μ_L - liquid viscosity, ρ_p - solid density, ρ_L - liquid density.

The condition of selecting *i* for a given value of *j* can be obtained on the basis of the inequality derived for the bidisperse suspension [14]: $d_i \geq \beta d_j$, where β is a constant, whose theoretical value confirmed by experiments, is in the range of 10 to 15.

Δm_i is the ratio of the particles volume of the *i*-th size fraction to the total volume of solid particles, which is related to the solid concentration c_i, because the ratio $\frac{c_i}{\sum c_i}$ also denotes the portion of volume of the *i*-th fraction. It can be written $\Delta m_i = \frac{c_i}{\sum c_i} = q(d_i)\Delta d_i$. Using the known or calculated concentrations the density of particle size distribution can be calculated at every point of apparatus as $q(d_i) = \frac{c_i}{\Delta d_i \sum c_i}$.

Definition of separation curve

Considering the width of the upper top output holes will be h_o (Fig. 1), then - $h_u = h - h_o$ the width of the underflow exhaust. The attitude *S* is called split-parameter where,

$$S = \frac{\int_0^{h_o} U_{inl}(x,y)dy}{\int_{h_o}^{h} U_{inl}(x,y)dy} \qquad (7)$$

At no injection, $U_{inl}(x) = U_{inl,0}$ and $S_0 = \frac{h_o}{h_u}$, and its value is usually is about 10. The flow of particles j-th factions through the upper and lower holes, respectively, defines the following functions:

$$R_{un,j} = \int_{h_o}^{h_u+h_o} U_{inl}(L) c_j(L,y) dy, \tag{8}$$

$$R_{ov,j} = \int_{0}^{h_o} U_{inl}(L) c_j(L,y) dy. \tag{9}$$

These features characterize the degree of separation of particles of each faction. Large particles mostly pass through the underflow (lower discharge), and the small ones across the overflow (upper discharge).

The separation function, showing the percentage of every particle fraction separated through the underflow (bottom) hole, in accordance with the model of separation [1] will be:

$$T(d_j) = \frac{R_{un,j}}{R_{un,j} + R_{ov,j}} \tag{10}$$

The function of separation and classification process is characterized, mainly, by the following parameters:

a) The fine percentage separated in the underflow and defined by the separation function for the smallest fraction T_0;

b) The $d_j^{[50]}$ - the diameter of the separation of particles recorded at 50% in the underflow (so-called cut size);

c) the sharpness of the separation, which is determined by the ratio of particle sizes, corresponded to the values of the separation functions of 0.25 and 0.75:

$$Qu = \frac{d_j^{[25]}}{d_j^{[75]}}, \tag{11}$$

Experimental test rig and procedures

The test-rig used in the experimental work consisted of a 50mm water injection cyclone positioned vertically above a feed tank (Fig.2a). This tank was connected to a centrifugal pump. The outlet of the pump is connected to the hydrocyclone feed inlet. A by-pass pipe with a control valve was connected to the outlet line to obtain the desired pressure drop inside the cyclone. A pressure gauge was fitted near the feed inlet to indicate the pressure drop. The water injection cyclone which used through this work is a conventional hydrocyclone with a modified conical part to have a water injection (Fig. 2b). The water injection assembly consists of an outer solid ring and inner solid ring with 5 inlet openings at equal distances open directly on the periphery of the cone part. This assembly is connected with a control valve of water through which the water can be entered in the assembly and is injected through these openings.

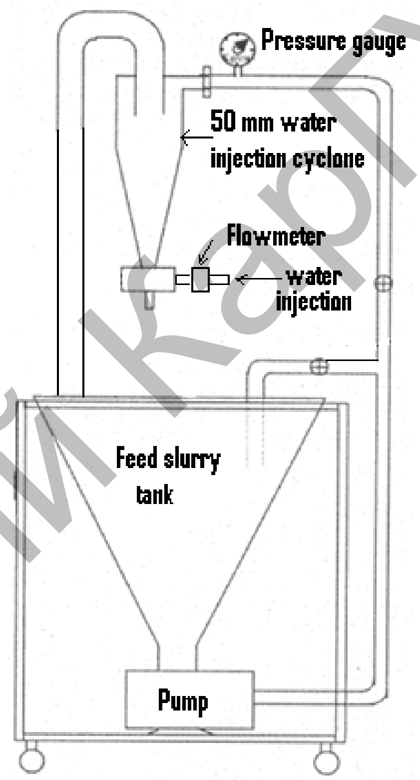
A digital manometer was fixed near the water injection to indicate the water injection rate. The ring was designed to permit the water to be injected in a tangential direction with the same swirling motion of the flow inside the hydrocyclone.

The water injection part was added near the apex of the cyclone without causing any extension of the total cyclone length.

Due to the water injection process, the feed water reporting to the underflow will be displaced by injected water carrying the misreported fines into the overflow. A pre-selected vortex finder and apex were fitted to the body of the water injection cyclone and then the feed is pumped at the required inlet pressure.

To investigate the effect of water injection rate on the hydrodynamics of the separation, the samples were taken at different flow rates. From these samples, the feed flow rate, overflow flow rate, and underflow rate can be calculated at every test from which the split parameter can be estimated.

a)



b)

Fig.2. Water injection hydrocyclone test rig. The photo (a) and the scheme (b)

Results and discussion

Choice of parameters for the calculation

To compare the measurements and the calculations, initially the agreement of the parameters in the theoretical model with parameters in the measurements must be determined. The hydrocyclone used in the experimental work can be characterized by the following sizes:

Hydrocyclone diameter D_c = 50x10-3 m, hydrocyclone length L = 0.6 m, inlet opening diameter D_f = 14.5 m 10-3, underflow diameter = 8x10-3 m, overflow diameter D_o = 16x10 - 3m, area of the feed S_f = 165x10-6m.

The calculations were made using the following parameters: constant of turbulent diffusion D_t = 10^{-3} m^2/s, split-parameter $S = 9$, initial inlet velocity 1.2 m/s, L=0.6 m, h = 50 mm=5*10^{-2} м, diameter of injection opening h_{in} =2.5*10^{-2} m (5 openings).

Initial total volumetric concentration of suspension is equal 0,094.

The number of fractions has been chosen to be equals to 51.

Obviously, these data on the schematized apparatus are taken only to understand as an approximation and serve only the purpose of the qualitative comparison of calculated and measured values.

Particle size distribution

The particle size distribution at the entrance of the apparatus used in the numerical simulation is shown in Fig. 3. In this Figure the particle size distribution of the suspension used in the apparatus entrance and calculated in both outlets (overflow and underflow) in the case of no water injection is also shown.

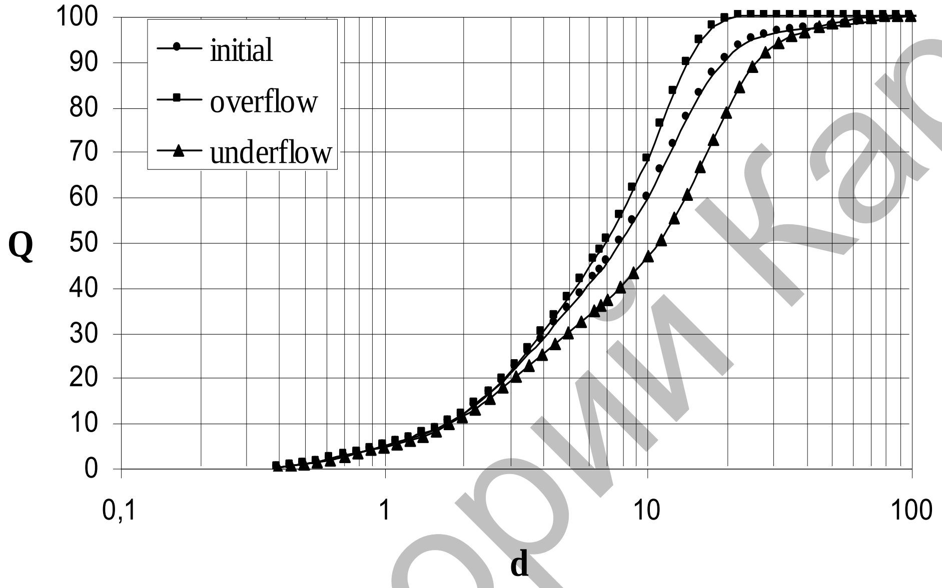


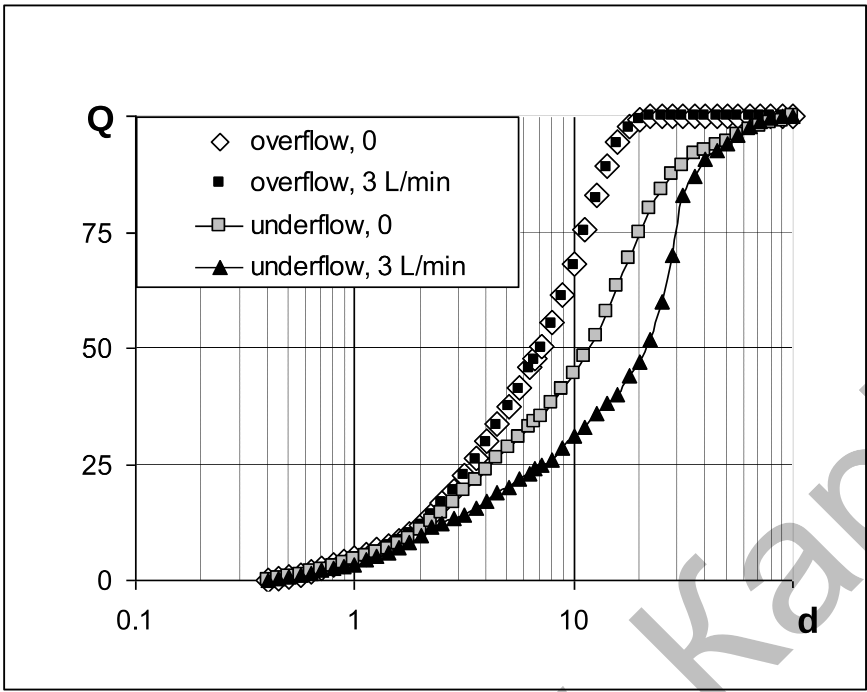
Fig. 3. Particle size distribution of suspension at the apparatuses inlet and in both outputs in the case of no water injection

These curves indicate the classification effect in apparatus in the normal operation (without water injection). The injection of water changes these distributions. Mostly this change has to occur only in the underflow (for the optimum washing effect).

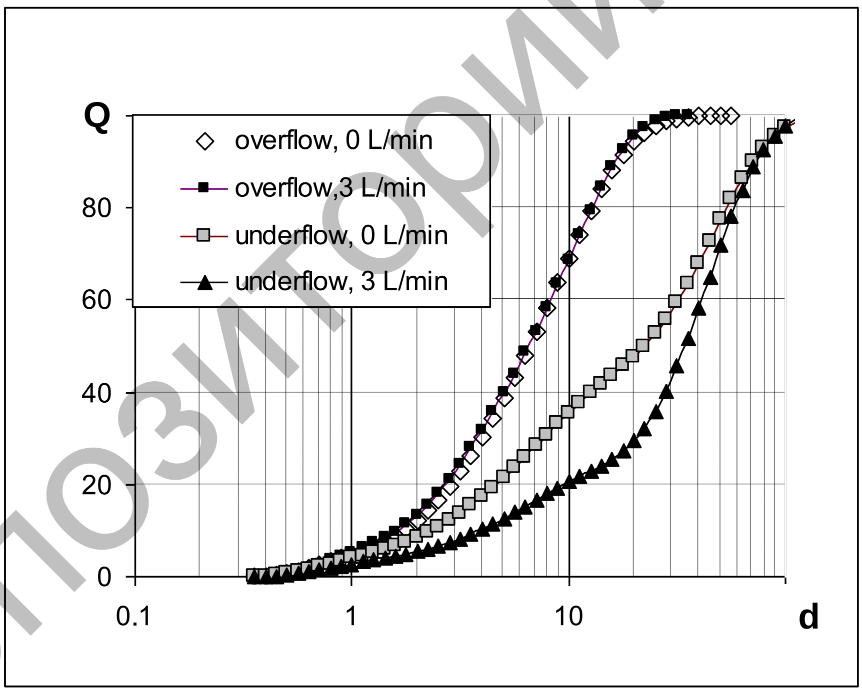
Fig. 4a shows, that for the computed results only the underflow material shows the difference in the particle size distribution due to the injection, whereas the material in the overflow does almost not influenced by the injection. Such situation is desired in the practice.

It can also be shown that, although the difference in size distribution between the calculated and the measured data for underflow material is rather greater as it for the material in overflow but there is also a clear qualitative coincidence.

The comparison of the separation curves obtained from numerical calculations and experiments can be seen in Fig. 5. It is indicated that the calculated separation curves are similar to the measured ones, but they show some of peculiarities. Firstly, by increasing the injection rate, the cut size increases numerically much stronger than experimentally. Further, in the theoretical model the “fish-hook” effect is less obvious than in the experiments. However, the change of the minimal value of separation curve T_0 in both cases (calculations and experimental) decreases approximately similar if the injection rate increases.

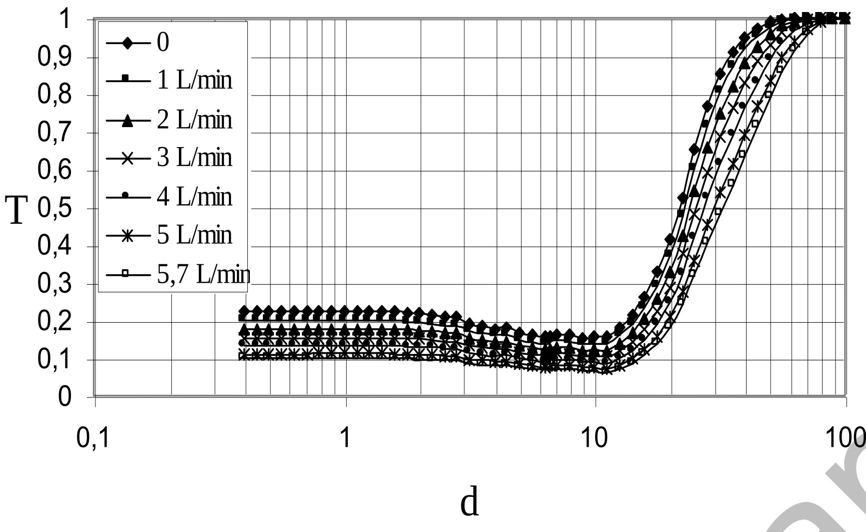


a)

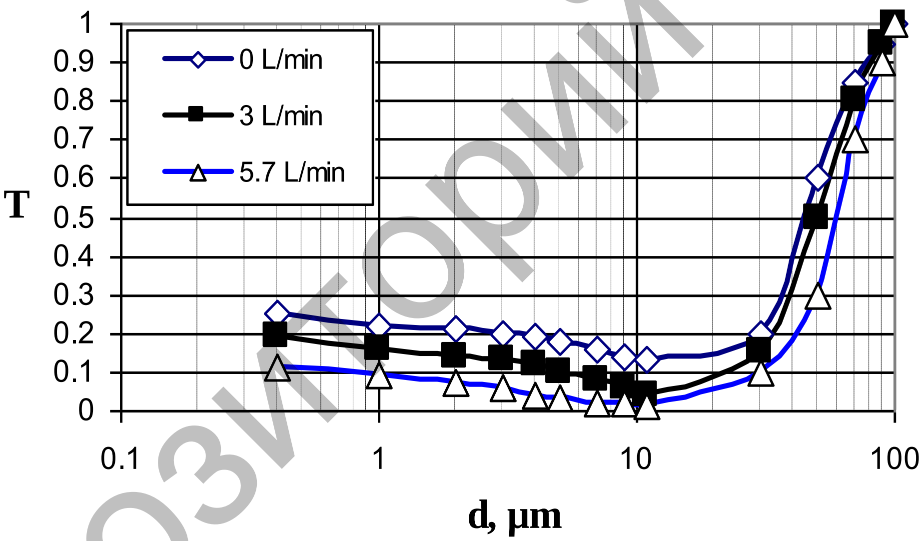


b)

Fig. 4. Comparison of the particle size distribution of overflow and underflow with ($V_{in,0} = 3$ L/min) and without water injection: a – calculation, b – measurements



a)



b)

Fig. 5. The separation curves at different injection velocities: a - numerical simulation, b - experiment

It is also shown that the non monotonous character of the separation curve becomes weaker if the injection becomes stronger (high injection rates).

The dependences of T_0 and d_{50} on the injection rate are shown in figures 6 and 7.

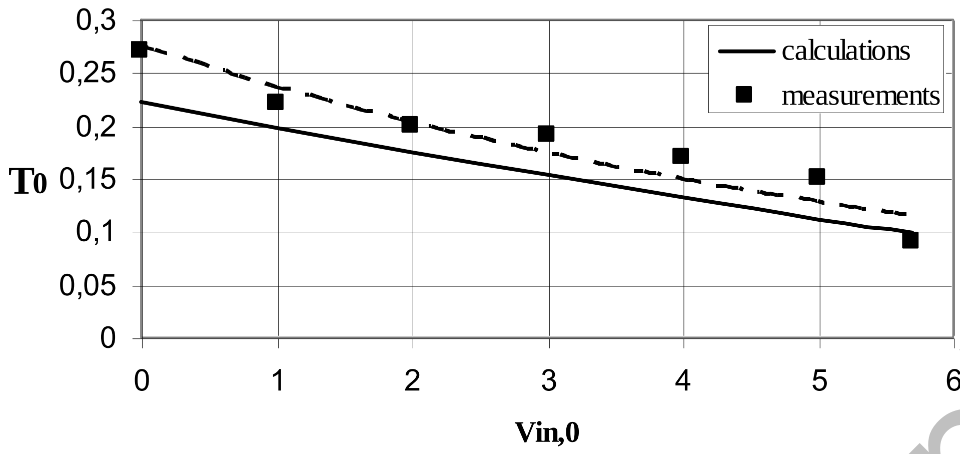


Fig. 6. Comparison of the calculated values of T_0 with the measured ones as a function of the injected water rate

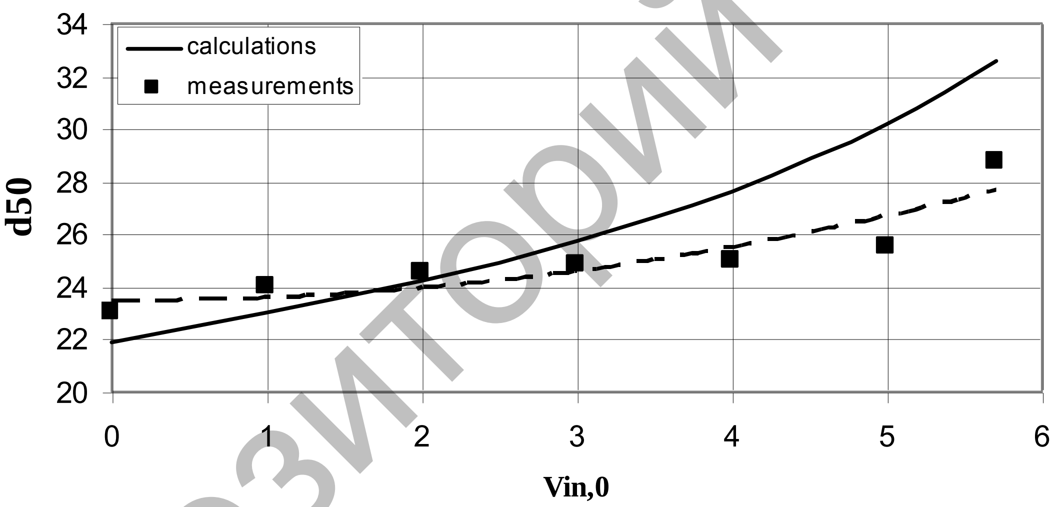


Fig. 7. Comparison of the calculated values of cut sizes d_{50} with the measured ones as a function of the injected water rate

The sharpness of the separation of the used disperse material through the apparatus with the considered characteristics decreases with the increase of injection rate in both calculations and experimental results as shown in Fig. 8.

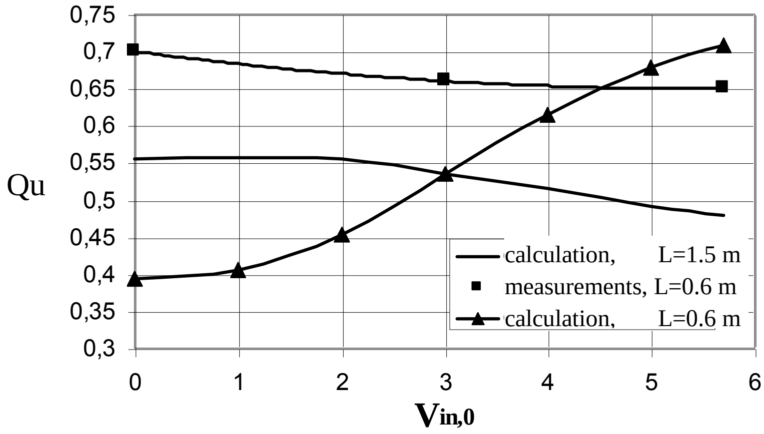


Fig. 8. Comparison of the calculated values of the separation sharpness with the measured ones as a function of the injected water rate

It should be noted also that the above presented results differ qualitatively from the dependence described in the literature in which Qu increases by increasing the injection rate as it has been shown in Fig.8. The possible reasons of this will be explained afterward.

Fig.9 shows that the total solid concentration decreases in the underflow and increases in the overflow by increasing the injection rate. It can be seen that both the calculated and the experimental results have a good agreement with each other.

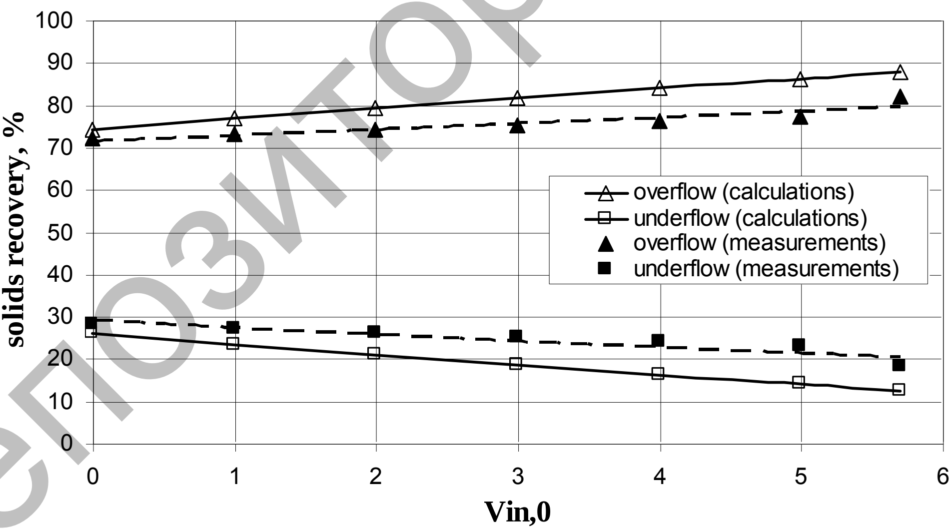


Fig. 9. Comparison of the calculated values of the solid concentration in underflow and in overflow with the measured ones as a function of the injected water rate

The analytic approximations.

The results shown in Figs. 5 to 8 can be explained with the use of the approximate solutions of system (1-3) in the limited case assuming that

1) the total solid concentration in suspension is very low;

2) the injection part is wide enough $H \approx L$.

Then the distribution of the particles concentration across the apparatus follows the equation:

$$\left(V_{s,j} + V_{in}\right) c_j - D \frac{dc_j}{dy} = 0. \qquad (12)$$

In frame of formulated model for injection jet the solution is

$$\ln \frac{c_j(y)}{c_j(0)} = \frac{V_{s,j}}{D} y - \frac{V_{in,0}}{Dh} \frac{y^2}{2} \qquad (13)$$

For the separation functions yields:

$$T(d_j) = \frac{1}{1 + S \exp\left[-\frac{h}{D}\left(V_s(d_j) - 0.5 V_{in,0}\right)\right]}. \qquad (14)$$

For $d_j \to 0$ from (12) follows

$$T(0) = \frac{1}{1 + S \exp\left[\frac{h}{2D} V_{in,0}\right]}, \qquad (15)$$

Obviously, that $T(0)$ decreases if the injection rate increases.

Considering $d^{[50]}(0)$ as the cut size in the absence of injection, the ratio is valid:

$$\frac{d^{[50]}}{d^{[50]}(0)} = \sqrt{1 + \frac{h}{2D \ln S} V_{in,0}}. \qquad (16)$$

Similarly, determining $d_j^{[25]}$ and $d_j^{[75]}$ from Eq. (14), the sharpness of the separation can be calculated as follows

$$Qu = Qu_0 \sqrt{\frac{1 + \frac{hV_{in,0}}{2D} \frac{1}{\ln(S/3)}}{1 + \frac{hV_{in,0}}{2D} \frac{1}{\ln(3S)}}} \qquad (17),$$

where - $Qu_0 = \frac{\ln(S/3)}{\ln(3S)}$ is the sharpness in absence of injection i.e., the separation sharpness increases with increasing of the injection speed. With increasing $V_{in,0}$ the sharpness tends to 1.

Discussion

The literature review has showed that many attempts were tried to regulate the characteristics of hydrocyclone classification by using the water injection near the underflow opening [1-7]. As a rule, such information considers limited and insufficient to describe of individual, concrete structures injectors and single measurements, indicating a significant impact on injection separation curve. In the overwhelming number of cases varies quantity of water.

The systematic measurements are random. So, in [2] provides $d^{[50]} \propto W_{in,0}^{0.6}$ for the dependence of cut sizes. The ratio of the solid material discharging through the overflow increases and decreases through the underflow.

According to Eq. 16, at high speed injection, the cut size should be in proportion to the square root of the speed of injected water.

In [5, 6] the effect of injection on the performance of 100 mm hydrocyclone has been studied. An empirical formula reflecting the facts of increase $d^{[50]}$ or decrease T_0 with the increase in speed injection is proposed. The experimental data on the cut size can be described as dependence $d^{[50]} \infty W_{in,0}^{1.1}$, which is more sensitive to that obtained by approximation calculations on a theoretical model $d^{[50]} \propto W_{in,0}^{0.66}$.

Experimental dependence of the minimum value of the separation curve (T_0) of speed injection [5] can be roughly describe by the dependence $T_0 \propto W_{in,0}^{-0.82}$, while the approximation (13) predicts exponential drop of T_0 by increasing $W_{in,0}$.

It should be noted also, that the theoretical dependence Eq. (15) reflected true the increase of the separation sharpness with an increase of injection speed, measured in [5, 6].

Thus the proposed model reflects a known fact which agrees with the literature concerning the changes happens in the separation curves of classifiers like hydrocyclone in the case of using water injection through the apparatus. Concerning to the present work experiments, they emphasize the strong differences between analytical assessments and the experimental data and the computer calculations as shown in figures 5 through 8. Probably, the reason is not full establishing of particles concentrations of different fractions.

Fig. 10 shows the evolution of concentration curves along the axis of apparatus. Obviously, at a distance of 0.6 m the concentrations significance is far from established.

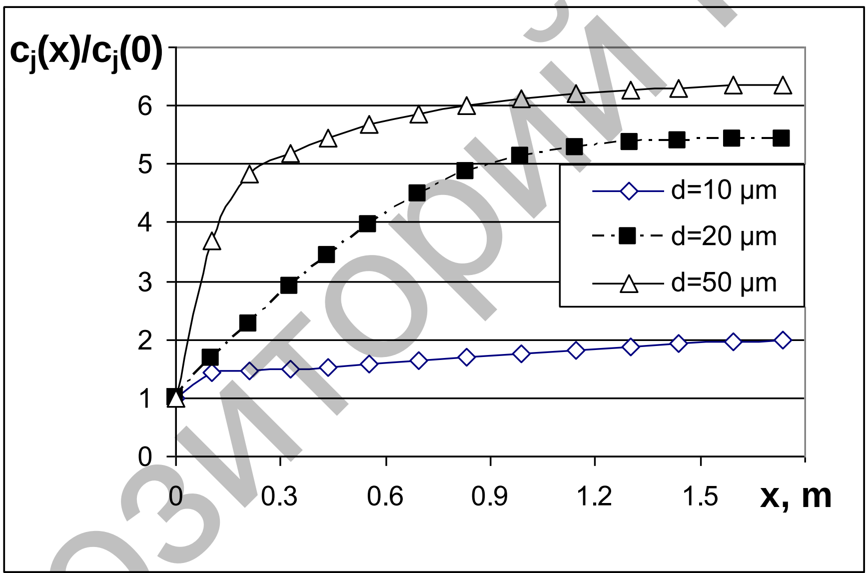


Fig. 10. Evolution of the solid concentration along the apparatus for the particles size fractions ($d = 10$ µm, $d = 20$ µm, $d = 50$ µm) at the case of no water injection

Fig. 11 shows the calculated values of d_{50} and T (0) in the case of L = 1.5 m.

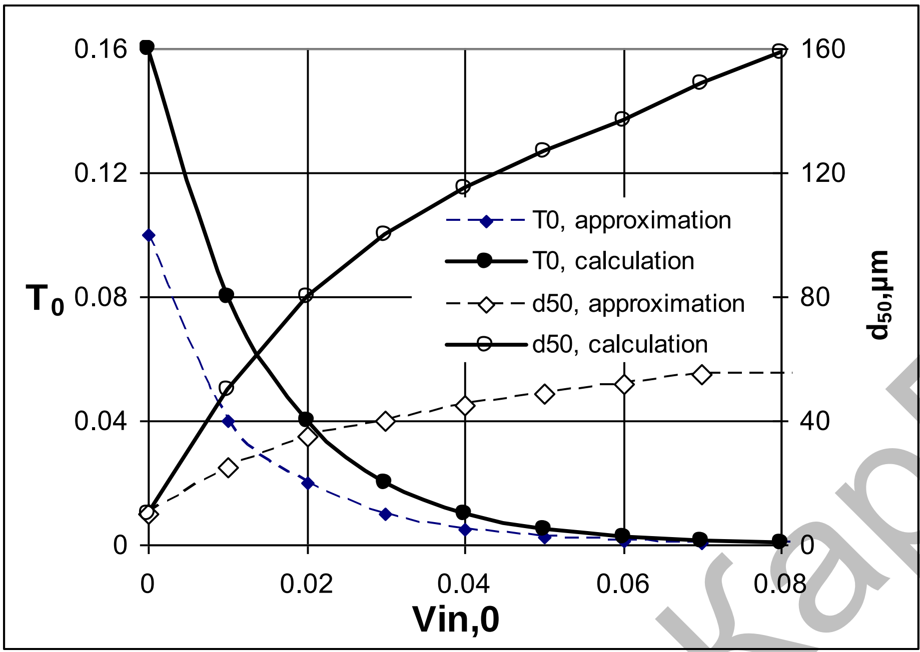


Fig. 11. Dependence of T(0) and d_{50} on the injection velocity (injection throughput) in the case of L=1.5 m. Comparing with the analytical evaluation

It is obvious that in this case the impact of injection velocity on d_{50} is much stronger than for a shorter apparatus. This dependence is more close to the theoretical dependencies (15, 16).

Conclusions

The conclusions of the present work can be summarized as follows:

Increasing the injected water speed leads to an increase in both cut size d_{50}, and the minimum value of the separation function T(0).

Injection promotes the extinction of non monotonic for the separation curve of dense suspensions.

The apparatus length has an important effect on the injection process i.e., the injection effect is different for a long and a short hydrocyclone. In other words, the separation sharpness for a short apparatus decreases and for a long apparatus increases if the velocity of injected water increases.

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