Modeling of the separation for system the liquid - solid in the battery of hydrocyclones

M Lamskova¹, M Filimonov¹,², A Novikov¹,²,³, L Samofalova¹ and S Pavlova¹

¹Department of Processes and devices of chemical and food industry, Volgograd State Technological University, 28 Lenin Avenue, 400005 Volgograd, Russian Federation
²Laboratory of irrigation and reclamation, All-Russian Research Institute of Irrigated Agriculture, 9 Timirjaseva Street, 400002 Volgograd, Russian Federation
³Agrarian-Technological Institute, Peoples' Friendship University of Russia, 6 Miklukho-Maklay Street, 117198 Moscow, Russian Federation

¹E-mail: lamskov@yandex.ru

Abstract. The mathematical model of the process of separation for the liquid – solid system in the hydrocyclone battery is considered, at that the devices are equipped with replaceable pairs of inserts for varying the diameters of the inlet and outlet pipes. It is established that when assessing the overall degree of purification of the suspension in the hydrocyclone battery with the same diameter of the corpuses and replaceable diameters of the pipes, it is necessary to take into account not only the separation factor, but also the average residence time of the liquid in the separation zone. In this connection, it is proposed the parameter P, equal to the product of these indicators. In this interpretation, increase the total degree of purification of the suspension concomitantly with increase the number of hydrocyclones in the battery is consistent with the corresponding value of the parameter R.

1. Introduction

Hydro-mechanical separation processes of heterogeneous systems are an integral part of the technological processes in chemical, petrochemical and other industries. Hydrocyclones are widely used for their implementation, which is due to number of advantages: simple of manufacture and operation, compactness, high performance. Although the geometry of the hydrocyclone is simple, even small changes in the configuration or size of its individual elements have a significant impact on the hydrodynamics of the process, and, as a consequence, on indicators such as performance and cleaning efficiency [1-2]. In a number of works the influence of the inlet diameter for the type design or a filtering hydrocyclone were analyzed by an experimental and computational fluid dynamics study [3-5].

To achieve the required degree of purification during cleaning fine suspensions it is often not enough one unit and it is necessary to conduct the separation of the suspension in the battery of hydrocyclones. Recently, in order to regulate the degree of purification, hydrocyclones are supplied with several pairs of replaceable inserts with variable sizes of inlet and drain pipes [6]. In this case, the diameter of the corpus of the device remains unchanged for each hydrocyclone in the battery, and the dimensions of inlet and outlet pipes are selected so that the total productivity the battery of hydrocyclones is equal to the required for one device.
Thus, the purpose of the research is developing a mathematical model of the liquid – solid separation process in a battery of hydrocyclone with a constant diameter of the corpus and variable sizes of the inlet and inlet pipes, providing a required degree of purification from particles of the dispersed phase.

2. Experimental Part
The algorithm for calculating the hydrocyclone includes its geometrical parameters (Figure 1): the inside radius of the corpus, the outer radius of the outlet pipe, the equivalent diameter of the inlet pipe and the height of the separation zone.

![Figure 1. Scheme of hydrocyclone with geometric parameters and velocity profiles.](image)

The reference literature, for example [6,7] contains information about the basic geometric parameters for hydrocyclones of NGASU class of GNS type with 3-5 pairs of sizes of replaceable inlet and drain pipes and the recommended consumption of treated water.

As the example, we calculate the hydrocyclone type GNS-125 capacity \( q_v = 20 \text{ m}^3/\text{h} \) with a range of diameters of captured particles from 6.67 to 311 \( \mu \text{m} \) and acceptable consumption from 4.4 to 21.1 \( \text{m}^3/\text{h} \).

The initial data on the suspension are given in Table 1.

| Table 1. Initial data and settlement parameters of the GNS-125 battery [8] |
|-----------------------------------------------|
| Name of parameter | Dimension | Designation | Amount   |
|-------------------|-----------|-------------|----------|
| Capacity of the suspension | m³/h | \( q_v \) | 20       |
| Density of the suspension | k/m³ | \( \rho \) | 1000     |
| Density of the particles of the dispersed phase | k/m³ | \( \rho_p \) | 2000     |
| Viscosity of the suspension | Pa·s | \( \mu \) | 0.001    |
| Number of fractions | – | \( n \) | 12       |
| Required degree of cleaning | – | \( \eta \) | 0.8      |
| Number of hydrocyclones | – | \( m \) | 1 2 3 4   |
| Radius of the corpus | m | \( R_c \) | 0.0625   |
| Radius of the outlet pipe | m | \( R_{out} \) | 0.025 0.02 0.016 0.0125 |
| Equivalent radius of the inlet pipe | m | \( R_{in} \) | 0.02 0.016 0.0125 0.008 |
| Height of the separation zone | m | \( L \) | 0.375 0.375 0.375 0.375 |
| Capacity of each hydrocyclone in the battery | m³/h | \( q_{v(i)} \) | 20.0 10.0 6.67 5.0 |
| Velocity in the inlet pipe | m/s | \( v_{in} \) | 4.42 3.46 3.77 6.91 |
| Rotational speed | m/s | \( \nu_r \) | 3.14 1.96 1.67 1.96 |
| Total degree of purification | – | \( \chi (i) \) | 0.66 0.56 0.59 0.802 |
| Separation factor | – | \( F \) | 16.0 6.27 4.56 6.27 |
| Nominal diameter of particles captured per 100% | \( \mu \text{m} \) | \( d_0 \) | 96.2 105.4 101.1 78.8 |
| Particle residence time | s | \( \tau_0 \) | 0.695 1.49 2.32 3.18 |
| \( F \cdot \tau_0 \) | s | \( P \) | 11.2 9.32 10.6 19.9 |
Consider the mathematical model of liquid–solid separation system of hydrocyclone battery. The capacity of one apparatus is determined by the formula [6, 7]:

$$ q_{in} = \frac{d_{v1}}{n}. $$

The estimation of the nominal particle diameter $d_0$ (particles captured at 100%). The fluid velocity in the inlet pipe is:

$$ v_{in} = \frac{q_{v}}{3600 \pi R_{in}^2}. $$

Tangential average radial velocity of flow is:

$$ v_r = \frac{3.15 \cdot v_{in} \cdot R_{in}}{R_c} \left(\frac{L}{2R_c}\right)^{0.32}. $$

The separation factor of the hydrocyclone is:

$$ F = \frac{v_r^2}{g \cdot R_c}. $$

From the condition of equality of residence time (as the ratio of the volume of the separation zone to the flow rate): $\tau = 3600 \cdot \pi \cdot L \cdot (R_c^2 - R_{out}^2) / q_{v}$, and the deposition time of particles of nominal diameter in the case when the deposition path is the largest and is $(R_c - R_{out}) / \tau_{oc} = (R_c - R_{out}) / v_{oc}$, get the equation for the rate of centrifugal deposition of particles of nominal diameter:

$$ v_d = \frac{q_{v}}{3600 \pi \cdot L \cdot (R_c + R_{out})}. $$

Lyashchenko number for particles of nominal diameter is:

$$ La_0 = \left(\frac{v_r^3 \cdot \rho^2}{g \cdot F \cdot \mu \cdot (\rho - \rho_p)}\right). $$

The Archimedes number for particles of nominal diameter is determined from the Todes equation by the method of half division [7] and is:

$$ La_0 = Ar_0^2 / [18 + 0.61 \cdot \sqrt[3]{Ar_0}]^3. $$

Nominal diameter of captured particles is [9, 10]:

$$ d_0 = \sqrt[3]{\frac{(Ar_0 \cdot \mu^2)}{[g \cdot F \cdot \rho \cdot (\rho_p - \rho)]}}. $$

Reynolds number for particles of nominal diameter is:

$$ Re_0 = \left(\frac{v_r \cdot \rho \cdot d_0}{\mu}\right). $$

The estimation of local and total purification degrees for particles of diameter $d_i$, less than nominal. Archimedes number for particles of diameter $d_i < d_0$ is:

$$ Ar(i) = Ar_0 \cdot (d_i / d_0)^3. $$

Reynolds number for particles of diameter $d_i$ is:

$$ Re(i) = Ar(i) / [18 + 0.61 \cdot \sqrt[3]{Ar(i)}]. $$

Deposition rate of particles of diameter $d_i$ in a centrifugal field is:

$$ v_i = \frac{(Re(i) \cdot \mu)}{(\rho \cdot d_i)}. $$

The time of centrifugal sedimentation of particles with diameter $d_i$ of the trajectory $R(i)$, when $R_{in} < R(i) < R_c$ (Figure 1) is:

$$ \tau_i = \frac{(R_c - R_{ij})}{v_i}. $$

Equating the right parts of the formulas for calculating the time of centrifugal deposition and the residence time of the particles of diameter $d_0$, we obtain the proportion:
Provided that the particles of each fraction are evenly distributed over the volume of the liquid to be purified, we obtain that the left part of the last proportion is numerically equal to the local degree of purification for the particles of this fraction. Then the local degree of capture of particles with diameter $d_i$ will be determined as follows:

$$d_{(i)} < d_0, \chi_{(i)} = \frac{v}{v_{m}};$$

$$d_{(i)} \geq d_0, \chi_{(i)} = 1.$$ 

Relative concentration of captured particles is:

$$C_p(i) = \chi(i) \cdot C(i)$$

the total degree of purification:

$$\chi = \sum_{i=1}^{n} C_p(i).$$

3. Results and Discussion

Table 1 presents the results of the calculation of one hydrocyclone and a battery of two, three and four hydrocyclones. All hydrocyclones in the battery have the same radius of the corpus – 0.0625 m. And the total productivity of hydrocyclones in the battery is equal to one - 20 m$^3$/h, what is provided by using of the removable pairs of nozzles input and output pipes.

For one hydrocyclone of the considered type (GNS-125), the total degree of purification ($\chi_1 = 0.66$) is lower than the set value ($\chi = 0.8$) by 14 %; in the battery of two hydrocyclones ($\chi_2 = 0.56$) is lower than in one apparatus by 10% and lower than the required by 24 %. In this case, the separation factor for the hydrocyclone battery decreases nonlinearly-compared with one hydrocyclone ($F_1 = 16$), respectively, 2.56 times for two ($F_2 = 6.27$); 3.51 times for three devices ($F_3 = 4.56$) and 2.56 times for four ($F_4 = 6.27$). The average residence time of particles on the contrary monotonically increases with the number of hydrocyclones in the battery: for $n = 2$ it increases by 2.14 times, for $n = 3$ – by 3.34 times, for $n = 4$ – by 4.57 times compared to one apparatus.

The assessment of the total degree of purification of single hydrocyclones is reduced to a comparison of the relevant separation factors, the higher this Figure, the higher the total degree of purification in the corresponding apparatus. When assessing the total degree of purification of the hydrocyclone battery with the same diameter of corpus, it is necessary to take into account not only the separation factor, but also the average residence time of the liquid in the separation zone. In this connection, we propose a parameter $P$ equal to the product of these indicators:

$$P = F \cdot \tau_0.$$ 

In this interpretation, the dependence of the total degree of purification of the suspension on the number of hydrocyclones in the battery is consistent with the change in the parameter $P$.

Figure 2 shows graphs of the particle density distribution in the initial suspension, the fraction of captured particles in one hydrocyclone and in a battery of four apparatus.
Figure 2. The density of the particle distribution in the suspension fractions and graphs of the fractions of the particles caught in the one hydrocyclone and the battery of four hydrocyclones ($d_{01}$ and $d_{04}$ are the nominal diameters of the particles in the one hydrocyclone and the battery of four hydrocyclones, respectively).

The ratio of the areas bounded by the abscissa axis and curves 2 and 3 to the area bounded by the abscissa axis and curve 1 characterizes the total degree of purification. The difference between area under curves 2 and 3 corresponds to a difference of 14% between the total degree of purification from solid particles in one hydrocyclone and in a battery of four apparatus.

As can be seen from the presented results of calculations, the capacity and efficiency of the separation of heterogeneous systems in the hydrocyclone is influenced by the size of the drain and inlet pipe, since the latter depends on the flow rate in the inlet pipe, determining the rotational motion of the liquid with particles in the apparatus.

4. Conclusion

Thus, for the battery of hydrocyclones with variable diameters of inlet and outlet pipes, the algorithm for calculating the total degree of purification is proposed. The decrease in the separation factor is compensated by an increase in the residence time of the liquid in the separation zone, it takes into account with the parameter $P$ equal to their product. With a certain number of hydrocyclones in the battery, the total degree of purification becomes higher than in one unit. In particular, for the given example, the total degree of purification for one devise is 0.66 as compared with the battery of four apparatus with the degree of purification 0.802.

References

[1] Jinyi T, Long N, Tao S, James O, Jianing Z 2018 An overview of operating parameters and conditions in hydrocyclones for enhanced separations Separation and Purification Technology 268–285
[2] Yanne N K, Danylo O S, Marcos A S 2018 Effect of variables related to the separation performance of a hydrocyclone with unprecedented geometric relationships Powder Technology 645–653

[3] Tang B, Xu Y, Song X 2017 Effect of inlet configuration on hydrocyclone performance Transactions of Nonferrous Metals Society of China 27 1645–1655

[4] Vieira L G, Silva D O 2016 Effect of inlet diameter on the performance of a filtering hydrocyclone separator Chemical Eng. and Technol. 39 1406–1412

[5] Fernanda F S, Marcos A B, Luiz G V 2019 Filtering cylindrical–conical hydrocyclones Particuology 980–989

[6] Ternovskiy I G 1994 Hydrocyclone (Moscow: Nayka) 350 p.

[7] Timonin A S 2015 Engineering and environmental directory (Kaluga: Publishing House “Noosphere”) vol 2 p. 1126

[8] Golovanchikov B A, Novikov A E, Lamskova M I, Filimonov M I 2018 The calculation of the battery of hydrocyclones to provide the intended degree of purification of the dispersed phase particles Chemical Technology 5 235–240

[9] Golovanchikov A B 1995 The application of computers in chemical technology and ecology: Modeling of hydro-mechanical processes (Volgograd: Tsaritsyn) 121 p.

[10] Golovanchikov A B, Novikov A E, Lamskova M I 2017 Modeling of hydrodynamic processes in the centrifugal field of hydrocyclones: monograph (Volgograd: VolgGTU) 200 p.