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The influence of operating and design parameters of a hydrocyclone on the efficiency of fine fraction classification

Abstract. The purpose of the study was to investigate the operation of the GTS-500 hydrocyclone battery, which is used in the third stage of classification at the enrichment plant of the mining and processing enterprise of the Kryvyi Rih iron ore basin, in order to assess its efficiency and optimise the particle separation process. The main focus is on analysing the effect of feed pressure, pulp density, discharge pipe diameter, and sand nozzle diameter on the nominal separation size, classification efficiency, and distribution of the -0.033 mm fraction between sand and discharge products. The study was carried out using actual production data and theoretical modelling of the classification process. The research methodology was based on calculating the mass balance, determining the classification efficiency using the Hancock parameter, and applying the Bradley theoretical model to evaluate the nominal separation size and construct a particle size distribution curve. It was established that the actual classification efficiency of the -0.033 mm fraction is 39.27%, and the results of theoretical modelling agree with industrial data with an absolute error of less than 2%, which confirms the correctness of the approach used for engineering calculations. It has been shown that an increase in pressure and feed density leads to an increase in the nominal separation size and a decrease in classification efficiency due to a change in the hydrodynamic operating mode of the hydrocyclone. At the same time, increasing the diameter of the discharge pipe helps to reduce the maximum particle size and increase the efficiency of the process, but is accompanied by an increase in the content of fine particles in the sand product. Changing the diameter of the sand nozzle significantly affects the distribution of fine particles and the selectivity of the classification process. Based on the results obtained, rational parameters for the operation of hydrocyclones are justified, which provide a compromise between classification efficiency and product quality and can be used to optimise the operating modes of hydrocyclone batteries at enrichment plants

Keywords: nominal separation size; classification efficiency; pulp density; discharge pipe; sand nozzle

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Introduction

The classification of crushed ore in hydrocyclones is a key stage in enrichment processes, as it is here that the particle size distribution of the products is formed, which determines the efficiency of further operations, especially concerning the clear separation of fine grades, in particular the -0.033 mm fraction, which significantly affects the quality of the concentrate and sand products and the technical and economic performance of the plants. Hydrocyclones are widely used due to their simplicity, high productivity and the ability to adjust operating modes, but the efficiency of classification significantly depends on the feed pressure, pulp density, geometric parameters of the apparatus, as well as the particle size distribution and properties of the ore, the interaction of which determines the separation size, selectivity and distribution of fine fractions. Despite a significant number of studies, a quantitative assessment of the influence of these parameters in real production conditions remains relevant, especially for large-diameter industrial hydrocyclone batteries, where deviations from optimal modes lead to an increase in the loss of fine particles, a decrease in efficiency and a deterioration in the stability of the entire technological scheme.

A. Jankovic (2022) noted that magnetite ores, due to their lower iron content, require fine grinding followed by magnetic enrichment and, if necessary, flotation, which results in higher energy costs compared to hematite ores. Grinding is performed in multi-stage schemes using various types of mills, mainly in a closed cycle with hydrocyclones. Hydrocyclones are effective for fine classification, but the difference in density between magnetite and silica leads to the false removal of magnetite into the sand. This causes over-grinding of the valuable mineral and reduces the efficiency of the closed "mill-hydrocyclone" cycle. M.T. Uysal *et al.* (2024) investigated the effect of hydrocyclone diameter, discharge nozzle size, pressure and solids content on classification efficiency in a closed cycle with ball mills. The study demonstrated that hydrocyclones with a diameter of 250 mm worsen the grinding conditions due to changes in product density, while 150 mm devices provide better process control. The study established that a discharge nozzle with a diameter of 20 mm is optimal, with which 88% of the -0.020 mm fraction was achieved in the discharge. The study also proved that an increase in solid content and a decrease in pressure negatively affect the extraction of the finished class and increase the circulation load. B.S. Costa *et al.* (2024) compared hydrocyclone classification with a combined hydrocyclone-high-frequency screen scheme before flotation. The study determined that the hydrocyclone forms a less selective distribution with an increased content of fine particles in the sand and coarse particles in the tailings. The combined scheme provides a particle concentration in the target zone of about 0.1 mm. At the same time, there is a 2-3% increase in the content of the -0.037 mm fraction, which can complicate flotation finishing. J.L. Lima *et al.* (2023) compared standard Cavex CVX hydrocyclones with the improved Cavex CVD model, which is designed to reduce turbulence and increase selectivity. Industrial tests showed that the use of CVD reduced the number of operating units and increased cluster productivity by up to 30%. Even with optimal settings, CVX did not achieve the efficiency level of CVD. Numerical modelling and experiments confirmed a reduction in sand yield of approximately 9% and improved fine separation when using CVD.

T. Su & Y. Zhang (2022) used CFD modelling to analyse the influence of drain pipe geometry and feed modes on hydrodynamics and classification selectivity. The study demonstrated that short-circuited flow is the key reason for the reduction in fine separation efficiency. Reducing the diameter and increasing the length of the discharge nozzle reduces the intensity of this phenomenon and improves selectivity. The study also determined that an increase in feed rate can reduce the maximum particle size, while an increase in solid concentration reduces selectivity. C. Zhang & S. Lu (2023) performed a CFD analysis of hydrocyclone classification of magnetite ores, considering particle density and size. The study determined that heavy magnetite particles, even small ones, are predominantly carried away into the sand due to the action of increased centrifugal forces. This leads to false separation, increased circulation load and over-grinding of magnetite. The authors showed that the particle size distribution of the feed significantly affects the maximum particle size and limits the effectiveness of traditional optimisation methods.

P. Liu *et al.* (2023a) investigated a prismatic hydrocyclone, emphasising velocity field characteristics and particle separation efficiency. The study used numerical modelling and experimental methods to evaluate the influence of prism geometry on vortex flow formation and particle separation. The study showed that the prismatic shape improved the separation of fine particles due to a more stable and controlled vortex flow. W. Zhou *et al.* (2022) conducted an experimental study of mineral separation in self-rotating hydrocyclones using flotation tailings. The study determined that the design of the self-rotating hydrocyclone increased the recovery of minerals and reduced the loss of fine particles, which improved the efficiency of the process. M.M. Mahat *et al.* (2023) applied CFD modelling of multiphase flow in hydrocyclones to evaluate the efficiency of separating particles of different densities and sizes. The study showed that phase distribution and flow velocity significantly affected the separation results and that numerical modelling was used to predict the efficiency of the hydrocyclone and to optimise its operation without experiments.

P. Liu *et al*. (2023b) investigated the influence of the width of spiral guide blades in the inlet zone of a hydrocyclone on flow structure and classification efficiency. The study determined that the blades stabilise the vortex motion and reduce turbulence by changing the tangential velocity component. The optimal width ensures uniform velocity distribution and increases the sharpness of particle separation. An excessive increase in this parameter leads to an increase in hydraulic resistance, energy losses and a decrease in productivity. In view of the above, the study aimed to analyse the efficiency of classification of the -0.033 mm fraction in a battery of HC-500 hydrocyclones.

Materials and Methods

The object of the study was the process of classifying intermediate products in a closed cycle of the third stage of grinding at the ore enrichment plant No. 1 of PJSC Northern Mining and Enrichment Combine. A battery of three GC-500 hydrocyclones with a diameter of 500 mm and a cone angle of 20° is used to classify the intermediate product. The classification unit operated in a variable mode, with the solid content in the pulp fed into the distributor ranging from 22 to 26%. To process experimental data and establish analytical dependencies between classification indicators and operating parameters, mathematical approximation methods were used, in particular linear regression analysis, which was performed using standard statistical data processing tools. During the work, samples of products from the third stage of classification were selected to calculate the mass balance and determine the actual particle size distribution of the products. The analysis showed that the solid content in the feed of the classification unit was 24.5%, the mass flow rate of solids was 181 t/h, and the volume flow rate of pulp was 600 m^3/h. The discharge yield was 72.97% with a solid content of 20.33%, while the sand yield was 27.03% with a solid content of 54.86%. The actual classification efficiency for the -0.033 mm class, determined by the Hancock parameter, was 39.27%. The particle size distribution of the tailings and sands of the third stage of classification is shown in Table 1.

Table 1. *Granulometric characteristics of sands and gravel of the third stage of classification*

Size class, mm								Product
+0.21	-0.21 ÷ +0.14	-0.14 ÷ +0.07	-0.07 ÷ +0.056	-0.056 ÷ +0.045	-0.045 ÷ +0.033	-0.033	Total	
0	0	1.1	3.7	3.1	5.4	86.7	100	Discharge
0	1.5	7.1	13.9	12.2	13.6	51.7	100	Sands

Source: *compiled by the author*

To quantitatively assess the effectiveness of the classification process for the -0.033 mm fraction and analyse the impact of the operating and design parameters of the hydrocyclone on the separation results, a combined method was used, combining analysis of actual production data and theoretical modelling of the process. The method is based on the sequential performance of mass balance calculations, determination of classification efficiency according to the Hancock parameter, calculation of nominal separation size according to the D. Bradley (1965) model, and construction of a theoretical separation curve with subsequent normalisation of the results. The classification efficiency for a size class was determined using the Hancock parameter, which is used to evaluate the selectivity of classification processes for finely dispersed materials. This parameter accounts for the distribution of particles of a given class between the drain and sand products, based on their yield and particle size distribution. The efficiency was calculated using the following formula:

$$\mathrm{E} = \frac{100\times\gamma\times(\beta-\alpha)}{(\alpha\times(100-\alpha)}, \quad (1)$$

where α – the content of the size class in the feed of the classifying apparatus; β – the content of the size class in the discharge of the classifying apparatus; γ – drainage output, calculated using the formula:

$$\gamma = \frac{100\times(\alpha-\theta)}{(\beta-\theta)}, \quad (2)$$

where θ – content of the size class in the sands of the classifying apparatus, respectively. To evaluate the limit separation size, the theoretical model of D. Bradley (1965) was used, which determines the nominal separation size d_{nom} covering the geometric parameters of the hydrocyclone and the characteristics of the initial pulp. The nominal separation size corresponds to the particle size for which the probability of entering the sand and the drain is equal and amounts to 50%. d_{nom} was calculated using the following formula:

$$d_{nom} = K_d \cdot D \cdot \left(\frac{\Delta^2}{d}\right)^{0.5} \cdot \left(\frac{P_o}{\rho - \rho_o}\right)^{0.25} \cdot \left(\frac{a}{100}\right)^{0.5}, \quad (3)$$

where d_{nom} – nominal grain diameter, μm; K_d – coefficient that reflects the conditions of grinding; D – hydrocyclone diameter, cm; Δ – diameter of sand nozzle, cm; d – drain pipe diameter, cm; P_o – pressure at the inlet to the hydrocyclone, kPa; ρ – density of solid, g/cm^3; ρ_o – pulp density, g/cm^3; α – solid content in pulp, %. According to the accepted interpretation of the D. Bradley model (1965), the nominal separation size d_{nom} corresponds to the particle size for which the probability of falling into the sand and discharge products is equal and amounts to 50%. To implement the Bradley model and calculate the nominal separation size, the actual geometric parameters of the HC-500 hydrocyclone and the characteristics of the feed pulp corresponding to industrial operating conditions were used. The initial data for the calculation are given in Table 2. The accepted nominal separation size is d_{nom} = 0.040 mm.

Table 2. *Input data for calculation of* d_{nom}

Value	Indicator name
50.0	D –HC diameter, cm
1	K_d – correction factor for HC diameter
15	d – drain pipe diameter, cm
24.50	α – solid content in pulp, mass %
150	P_o – working pressure at the inlet to the PC, kPa
4.300	ρ – density of solid, g/cm^3
1.232	ρ_o – pulp density, g/cm^3
7.6	Δ – diameter (size of the discharge pipe) of the sand nozzle, cm

Source: *compiled by the author*

The obtained value d_{nom} was used to construct a theoretical separation curve according to the D. Bradley (1965) function, which describes the probability of particles of a given size entering the sand product. The theoretical separation curve was determined by the formula:

$$P_{(d)} = \frac{1}{1+\left(\frac{d_{nom}}{d}\right)^n}, \quad (4)$$

where P_d – proportion of particles remaining in the sand; d_{nom} – nominal grain diameter, mm; d – average particle size, mm; n – resolution index. To determine the mass distribution of individual fractions between sand and drain products, the results of the theoretical separation curve were normalised according to the mass fraction of each fraction in the source material. The masses of fractions falling into the sand and drain were calculated using the following formulas:

$$M_{A,i} = F_i \cdot P_{(di)}; \quad (5)$$

$$M_{O,i} = F_i \cdot (1 - P_{(di)}, \quad (6)$$

where $M_{A,i}$ – mass of the fraction that enters the starts; $M_{O,i}$ – mass of the fraction that enters the drain; F_i – mass fraction in the source material; $P_{(di)}$ – calculation of the probability of particles falling into sand. To assess the validity of the mathematical model used, the results of theoretical calculations were compared with actual data on product separation in the GC-500 hydrocyclone battery.

Results and Discussion

The comparison results show that the absolute error between the theoretical and experimental values does not exceed 2%, which indicates that the model can be used for further analysis of the impact of operating and design parameters on classification efficiency. A comparative analysis of the actual values of hydrocyclone discharge products and sands is shown in Figure 1.

A comparative analysis of the modelling results and experimental data shows different types of deviations between the actual and theoretically calculated particle size distribution of hydrocyclone classification products. While for the discharge product there is a relatively close correspondence between the calculated and actual curves in the fine class range, for the sand product the discrepancies are more pronounced, which can be attributed to the influence of hydrodynamic conditions, circulation load and the selectivity of separation of particles of increased density (Fig. 2). Thus, a comparison of the results of theoretical calculations with actual data from the industrial operation of the GC-500 hydrocyclone battery showed a high degree of correspondence between the model and the actual classification process. The absolute deviations between the calculated and experimental values of the particle size distribution of the discharge and sand products do not exceed 2%, which confirms the validity of the mathematical model used. This facilitates further analysis of the impact of the operating and design parameters of the hydrocyclone on the efficiency of classifying the -0.033 mm fraction.

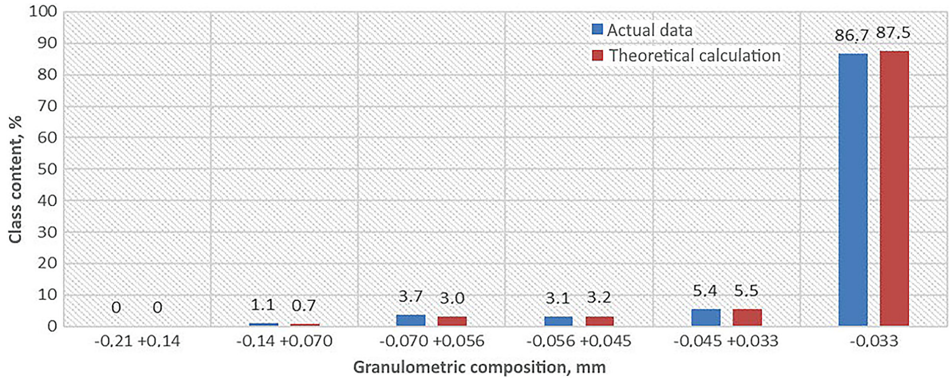

Figure 1. *Comparison of the actual and theoretically calculated particle size distribution of the discharge product of the HC-500 hydrocyclone*

Source: *compiled by the author*

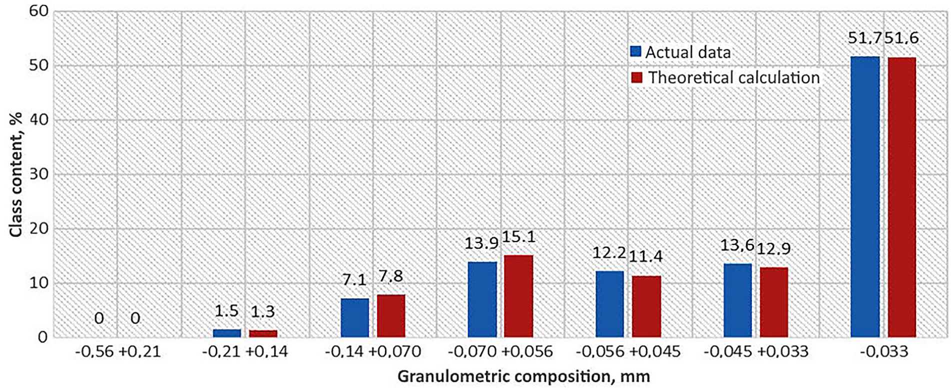

Figure 2. *Comparison of the actual and theoretically calculated particle size distribution of the sand product of the HC-500 hydrocyclon*

Source: *compiled by the author*

A theoretical separation model was used to quantitatively assess the impact of hydrocyclone operating parameters on classification indicators. Based on the results of the theoretical calculation of the classification of the -0.033 mm fraction in the hydrocyclone, an analysis was performed of the effect of feed pressure on the nominal separation size d_{nom}, classification efficiency, and distribution of the fine class between the discharge and sand products. The obtained dependencies are shown in Figure 3. The calculations were performed in the feed pressure range from 80 to 200 kPa, which corresponds to the conditions of industrial operation of the GC-500 hydrocyclone battery.

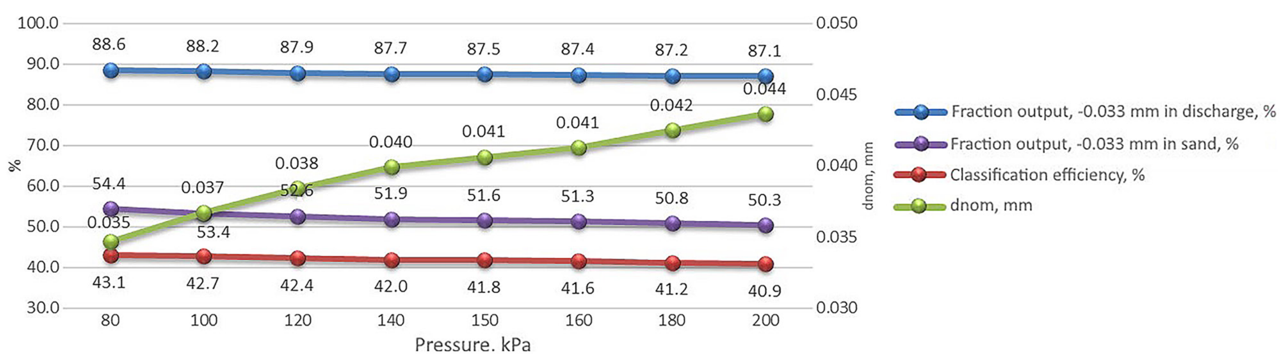

Figure 3. *Dependence of classification indicators for the -0.033 mm fraction in a hydrocyclone on changes in feed pressure*

Source: *compiled by the author*

With an increase in supply pressure in the studied range, a monotonic increase in the nominal separation size is observed. When the pressure increases from 80 to 200 kPa, the value of d_{nom} increases from 0.035 to 0.044 mm, which corresponds to an absolute increase of 0.009 mm. In relative terms, this is 25.7% of the initial value, which indicates a significant influence of the feed pressure on the position of the limiting separation size. In terms of pressure per unit, the average growth intensity d_{nom} is 0.007-0.008 mm per 100 kPa, which indicates a high sensitivity of the classification process to changes in the pulp feed mode. The growth of d_{nom} is accompanied by changes in the distribution of the -0.033 mm fraction between the classification products. Analysis of relative indicators shows that with an increase in feed pressure, the output of this fraction in the sand product decreases from 54.4% at a pressure of 80 kPa to 50.3% at a pressure of 200 kPa, i.e. by 4.1%, which corresponds to a relative decrease of 7.5%. The average intensity of the decrease in the content of the fine fraction in the sands is about 3-4% per 100 kPa. A similar, albeit less pronounced, trend is observed for the discharge product, where the yield of the -0.033 mm fraction decreases from 88.6% to 87.1%, which corresponds to an absolute decrease of 1.5% or 1.7% in relative terms. The lower sensitivity of the discharge product to pressure changes indicates a more stable nature of its granulometric composition compared to the sand product.

The simultaneous decrease in the relative content of the -0.033 mm fraction in both sand and wash products indicates a general coarsening of the particle size distribution of both products at elevated feed pressures. This is manifested in an increase in the proportion of larger classes in each of the products, resulting in a decrease in the specific proportion of fine particles in their composition. Thus, the recorded changes in relative indicators reflect not the redistribution of the -0.033 mm fraction between the discharge and sand, but a change in the structure of the classification products, which is a characteristic consequence of an increase in the maximum separation size. The classification efficiency, determined by the Hancock parameter, also demonstrates a stable dependence on the feed pressure. When the pressure increases from 80 to 200 kPa, the efficiency decreases from 43.1% to 40.9%, i.e. by 2.2%, which corresponds to a relative decrease of 5.1%. The average rate of decrease in classification efficiency is 1.7-1.9% per 100 kPa. The change in this indicator is smooth, without sharp jumps, which indicates a gradual degradation of the selectivity of the process throughout the entire pressure range studied. As a result of processing the calculated data, the dependence of classification efficiency on feed pressure is approximated by a linear equation:

$$\varepsilon = -0.301x + 43.312,$$

where x – power pressure, kPa. The coefficient of determination of the approximation is:

$$R^2 = 0.99.$$

This indicates a high degree of correspondence between the obtained dependence and the calculated data and confirms the systematic nature of the influence of feed pressure on classification efficiency. Analysis of the results obtained identified the pressure range of 100-140 kPa as the zone of relatively stable operation of the hydrocyclone. In this range, the change in the nominal separation size d_{nom} does not exceed 0.003 mm, while the classification efficiency remains at 42.0-42.7%. A further increase in pressure above 150-160 kPa is accompanied by a more intense increase in d_{nom} and an accelerated decrease in classification efficiency, which indicates a decrease in the selectivity of the process and the transition of the hydrocyclone to a less favourable operating mode. To assess the effect of the density of the feed on the separation of the -0.033 mm fraction in the hydrocyclone, the classification efficiency and the distribution of the fine class between the sand and discharge products in the theoretical calculation, three feed pressure values were used: 100, 120 and 140 kPa. The calculations were performed for three pulp density values – 1,198, 1,231 and 1,277 g/l, corresponding to solid contents of 21.58, 24.50 and 28.33 %, respectively. The calculation results are shown in Table 3.

Table 3. *Dependence of classification indicators for the -0.033 mm fraction in a hydrocyclone on changes in feed density*

Indicator	Reached results								
	Nutrient density 1,231 g/l (solid content 24.5%)			Nutrient density 1,277 g/l (solid content 28.33%)			Nutrient density 1,198 g/l (solid content 21.58%)		
	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa
Fraction exit -0.033 mm in drain, %	88.2	87.9	87.7	87.7	87.4	87.1	88.6	88.3	88.1
Fraction exit -0.033 mm in sand, %	53.4	52.6	51.9	52.0	51.2	50.6	54.6	53.8	53.1

Table 3. Continued

Indicator	Reached results								
	Nutrient density 1,231 g/l (solid content 24.5%)			Nutrient density 1,277 g/l (solid content 28.33%)			Nutrient density 1,198 g/l (solid content 21.58%)		
	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa	Pressure 100 kPa	Pressure 120 kPa	Pressure 140 kPa
Mass of fraction -0.033 mm in drain, t	116.5	116.1	115.8	87.5	87.2	87.0	145.7	145.2	144.8
Mass fraction -0.033 mm in sands, t	26.1	25.7	25.4	42.3	41.6	41.1	9.1	8.9	8.8
d_{nom}, mm	0.037	0.038	0.040	0.040	0.041	0.043	0.034	0.036	0.037
Classification efficiency, %	42.7	42.4	42.0	42.1	41.5	41.1	43.1	42.9	42.6

Source: *compiled by the author*

Analysis of the results for three feed density values showed that an increase in the concentration of the solid phase in the pulp is accompanied by a systematic increase in the nominal separation size d_{nom}. At a pressure of 100 kPa, the d_{nom} value varies from 0.034 mm at a density of 1,198 g/l to 0.040 mm at a density of 1,277 g/l, which corresponds to an absolute increase of 0.006 mm or a relative increase of 17.6%. A similar trend is observed at other pressure values: at 120 kPa, d_{nom} increases from 0.036 to 0.041 mm (an increase of 0.005 mm or 13.9%), and at 140 kPa, from 0.037 to 0.043 mm (an increase of 0.006 mm or 16.2%). The results obtained indicate a decrease in the sharpness of the cut-off of fine classes in more concentrated pulp and a change in the conditions of sand flow formation. The study established that an increase in the feed pressure of the hydrocyclone throughout the entire range studied leads to an increase in d_{nom} regardless of the pulp density. In particular, for a density of 1,198 g/l, when the pressure increases from 100 to 140 kPa, d_{nom} increases from 0.034 to 0.037 mm (an increase of 0.003 mm or 8.8%), for a density of 1,231 g/l – from 0.037 to 0.040 mm (an increase of 0.003 mm or 8.1%), and for a density of 1,277 g/l – from 0.040 to 0.043 mm (an increase of 0.003 mm or 7.5%). This indicates the systemic nature of the influence of pressure as a parameter that determines the hydrodynamic mode of operation of the apparatus and the position of the limiting separation size, while the feed density acts as a factor that modifies the intensity of this influence.

Analysis of the relative distribution indicators of the -0.033 mm fraction shows that with an increase in both pressure and feed density, the yield of the fine fraction in the sand product decreases. At a pressure of 100 kPa, an increase in feed density from 1,198 to 1,277 g/l leads to a decrease in the yield of the -0.033 mm fraction in sand from 54.6 to 52.0 %, i.e. by 2.6 %, which corresponds to a relative decrease of 4.8 %. At a pressure of 140 kPa, a similar increase in density is accompanied by a decrease in this indicator from 53.1 to 50.6%, i.e. by 2.5% or 4.7% in relative terms. The decrease in the content of the fine fraction in the sand product with an increase in density is due to the general coarsening of the granulometric composition of the sands. A similar trend can be observed for the discharge product. At a pressure of 100 kPa, the yield of the -0.033 mm fraction in the discharge decreases from 88.6% at a density of 1,198 g/l to 87.7% at a density of 1,277 g/l, i.e. by 0.9% or 1.0% in relative terms. At a pressure of 140 kPa, the corresponding decrease is 1.0% (from 88.1 to 87.1%), which confirms the general trend towards a decrease in the specific proportion of fine particles in the discharge with an increase in the concentration of the solid phase.

The classification efficiency, determined by the Hancock parameter, decreases in the studied modes with both increasing pressure and increasing feed density. At a pressure of 100 kPa, an increase in density from 1,198 to 1,277 g/l leads to a decrease in efficiency from 43.1 to 42.1%, i.e. by 1.0% or 2.3% in relative terms. At a pressure of 140 kPa, the corresponding decrease is 1.5% (from 42.6 to 41.1%), which is equivalent to a relative decrease of 3.5%. The highest efficiency values are recorded at minimum pulp density and lower pressure values, while an increase in solid phase concentration leads to a systematic deterioration in the selectivity of the classification process. Thus, the results of the theoretical calculation confirm that a combined increase in pressure and feed density leads to an increase in the nominal separation size and a decrease in the efficiency of the classification process. To ensure clearer separation and increase the efficiency of the -0.033 mm fraction extraction, it is advisable to use moderate pressure values (100-120 kPa) in combination with a base or reduced feed density, which provides an optimal balance between process selectivity and hydrocyclone stability. To determine the effect of changing the diameter of the hydrocyclone discharge pipe on the separation of the 0.033 mm fraction, the efficiency of classification and the distribution of the fine class between sand and discharge products in the theoretical calculation used feed pressures of 100 and 120 kPa at an output product density of 1,230 g/l (solid content 24.5%). The diameter of the discharge pipe varied in the range of 130-170 mm. The obtained dependencies are shown in Figure 4.

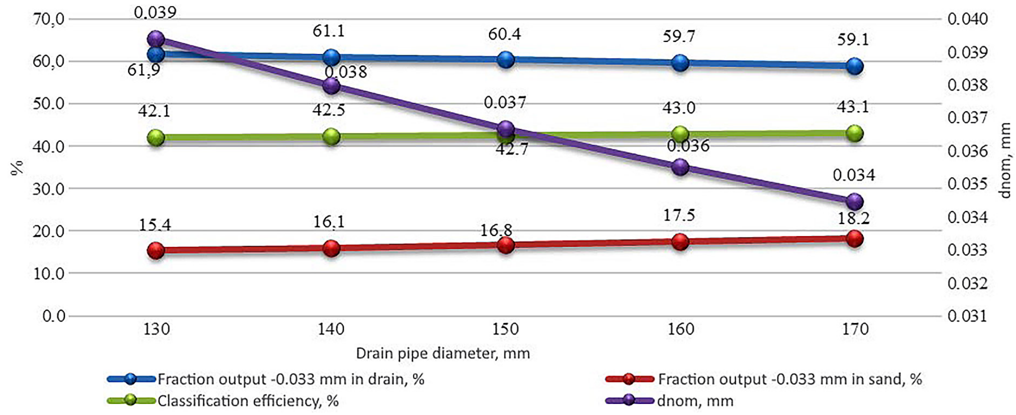

Figure 4. *Dependence of the classification indicators of the -0.033 mm fraction in a hydrocyclone at a feed pressure of 1.0 kgf/cm² on the diameter of the discharge pipe*
Source: *compiled by the author*

The obtained results demonstrate patterns of distribution of finely dispersed particles between the drain and sand products and substantiate the choice of the optimal diameter of the drain pipe (Fig. 5).

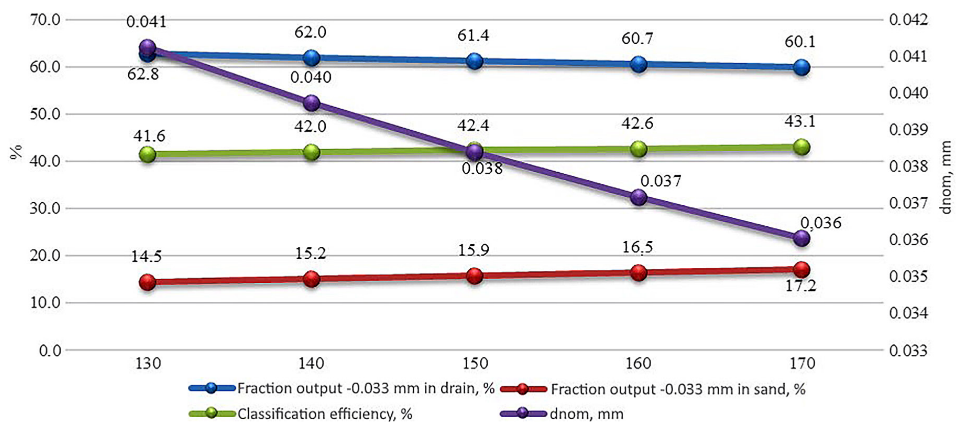

Figure 5. *Dependence of the classification indicators of the -0.033 mm fraction in a hydrocyclone at a feed pressure of 1.2 kgf/cm² on the diameter of the discharge pipe*
Source: *compiled by the author*

Analysis of the results obtained shows that the diameter of the discharge pipe is one of the determining design parameters that significantly affects the nominal separation size d_{nom}, classification efficiency, and distribution of the -0.033 mm fraction between hydrocyclone products. At a fixed feed density of 1,230 g/l and in the studied range of diameters, an increase in feed pressure from 100 to 120 kPa is accompanied by an increase in the nominal separation size and a decrease in classification efficiency. With a discharge pipe diameter of 130 mm, the value of d_{nom} increases from 0.039 to 0.041 mm, which corresponds to an absolute increase of 0.002 mm or a relative increase of 5.1%. A similar difference between the 100 and 120 kPa modes is maintained for other diameters, indicating a systematic effect of pressure on the position of the limit separation size. At the same time, an increase in the diameter of the discharge pipe in the range of 130-170 mm leads to a monotonous decrease in the nominal separation size. At a pressure of 100 kPa, d_{nom} decreases from 0.039 to 0.034 mm, which corresponds to an absolute decrease of 0.005 mm or a relative decrease of 12.8%. At a pressure of 120 kPa, the corresponding decrease is 0.005 mm (from 0.041 to 0.036 mm), which corresponds to a relative decrease of 12.2%. The results obtained indicate a shift in the limiting separation size towards finer classes with an increase in the cross-sectional area of the drain pipe, which is associated with a decrease in hydraulic resistance and a weakening of internal flow circulation.

At the same time, an increase in the diameter of the discharge pipe is accompanied by an increase in the yield of the -0.033 mm fraction in the sand product. At a pressure of 100 kPa, the yield of this fraction in sand increases from 15.4% at a diameter of 130 mm to 18.2% at a diameter of 170 mm, i.e. by 2.8%, which corresponds to a relative increase of 18.2%. At a pressure of 120 kPa, a similar trend is observed in the increase in the yield of the -0.033 mm fraction in the sand from 14.5 to 17.2%, i.e. by 2.7% or 18.6% in relative terms. This indicates an intensification of the removal of fine particles in the sand product when the diameter of the discharge pipe is excessively increased. The classification efficiency shows a moderate increase with an increase in the diameter of the discharge pipe. At a pressure of 100 kPa, the efficiency increases from 42.1% at a diameter of 130 mm to 43.1% at a diameter of 170 mm, which corresponds to an absolute increase of 1.0% or a relative increase of 2.4%. At a pressure of 120 kPa, efficiency increases from 41.6% to 43.1%, i.e. by 1.5% or 3.6%. The maximum efficiency values are recorded in the diameter range of 150-160 mm, after which a further increase in diameter does not lead to a significant increase in efficiency, but is accompanied by an increase in the loss of the fine fraction in the sand product. As a result of processing the calculated data, the dependence of classification efficiency on the diameter of the drain pipe at a pressure of 100 kPa is approximated by a linear equation:

$$\varepsilon = 0.2539x + 41.911,$$

where x – diameter of the hydrocyclone discharge pipe, mm. The coefficient of determination of the approximation is:

$$R^2 = 0.9807.$$

For a pressure of 120 kPa, the corresponding relationship is as follows:

$$\varepsilon = 0.3651x + 41.249,$$

where x – diameter of the hydrocyclone discharge pipe, mm. The coefficient of determination of the approximation is:

$$R^2 = 0.9925.$$

High values of approximation determination coefficients confirm the stable nature of the influence of the drain pipe diameter on the classification efficiency in the studied range. Thus, at a feed density of 1,230 g/l and a feed pressure of 100-120 kPa, the optimal operating mode of the hydrocyclone should be defined as the operation of a hydrocyclone with a discharge pipe diameter of 150-160 mm. Under these conditions, a balanced combination of reduced nominal separation size, increased classification efficiency and an acceptable level of loss of the -0.033 mm fraction in the sand product is ensured. To quantitatively assess the effect of the diameter of the sand nozzle of the hydrocyclone on the classification indicators of the -0.033 mm fraction, the following theoretical calculations were made: feed pressure of 100 kPa and 120 kPa, a drain pipe diameter of 150 mm, and an inlet feed density of 1,230 g/l. Under these conditions, an analysis was performed of the change in nominal separation size, classification efficiency, and distribution of the fine class between the sand and drain products when varying the diameter of the sand nozzle in the range of 68-84 mm. The dependencies obtained for different feed pressure values are shown in Figure 6, which shows the influence of the sand nozzle design parameter on the classification process under different hydrodynamic operating modes of the hydrocyclone.

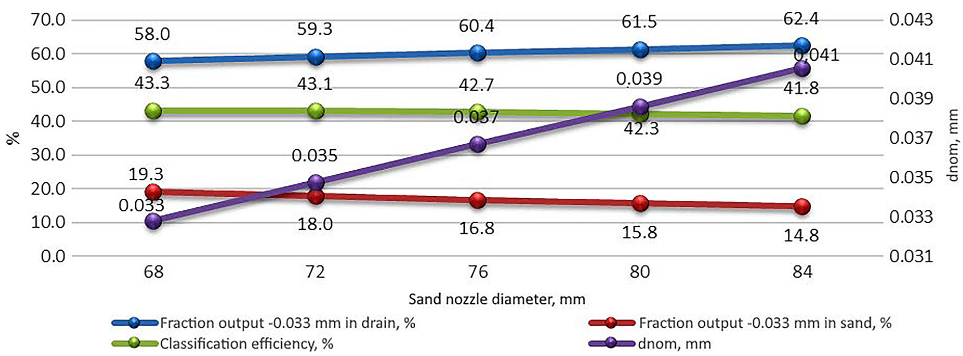

Figure 6. *Dependence of the classification indicators of the -0.033 mm fraction in a hydrocyclone at a feed pressure of 100 kPa on the diameter of the sand nozzle*

Source: *compiled by the author*

A change in the diameter of the sand nozzle significantly affects the conditions for unloading the sand product and, accordingly, the distribution of fine particles in the hydrocyclone. At different feed pressures, the nature of this dependence changes, which is reflected in the classification indicators for the -0.033 mm fraction. Figure 7 shows the results illustrating the effect of the sand nozzle diameter on the efficiency of fine class separation at feed pressures of 100 and 120 kPa.

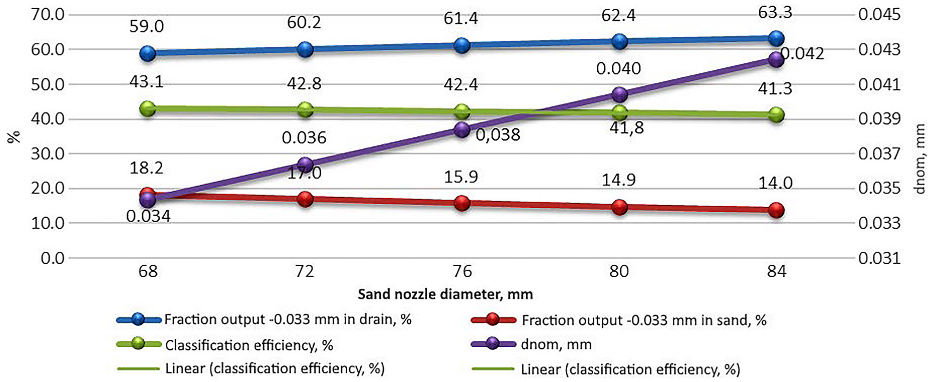

Figure 7. *Dependence of the classification indicators of the -0.033 mm fraction in a hydrocyclone at a feed pressure of 120 kPa on the diameter of the sand nozzle*
Source: *compiled by the author*

The analysis of the results showed that changing the diameter of the sand nozzle significantly affects the nature of the classification and distribution of the fine fraction of -0.033 mm between the hydrocyclone products at both 100 kPa and 120 kPa at a fixed feed density of 1,230 g/l. The patterns identified are stable and remain consistent across the entire range of diameters studied. With an increase in the diameter of the sand nozzle from 68 to 84 mm for both pressure values, there is an increase in the yield of the -0.033 mm fraction in the discharge product and a corresponding decrease in its yield in the sand product. At a pressure of 100 kPa, the yield of this fraction in the sand decreases from 19.3% to 14.8%, which corresponds to an absolute decrease of 4.5% and a relative decrease of 23.3%.

At a pressure of 120 kPa, the same indicator decreases from 18.2% to 14.0%, i.e. by 4.2%, which corresponds to a relative decrease of 23.1%. The recorded changes indicate a decrease in the carryover of fine particles into the sand product due to an increase in the cross-sectional area of the sand nozzle and a decrease in the hydrodynamic resistance of the sand flow. The nominal separation size d_{nom} increases monotonically with an increase in the diameter of the sand nozzle. For a pressure of 100 kPa, the value of d_{nom} increases from 0.033 to 0.041 mm, which corresponds to an absolute increase of 0.008 mm and a relative increase of 24.2%. For a pressure of 120 kPa, d_{nom} increases from 0.034 to 0.042 mm, i.e. by 0.008 mm, which corresponds to a relative increase of 23.5%. This indicates a shift in the maximum separation size towards larger values, which is associated with a decrease in the intensity of the centrifugal field in the sand flow formation zone and an increase in the probability of larger particles being swept into the drain.

The efficiency of classification gradually decreases with an increase in the diameter of the sand nozzle. The maximum efficiency values of 43.3-43.1% are achieved with a minimum nozzle diameter of 68 mm. When the diameter is increased to 84 mm, the efficiency decreases to 41.8% (100 kPa) and 41.3% (120 kPa). Thus, at a pressure of 100 kPa, the absolute decrease in efficiency is 1.5%, which corresponds to a relative decrease of 3.5%, and at a pressure of 120 kPa, it is 1.8%, or 4.1%. The decrease in efficiency indicates a deterioration in the selectivity of the process, caused by a simultaneous increase in d_{nom} and a decrease in the sharpness of the cut-off of fine classes. Analysis of absolute masses confirmed the established trends: with an increase in the diameter of the sand nozzle, the mass of the -0.033 mm fraction in the sand product decreases, while the mass of this fraction in the discharge changes insignificantly. This indicates a redistribution of fine particles between products without a significant change in their total amount and confirms the dominant influence of the design parameter of the sand nozzle on the selectivity of classification. As a result of processing the calculated data, the dependence of classification efficiency on the diameter of the sand nozzle at a pressure of 100 kPa is approximated by a linear equation:

$$\varepsilon = -0.3813x + 43.789,$$

where x – sand nozzle diameter, mm. The coefficient of determination of the approximation is:

$$R^2 = 0.9819.$$

For a pressure of 120 kPa, the corresponding relationship is as follows:

$$\varepsilon = -0.4723x + 43.692,$$

where – sand nozzle diameter, mm. Coefficient of determination of approximation:

$$R^2 = 0.9903.$$

Thus, the diameter of the sand nozzle is one of the key design parameters that determines the position of the maximum separation size and the efficiency of classification at fixed values of pressure and feed density. Under conditions of pressure 100-120 kPa, feed density of 1,230 g/l and a discharge pipe diameter of 150 mm, the optimal range of sand nozzle diameters is considered to be 72-76 mm, in which a balanced ratio between classification efficiency, d_{nom} value and permissible content of the -0.033 mm fraction in the sand product is achieved. Based on a comprehensive analysis of the influence of the operating and design parameters of the hydrocyclone, the study established that the classification efficiency and separation quality of the fine fraction of -0.033 mm are determined not by individual parameters, but by their coordinated combination. Changes in feed pressure, pulp density, drain pipe diameter and sand nozzle significantly affect the nominal separation size, process selectivity and distribution of the fine fraction between the drain and sand products.

According to theoretical calculations, the stud established that for a hydrocyclone with a diameter of 500 mm, the optimal operating mode, aimed at ensuring clear separation and an acceptable content of the -0.033 mm fraction in the sand product, is achieved with the following combination of parameters: pressure in the hydrocyclone within the range of 100-120 kPa, at which a stable hydrodynamic mode is formed without a significant increase in the nominal separation size; pulp feed density at 1,198-1,231 g/l, which ensures increased classification efficiency and better separation selectivity; drain pipe diameter of 150-160 mm, which provides a compromise between reducing d_{nom} and acceptable losses of the fine fraction in the sand product; sand nozzle diameter of 72-76 mm, which can combine sufficiently high classification efficiency with moderate values of nominal separation size and controlled content of the -0.033 mm fraction in the sand. The proposed combination of parameters can be recommended for practical application as a rational operating mode for GC-500 type hydrocyclones with the possibility of further adjustment depending on the requirements for the particle size distribution of the final products and the specific operating conditions of the enrichment plants.

The efficiency of classifying finely dispersed particles in hydrocyclone devices is a determining factor in the stability of closed grinding cycles and the energy efficiency of enrichment process schemes. Analysis of the results obtained for the GC-500 hydrocyclone battery showed that even relatively small changes in operating and design parameters lead to a significant shift in the limit separation size, which is particularly critical for fractions smaller than -0.033 mm. An increase in feed pressure is accompanied by an increase in the nominal separation size and a decrease in the selectivity of fine fraction classification. It has been established that when the pressure is increased from 80 to 200 kPa, the limit separation size of the -0.033 mm fraction increases from 0.035 to 0.044 mm, i.e. by 0.009 mm, which corresponds to a relative increase of 25.7%. This change in d_{nom} indicates a significant restructuring of the hydrodynamic regime in the apparatus and an increase in the proportion of finely dispersed particles that are mistakenly attributed to the sand product. From a physical point of view, an increase in feed pressure leads to an intensification of the tangential flow velocity, an increase in turbulent pulsations and an intensification of short-circuited flows in the near-axis zone of the hydrocyclone. As a result, fine particles, which under optimal conditions should be moved into the drain, are drawn into the peripheral flow and move into the sand. The scale of the relative increase in d_{nom} obtained in this study correlates with analytical estimates of L.R. Plitt (1976), according to which a 2-2.5-fold increase in feeding pressure causes an increase in d_{nom} by 20-30%. Similar trends are present in the industrial studies by S.K. Palaniandy *et al.* (2017), where an increase in feed pressure was accompanied by an increase in d_{nom} by 15-25%. Together, these results indicate that the effect of feed pressure on classification efficiency is systemic and manifests itself regardless of the type of hydrocyclone and the specific technological scheme.

Studies also show that the efficiency of hydrocyclone classification largely depends on feed characteristics, in particular on changes in the average particle size in the feed ($d_{50}f$). Q. Zhao *et al.* (2024), using experimental methods and CFD analysis, demonstrated that varying $d_{50}f$ in the range of approximately 0.020-0.060 mm with constant design and operating parameters of the hydrocyclone leads to a shift in the separation limit size (d_{50}) and a decrease in the selectivity of the process. At the same time, with a decrease in the average particle size and an increase in the proportion of fine fractions in the feed, the number of falsely separated particles that enter the sand product increases, even at stable values of pressure and pulp density. A decrease in the sharpness of the cut-off and deformation of the distribution curve are noted, which is most pronounced in the fine fraction range.

Pulp density is another key parameter that determines the nature of the separation of finely dispersed particles. When the pulp density increases from 1,198 to 1,277 g/l, the limit size of the fraction separation -0.033 mm increases by 0.005-0.006 mm, which corresponds to a relative increase in d_{nom} of 13.9-17.6%. The data obtained indicate a decrease in the sharpness of classification and an increase in the role of interparticle interactions. An increase in the concentration of the solid phase leads to an increase in the effective viscosity of the pulp and a decrease in the differences in the speeds of particles of different sizes. As a result, the effectiveness of centrifugal forces decreases, which has a particularly negative effect on the separation of fine fractions. Similar effects were noted by T.C. Rao *et al.* (1976), where an increase in pulp density was accompanied by a decrease in classification sharpness by 10-20%, as well as by M. Padhi *et al.* (2019), where the decrease in the extraction of the -0.020 mm fraction was 8-12% with an increase in the solid content in the pulp. Thus, the results obtained confirm that the influence of pulp density on d_{nom} displacement is universal in nature.

The geometric parameters of the hydrocyclone, in particular the diameters of the discharge pipe and sand nozzle, have a significant impact on the classification indicators. Increasing the diameter of the drain pipe from 130 to 170 mm reduces the maximum separation size by 0.005 mm, which corresponds to a relative decrease in d_{nom} of 12.2-12.8%. This is due to a decrease in the intensity of the short-circuited flow and stabilisation of the axial vortex, which contributes to more selective particle cutting. Quantitative confirmation of this mechanism is provided in the CFD study by T. Su & Y. Zhang (2022), where a reduction in the diameter of the discharge pipe led to a decrease in d_{nom} by 10-18% and a decrease in the intensity of the short-circuited flow by up to 30%. At the same time, the results of the study show that an excessive increase in the diameter of the discharge pipe is accompanied by an increase in the carryover of fine particles into the sand product. A similar trade-off between a decrease in d_{nom} and the loss of fine fractions was noted in the work of C. Zhang & S. Lu (2023), where the mass fraction of fine particles in the sand increased by 5-9% with unfavourable geometry of the discharge node. The study by M. Narasimha et al. (2006) was devoted to modelling large vortices in hydrocyclones to predict the diameter and shape of the air stem. The authors showed that the large vortex modelling method can accurately assess the flow structure inside a hydrocyclone, which is important for improving particle classification efficiency.

The study by J. Li *et al.* (2019) conducted a numerical analysis of the influence of different inlet designs, in particular involute and laminar-spiral shapes, on the internal flow and phase separation in hydrocyclones. The study demonstrated that the choice of a laminar-spiral configuration reduced energy consumption and better reduced the displacement of coarse and fine particles in the outlet flows compared to the standard involute configuration, especially at different particle concentrations and densities, indicating the potential of geometric optimisation to improve the separation process.

Changing the diameter of the sand nozzle also significantly affects the distribution of particles between the classification products. Increasing its diameter from 68 to 84 mm leads to an increase in the maximum separation size from 0.033 to 0.041 mm at a pressure of 100 kPa. This is due to a decrease in hydraulic resistance in the sand node and an increase in the rate of particle removal into the lower product. Similar quantitative patterns were presented by D. Hou *et al.* (2021), where the proportion of fine particles in the sand product increased by 6-10% when the geometry of the sand nozzle was changed. Modern CFD studies generalised the experimental patterns obtained and explained their hydrodynamic nature. E. Dianyu *et al.* (2024) demonstrated that changing the configuration of the inlet part of the hydrocyclone significantly changes the velocity structure, the position of the axial vortex, and the intensity of turbulent pulsations. This, in turn, leads to a shift in the separation limit size and a decrease in classification selectivity, especially for fractions smaller than 0.050 mm. The CFD results obtained explain well the changes in d_{nom} recorded in this study when varying the feed pressure and geometric parameters of the apparatus. L. Svarovsky (1984) conducted a detailed review of the design, principle of operation and application of hydrocyclones in industrial classification and particle separation. The author systematised the hydrodynamics of flow, factors affecting separation efficiency, and practical recommendations for the design and operation of hydrocyclones.

A summary of the results of this study and the literature data shows that the influence of feed pressure, pulp density, and the diameters of the discharge pipe and sand nozzle has a common physical nature and manifests itself in similar numerical ranges of change in the limit separation size. For industrial conditions, this means that increasing the intensity of the process by increasing the pressure or pulp concentration without hydrodynamic limitations can lead to an increase in the loss of fine fractions and a decrease in the overall efficiency of the technological scheme. The best classification results are achieved with a rational combination of operating and design parameters, which provides a compromise between separation selectivity and minimisation of losses of valuable fine-grained material.

Conclusions

The analysis of actual production data for the GC-500 hydrocyclone battery at enrichment plant No. 1 of PJSC Northern Mining and Enrichment Combine established that the classification efficiency for the -0.033 mm fraction in the third stage of classification is 39.27% according to the Hancock parameter, which indicates insufficient selectivity of the process and the presence of a significant reserve for optimising the operating modes of hydrocyclones. A mathematical classification model based on the calculation of mass balance, the Hancock parameter and the theoretical Bradley separation function has been developed, which adequately describes the hydrocyclone classification process. The relative error between the theoretical and actual class distribution indicators in sand and discharge products does not exceed 2%, which confirms the correctness of the applied model for engineering calculations and operating mode forecasting.

The study established that feed pressure is one of the key operating factors determining the nominal separation size and classification efficiency. With an increase in pressure from 80 to 200 kPa, the nominal separation size increases from 0.035 to 0.044 mm, which is accompanied by a coarsening of the granulometric composition of the products and a decrease in classification efficiency. The study demonstrated that an increase in feed pressure leads to a decrease in the mass and relative share of the -0.033 mm fraction in both sand and discharge products, which is due to a shift in the nominal particle size distribution towards larger classes and a deterioration in the selectivity of the process. A study of the effect of feed density showed that an increase in the concentration of the solid phase in the pulp is accompanied by an increase in the nominal separation size and a decrease in classification efficiency across the entire pressure range studied. The most favourable conditions for the separation of the fine fraction of -0.033 mm are achieved at base or reduced pulp density values.

The generalisation of the results showed the systematic nature of the influence of feed pressure on the classification process, regardless of pulp density, which confirms the decisive role of the hydrodynamic mode of operation of the hydrocyclone in determining the maximum separation size. Analysis of the influence of the discharge pipe diameter showed that its increase contributes to a decrease in the nominal separation size and an increase in classification efficiency, but is accompanied by an increase in the carryover of the -0.033 mm fraction into the sand product, which requires consideration of the quality requirements for sand. The study established that the diameter of the sand nozzle significantly affects the distribution of the fine fraction between the products of the hydrocyclone. With an increase in its diameter, the content of the -0.033 mm fraction in the sand decreases and its discharge increases, while at the same time, there is an increase in the nominal separation size and a decrease in classification efficiency.

Based on a comprehensive analysis of operating and design parameters, the optimal operating conditions for the GC-500 hydrocyclones have been determined: feed pressure of 100-120 kPa, output product density of about 1,230 g/l, discharge pipe diameter of 150-160 mm, and sand nozzle diameter of 72-76 mm, at which a compromise is achieved between classification efficiency, nominal separation size, and permissible content of fine particles in the sand product. The results obtained provide a basis for further research aimed at substantiating the optimal operating modes of hydrocyclone batteries at ore processing plants, in-depth analysis of factors affecting classification selectivity, and the development of approaches to reduce losses of fine classes and increase the stability of enrichment performance indicators.

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Conflict of Interest

None.

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Вплив режимних і конструктивних параметрів гідроциклона на ефективність класифікації тонких фракцій

Анотація. Метою дослідження було вивчення роботи батареї гідроциклонів ГЦ-500, яка експлуатується у циклі третьої стадії класифікації на збагачувальній фабриці гірничо-збагачувального підприємства Криворізького залізорудного басейну, з метою оцінки її ефективності та оптимізації процесу поділу частинок. Основну увагу зосереджено на аналізі впливу тиску живлення, щільності пульпи, діаметра зливного патрубка та діаметра піскової насадки на номінальну крупність розділення, ефективність класифікації та розподіл фракції -0,033 мм між пісковим і зливним продуктами. Дослідження виконано з використанням фактичних виробничих даних і теоретичного моделювання процесу класифікації. Методика дослідження базувалась на розрахунку масового балансу, визначенні ефективності класифікації за параметром Хенкока та застосуванні теоретичної моделі Бредлі для оцінки номінальної крупності розділення і побудови кривої розподілу частинок за крупністю. Встановлено, що фактична ефективність класифікації фракції -0,033 мм становить 39,27 %, а результати теоретичного моделювання узгоджуються з промисловими даними з абсолютною похибкою менш як 2 %, що підтверджує коректність застосованого підходу для інженерних розрахунків. Показано, що підвищення тиску та щільності живлення призводить до зростання номінальної крупності розділення та зниження ефективності класифікації внаслідок зміни гідродинамічного режиму роботи гідроциклона. Водночас збільшення діаметра зливного патрубка сприяє зменшенню граничної крупності розділення та підвищенню ефективності процесу, однак супроводжується зростанням вмісту тонкої фракції у пісковому продукті. Зміна діаметра піскової насадки істотно впливає на розподіл тонких частинок і селективність процесу класифікації. На підставі отриманих результатів обґрунтовано раціональні параметри роботи гідроциклонів, які забезпечують компроміс між ефективністю класифікації та якістю продуктів і можуть бути використані для оптимізації режимів роботи гідроциклонних батарей на збагачувальних фабриках

Ключові слова: номінальна крупність розділення; ефективність класифікації; щільність пульпи; зливний патрубок; піскова насадка