A MODIFICATION IN PLITT´S FOR HYDROCYCLONES SIMULATION

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ABSTRACT
Hydrocyclones are devices worldwide used in mineral processing and used for desliming, classification, selective classification, thickening and pre-concentration. Versatile in application, the hydrocyclone is the standard classifier used in closed circuit milling in mineral processing plants. A hydrocyclone is composed by a cylindrical and a conical section joint together, without any moving parts and it is capable of perform granular material separation in pulp. The pulp is feed under pressure tangentially to the cylindrical section. The granular separation mechanism is complex and its mathematical modelling is empirical. The most used model for hydrocyclone dimensioning was proposed by Plitt (1976). Combining the first industrial database on cyclones generated at JKMRC with his own laboratory data, Plitt developed an alternative general- purpose cyclone model. Over the years many revisions and corrections to Plitt´s model were proposed. The present paper shows a modification in the Plitt´s model constant, obtained by exponential regression of simulated data for three different hydrocyclones geometries (Rietema, Bradley and Krebs). The proposed model validation used literature data obtained from phosphate ore using fifteen different hydrocyclones geometries. The proposed model shows a correlation equals to 88.2% between experimental and calculated corrected cut size, while the correlation obtained using Plitt´s model was 11.5%.

Keywords: *hydrocyclones; simulation; Plitt´s model.*

1. INTRODUCTION

According to Sampaio et al (2007) only after 1940 the hydrocyclone manufacture has adopted high technology material, though the existence of this equipment report to 1890. In the following years, thousands of hydrocyclones were installed and nowadays it is considered the standard classifier for closed circuit milling and the most used equipment used for fine particles classification (from 2 to 837 μm). It is a versatile, high capacity and without moving parts equipment.

Hydrocyclones major application is granulometric classification in closed circuit milling, but it is possible to highlight its operation in desliming, selective classification, thickening and pre-concentration. It is possible to use hydrocyclones for water, liquid effluents and even some types of bacteria filtering.

Centrifuge sedimentation is hydrocyclone operation basic principle and its performance is influenced by its geometry, size, operational variables and solids and pulp physics properties. The separation mechanisms and hydrodynamics acting in hydrocyclones are very complex and hard to be theoretical modelled being common the adoption of empiric models based in laboratories tests to estimate hydrocyclones performance. The most used model for hydrocyclone corrected cut size calculation was proposed by Plitt (1976) and over the years many revisions and corrections to Plitt´s model were proposed. The present paper shows a statistical analysis between Plitt´s model and five other models based in the first one, which allowed a new model proposal. The proposed model validation used literature data obtained from phosphate ore using fifteen different hydrocyclones geometries. The proposed model shows a correlation eight times higher than the correlation obtained using the Plitt´s model.

2. MATERIAL AND METHOD

2.1. Hydrocyclone empirical models

Within the empirical models used to hydrocyclones dimensioning the most used is the model proposed by Plitt (1976). This model can be used to predict the hydrocyclones operation without additional experimental data for a wide range of operational conditions. According to Plitt (1976) the experimental data used to produce the model were processed using a stepwise multiple linear regression program to formulate the functional relationships between the measured and calculated parameters (cut size, flow split, capacity and sharpness of separation) and the design and operational hydrocyclone variables. The linear regression procedure was repeated using different functional forms of the variables (linear, power, exponential) and different variable combinations. The mean sum of the residuals squared was used as the main criterion as to the goodness of fit. Only variables which were significant at the 99 per cent confidence level were added to the regression equation. Plitt´s model for corrected cut size (in μm) is given by:

$$d_{50c} = \frac{50{,}5\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho_s - \rho_l)^{0{,}5}} \tag{1}$$

Where: D_c is the inside diameter of a hydrocyclone measured at the bottom of the vortex finder [cm]; D_i is the inside diameter of a hydrocyclone inlet [cm]; D_o is the inside diameter of the overflow or vortex finder [cm]; D_u is the inside diameter of the underflow, or apex, orifice [cm]; h is the free vortex height of a cyclone, which is defined as the distance from the bottom of the vortex finder to the top of the underflow orifice [cm]; Q is the volumetric flow rate of hydrocyclone feed [l/min]; ρ_l is the liquid phase density [g/cm^3]; ρ_s is the solid density [g/cm^3] and ϕ is the volumetric fraction of solids in the feed [%].

Over the years Plitt´s model has suffered many modifications and corrections. The addiction of the fluid dynamic viscosity (μ in cP) to the original model was proposed by Plitt et al (1980), resulting in the expression:

$$d_{50c} = \frac{50{,}5\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} \mu^{0{,}5} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho s - \rho l)^{0{,}5}} \tag{2}$$

Flintoff et al (1987) proposed two modifications in equation 2: a calibration factor (k_1) dependent on the solid fed in the hydrocyclone and a constant (α) dependent on the feed flow rate, given by:

$$d_{50c} = k_1 \frac{39{,}7\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} \mu^{0{,}5} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} \left(\frac{\rho s - \rho l}{1{,}6}\right)^{\alpha}} \tag{3}$$

According to Valadão et al (2007) the following equation can be used to estimate big diameter hydrocyclones performance fed with high volumetric fraction of solids pulp.

$$d_{50c} = \frac{14{,}8\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho_s - \rho_l)} \tag{4}$$

The difference between the solid and the liquid density in the equation 4 is raised by one and not by 0.5 as in the original model. A model proposed using laboratory hydrocyclones fed with pulp containing high purity silica suspensions was proposed by Gupta e Yan (2006), given by:

$$d_{50c} = k_2 \frac{2{,}6892\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} \mu^{0{,}5} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho_s - \rho_l)^{0{,}5}} \tag{5}$$

Where: k_2 is a dimensionless calibration factor (adopted as 1.0 when there is no experimental data available).

Another model, different from Plitt´s model only in the model constant, was proposed by Luz (2005), in a work demonstrating the convertibility between probabilistic distribution used in hydrocyclones model, given by:

$$d_{50c} = \frac{52{,}45\ D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} e^{0{,}063\,\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho s - \rho l)^{0{,}5}} \tag{6}$$

2.2. Hydrocyclones typical geometries

It is possible to group hydrocyclones in families according to their geometric characteristics and according to Svarovsky (2000) the three main hydrocyclones families are Bradley, Krebs and Rietema. Table 1 summarizes the geometric relations between the three families.

Table 1. Three main hydrocyclones families

Family	D_i/D_c	D_o/D_c	l/D_c	L/D_c	θ
Bradley	0.133	0.200	0.330	6.850	9.0°
Krebs	0.267	0.159	-	5.874	12.7°
Rietema	0.280	0.340	0.400	5.000	15 - 20.0°

Where: l is the vortex finder length [cm] and L is the total hydrocyclone length, given by $h = L – l$ [cm].

2.3. Mathematical model proposition

Hydrocyclone operation simulations using equations 1 to 6 were realized to generate the proposed mathematical model, using three hydrocyclone geometries (one for each family) and operational conditions. The adopted pulp was composed by iron ore (ρ_s = 3.53 g/cm^3) and water (ρ_l = 1.00 g/cm^3). The volumetric fraction of solids in the feed (ϕ) assumed eleven different values: 0.5, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 40.0, 45.0 and 50.0%. Ten volumetric flow rate of hydrocyclone feed were used (from 0.5 to 5.0 m^3/h with increment equals to 0.5 m^3/h). Table 2 shows the adopted hydrocyclones dimensions for each geometry.

Table 2. Hydrocyclones dimensions used in the simulations

Family	D_c [cm]	D_i [cm]	D_o [cm]	D_u [cm]	h [cm]	θ [°]
Bradley	10.0	1.33	2.00	1.00	65.20	9.0
Krebs	10.0	2.67	1.59	1.00	54.74	12.7
Rietema	10.0	2.80	3.40	2.50	46.00	20.0

Altogether 330 simulations (110 simulations for each geometry) were realized. Exponential regressions were made using the corrected cut size calculated in the simulations for each geometry, intending to recalculate Plitt´s model coefficients and therefore proposing a model which fits better to the calculated data. Equation 7 presents the proposed model which differs from Plitt´s model in the constant model and the adoption of fluid dynamic viscosity in agreement with equation proposed by Plitt et al (1980).

$$d_{50c} = \frac{2{,}54\, D_c^{0{,}46} D_i^{0{,}6} D_o^{1{,}21} \mu^{0{,}5} e^{0{,}063\phi}}{D_u^{0{,}71} h^{0{,}38} Q^{0{,}45} (\rho s - \rho l)^{0{,}5}} \qquad (7)$$

Figure 1 shows a comparison between the proposed model (represented as a gray line) and the simulated data from equations 1 to 6 (black dots) for a Rietema hydrocyclone fed with 4.5 m3/h of iron ore pulp.

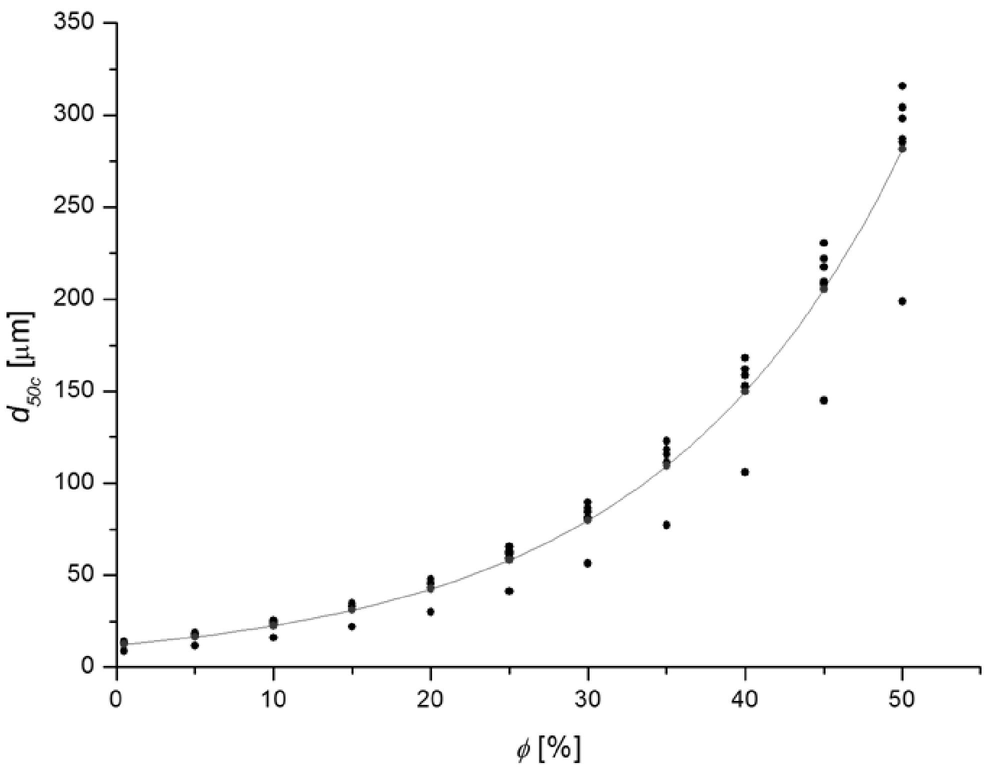

Figure 1. Proposed model (red line) versus simulated data (black dots) for a Rietema hydrocyclone operation with 4.5 m3/h of iron ore pulp.

2.4. Proposed model validation

Experimental data from sixty hydrocyclone tests published by Vieira (2006) were used to validate the proposal model. The author worked with phosphate ore (ρ_s = 2.98 g/cm^3) pulps in a wide range of volumetric fraction of solids and volumetric flow rate feed. Fifteen different hydrocyclone geometries were tested with four different volumetric flow rate of hydrocyclone feed. Table 3 show the geometric variables and the volumetric fraction of solids used in the tests.

Table 3. Geometric variables and volumetric fraction of solids used to validate the proposed model (adapted of Vieira, 2006).

Hydrocyclone	D_c[cm]	D_i[cm]	D_o[cm]	D_u [cm]	h [cm]	θ [°]	φ [%]
1	3.0	4.8	6.6	5.0	13.0	11.2	0.73
2	3.0	4.8	6.6	5.0	13.0	17.8	0.88
3	3.0	4.8	6.6	5.0	19.5	17.8	0.83
4	3.0	4.8	9.6	5.0	13.0	11.2	0.73
5	3.0	4.8	9.6	5.0	19.5	11.2	0.85
6	3.0	4.8	9.6	5.0	19.5	17.8	0.80
7	3.0	7.8	9.6	5.0	19.5	17.8	0.83
8	3.0	7.8	9.6	5.0	13.0	17.8	0.88
9	3.0	7.8	9.6	5.0	19.5	11.2	0.85
10	3.0	7.8	9.6	5.0	19.5	17.8	0.83
11	3.0	3.9	8.1	5.0	16.2	14.5	0.82
12	3.0	8.7	8.1	5.0	16.2	14.5	0.82
13	3.0	6.3	8.1	5.0	16.2	14.5	1.05
14	3.0	6.3	8.1	5.0	16.2	9.0	0.83
15	3.0	6.3	8.1	5.0	16.2	20.0	0.80

3. RESULTS

The corrected cut size was calculated using the Plitt´s model (1976) and the proposed model for the dataset published by Vieira (2006). Figure 2 shows the correlation between experimental and calculated data using Plitt´s model. The correlation coefficient obtained for the sixty hydrocyclones tests was equal to 11.5%, which indicated a poor correlation between then.

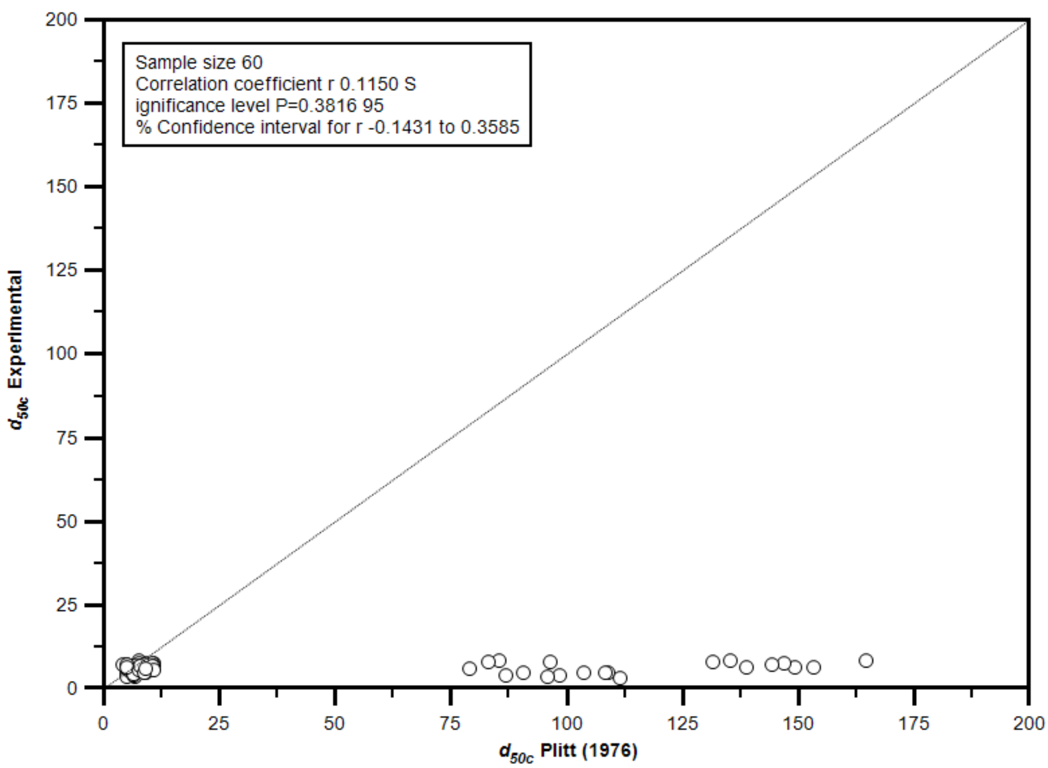

Figure 2. Correlation between experimental and calculated d_{50c}using Plitt´s model (1976) for sixty hydrocyclone tests.

It is possible to note that in twenty tests the corrected cut size calculated by Plitt´s model were higher than 75 µm though the experimental corrected cut size were lower than 10 µm. These twenty tests were obtained for low volumetric flow rate of hydrocyclone feed. Figure 3 show the correlation between experimental and calculated data using Plitt´s model purging the twenty tests, which obtained the worst calculated results. For this data set the correlation coefficient obtained was 26.73% still indicating a poor correlation between experimental and calculated data.

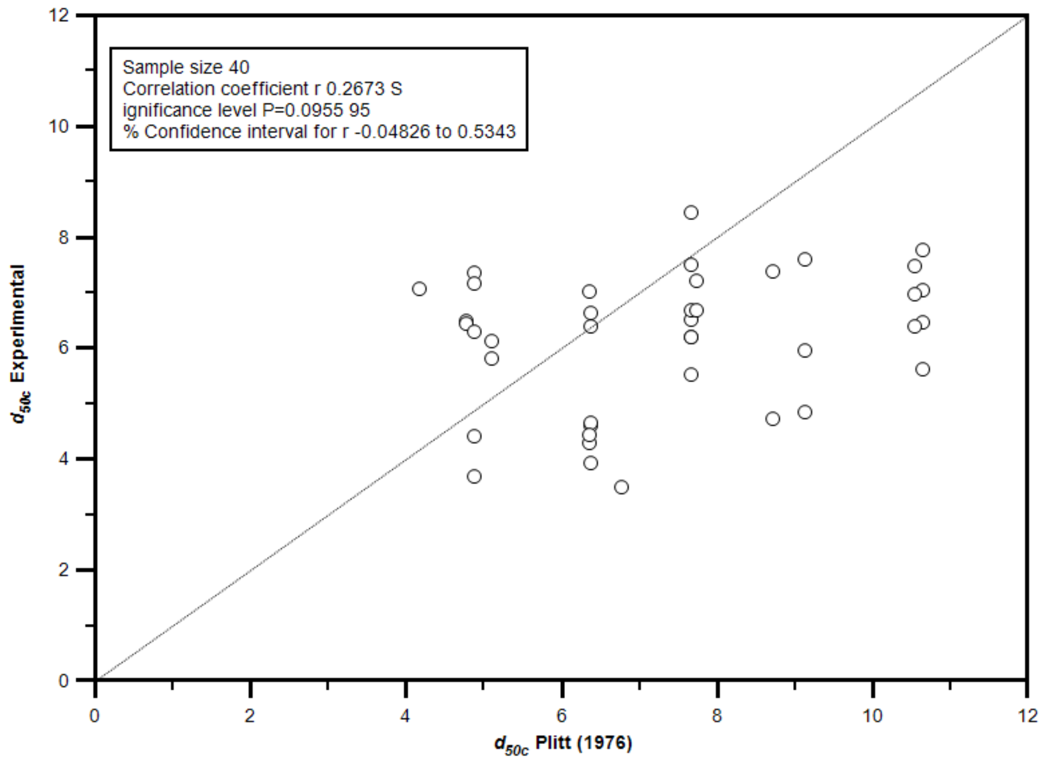

Figure 3. Correlation between experimental and calculated d_{50c} using Plitt´s model (1976) for forty hydrocyclone tests.

Figure 4 show the correlation between experimental and calculated data using the proposed model and the complete experimental dataset (sixteen tests). The correlation coefficient obtained for the sixty hydrocyclones tests was equal to 88.2%, which indicated a strong correlation between then. Notice that none anomalous results were obtained as occurred with Plitt´s model.

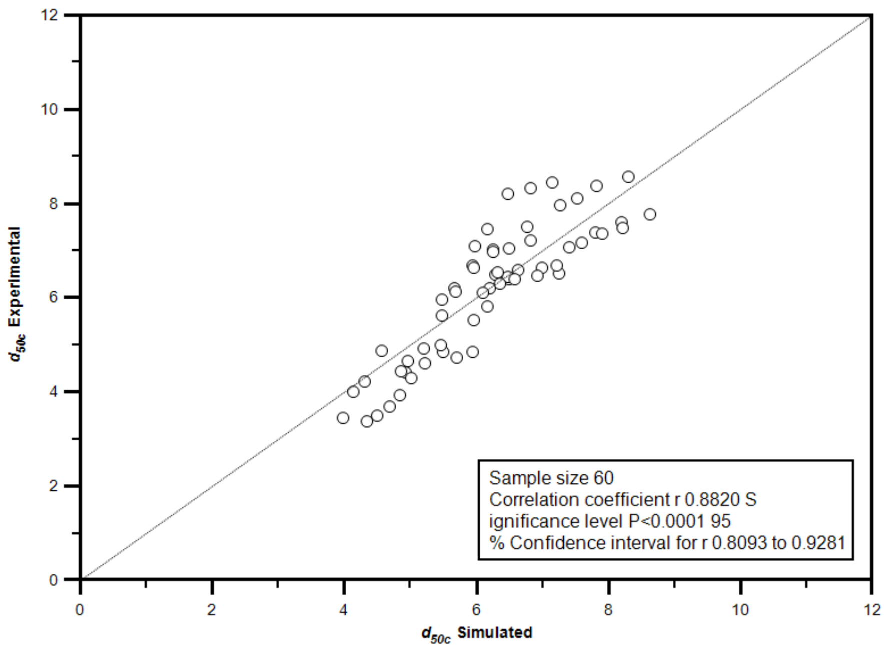

Figure 4. Correlation between experimental and calculated d_{50c}using the proposed model for sixty hydrocyclone tests.

4. CONCLUSIONS

Through the study of the models based on Plitt´s model (1976) used to calculate the hydrocyclone corrected cut size was possible to propose a new empirical model, very similar to the original one. Iron ore pulps operating with three different hydrocyclone geometries were simulated to propose the new model and experimental data using phosphate ore pulp in fifteen hydrocyclones different geometries were used to validate the new model. The obtained correlation coefficient between experimental and calculated data using the proposed model was almost eight times higher than the coefficient using Plitt´s model (1976). It is possible to affirm that Plitt´s model is incapable of accurate calculate the corrected cut size for pulps with low volumetric fraction of solids in the feed and this incapacity was not observed in the proposed model.

Future works are needed to test the new model against wide chances in operational variables, pulps with two or more types of ores, fluid dynamic viscosityand volumetric flow rate of hydrocyclone feed and even pulp temperature.

5. ACKNOWLEDGES

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