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Evaluation of hydrocyclone models for practical applications

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Abstract

Hydrocyclone is an important industrial solids–liquid separation equipment. Although widely used nowadays, the selection and design of hydrocyclones are still empirical and experience based. Although quite a few hydrocyclone models had been developed over the years, the validity of these models for practical applications was still not clear to all users. In this work, seven hydrocyclone models were evaluated. They are the more theoretically oriented models by Bohnet, Braun, and Mueller, semi-empirical models by Schubert/Neese and Svarovsky, plus the empirical models by Plitt and Krebs Engineers. Plant operation data from the Dow Chemical Company were used to compare with the predictions from these models. It was found that most of the models studied work well for certain cases but none of the models can predict all applications. The best results are obtained by using more than one model for predictions. Some experimental data are very important in choosing the models.

Keywords: Hydrocyclone; Model; Cut size; Grade efficiency; Solid–liquid separation

1. Introduction

One type of the industrial centrifugal separators is the hydrocyclone. It has been used as an industrial separation device for more than 50 years. Due to the simple design, low cost, easy operation and low maintenance, hydrocyclones have become important equipment for solid–liquid separations. Although hydrocyclones are widely used nowadays, the separation phenomena are still not fully understood. The selection and design of hydrocyclones are empirical and experience based. There is a need to have a reliable hydrocyclone model that allows design engineers to predict the performance of hydrocyclones and make the proper selections.

A few hydrocyclone models have been developed over the years. These models can be very empirical in nature, theoretically based, or in between. These models often have their limitations due to the specific system the model development was based on. So far there has not been a model which can simulate most hydrocyclone operations and earned recognition among cyclone users and researchers.

It is the purpose of this study to understand how well the hydrocyclone models work for industrial processes and develop a recommendation for industrial users for using these models. A few hydrocyclone models, both empirical and theoretical based, were selected to simulate hydrocyclone operations and the results were compared with data obtained from pilot tests and production plants at the Dow Chemical Company's production complex at Freeport, Texas. The comparisons were done with pressure drop, cut size, reduced grade efficiency, particle size distribution, flow split, and concentration in the underflow. The goal was to understand how well these models could predict separation results for a wide range of cyclone geometries, operating parameters and material properties.

2. The hydrocyclone

The drawing of a typical hydrocyclone is shown in Fig. 1. A hydrocyclone consists of a cylindrical section joined to a conical section. The suspension is fed tangentially through the inlet opening into the cylindrical portion. The fast movement of suspension develops an intense whirling motion that causes a separation of solid particles from the liquid by virtue of the centrifugal acceleration. One part of the feed stream is discharged out of the top of the hydrocyclone, through a cylindrical pipe called the vortex finder. This stream is called the overflow which contains more liquid and finer particles. The second stream is called the underflow which is discharged through a circular opening (the apex) at the end of the conical section. Normally, larger and/or heavier solids are discharged through the underflow.

For industrial applications, it is desired to know the flow rate, solid concentration, and particle size distribution in the underflow and overflow for a given feed under certain operating conditions.

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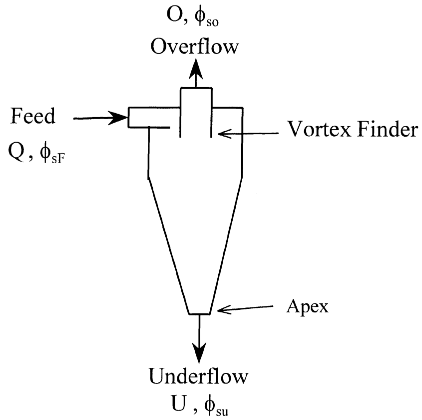

Fig. 1. Cross sectional view of a hydrocyclone.

3. Hydrocyclone models

Hydrocyclone models are available to calculate the separation efficiencies of solid particles and pressure drops in hydrocyclones. These models are normally based on one or more of the following principles [1–3].

1. The empirical models: These models are determined by fitting formulas to experimental data.
2. The equilibrium orbit theory: A particle attains an equilibrium radial position in the cyclone where their terminal settling velocity is equal to the radial velocity of the liquid. That means, if the liquid flows outward, the particles will go toward to the wall and are separated through the underflow. If the liquid flows inward, the particles will go with the liquid to the overflow.
3. The residence time theory: A particle is considered separated if it can travel to the cyclone wall region within the residence time of that particle in the hydrocyclone.
4. The turbulent two-phase flow theory: The separation is caused by the turbulent cross flow flowing in perpendicular to the direction of the force field.

In this work, seven models were evaluated. The underlining principal and the characteristics of each model are briefly discussed in the following. The first three models were developed at the Technical University of Braunschweig, Germany and carried some similarities.

3.1. Bohnet's model

This is based on the equilibrium orbit theory [4]. Bohnet defined a critical particle size as the size of particles which neither move toward the wall of the hydrocyclone (and thus being separated) nor move inward and out from the vortex finder. Therefore, a particle with the critical particle size has 50–50% chance of either being separated or not. This critical size is considered equivalent to the d_{50} cut size. Bohnet used the force balance at the radius of the vortex finder to calculate the critical particle size. This model does not propose a correlation for grade efficiency calculation.

3.2. Braun's model

This model is built upon Bohnet's model. A cyclone is divided into three sections (entrance, downflow and upflow) according to Dietz [5]. The solid concentration in each section is described with a differential equation. These equations are solved numerically to obtain the concentration of each individual particle size in the underflow and overflow. To calculate the grade efficiency, the underflow or overflow rate is required. Braun did not propose a correlation to simulate the flow split ratio of the underflow rate to the feed rate. The users need to know or guess a underflow to feed flow ratio to perform the calculation.

3.3. Mueller's model

Mueller [6] modified Braun's model by incorporating the development of Harms [7] and took into account of the secondary flow along the top of the hydrocyclone roof and along the vortex finder. If the particles following this flow have low specific gravity, the centrifugal forces are not strong enough to push these particles towards the wall of the hydrocyclone and these particles may bypass to the overflow without getting to the downflow area.

Above three models have very sound theoretical basis and are able to take the cyclone geometry into account. However, they adopted in their models some correlations which might not be appropriate for some systems and parameters in those correlations might be hard to determine by users. For example, Eiler's [8] correlation was used to calculate the viscosity of suspensions. Since the prediction of suspension viscosity is still not an exact science and the use of any correlation may lead to erroneous results. Friction factors along the wall of cyclone inlet, cyclone top and conical section were also used in these models. The values of these friction factors are empirical and not readily available unless the actual hydrocyclone data is available to fit these parameters.

3.4. Schubert/Neesse's model

This semi-empirical model was developed by H. Schubert and T.H. Neesse [9]. The theoretical part is based on the turbulent two-phase flow theory. The cut size and pressure drop are calculated by iterations. Based on the feed concentration, this model was divided into dilute flow (<25% volume fraction) and dense flow (>25% volume fraction) models.

3.5. Plitt's model

Plitt [10] developed an empirical model with the constants and the relationships between the operating parameters determined from 297 experiments. This model provides a simple equation for direct calculations of cut size, grade efficiency, flow split and pressure drop.

Table 1
Required input parameters in each model

	Bohnet	Braun	Mueller	Schubert	Plitt	Svarovsky	Krebs
Hydrocyclone Geometry							
Diameter	*	*	*	*	*	*	*
Vortex finder diameter	*	*	*	*	*		
Inlet geometry	*	*	*	*	*		
Total length	*	*	*		*		
Vortex finder immersion	*	*	*		*		
Apex size		*	*	*	*	*	
Cone angle		*	*	*			
Material properties							
Feed particle size distribution				*			
Feed solid concentration		*	*	*	*	*	*
Maximum solid volume concentration		*	*	*	*		
Liquid viscosity	*	*	*	*	*	*	*
Liquid density	*	*	*	*	*	*	*
Solid density	*	*	*	*	*	*	*
Feed rate	*	*	*	*	*	*	*
Overflow rate		*	*				
Others (experimental parameters)							
Wall friction factor	*	*	*				
Friction coefficient at inlet		*	*				
Friction coefficient at top		*	*				
Friction coefficient at cone		*	*				
Wall roughness		*	*				
Empirical constants				*	*		

3.6. *Svarovsky's model*

Svarovsky proposed a dimensionless group correlation for analyzing hydrocyclones [1]. His correlation derived from Rietma's optimum hydrocyclone proportions [11] were used in the work for calculation of the pressure drop, flow split, and the cut size. The closer the cyclone's geometry proportions are to the Rietema's proportions, the better fit of this model. Svarovsky did not propose a correlation to predict the grade efficiency from the cut size.

3.7. *Krebs Engineers' model*

This model was described by Besendorfer [12]. It is an empirical model and a flow rate–pressure drop relationship is required for calculation. This model is very simple and uses the least number of parameters compared to other models.

The parameters used for model calculation are different from model to model. Some use more and some use less. A summary of the input parameters for each model is shown in Table 1. The cyclone size (diameter of the cylindrical section) is the only parameter used by all models. Braun and Mueller use more input parameters than other models. As for the simulation results, all models calculate pressure drop and cut size. Braun's and Mueller's models calculate particle size distribution while Schubert's, Plitt's and Krebs' models predict grade efficiency. With the knowledge of flow split (by measuring or guessing), all the data can be calculated (Table 2).

4. Verification of models

The comparisons of the above mentioned models were made with data collected from a series of pilot tests and

Table 2
Data predicted by each model

	Bohnet	Braun	Mueller	Schubert	Plitt	Svarovsky	Krebs
Pressure drop	*	*	*	*	*	*	*
Cut size	*			*	*	*	*
Grade efficiency				*	*		*
Flow split				*	*	*	
Particle size distribution		*	*				

Table 3
Hydrocyclone systems used for model comparison

System	Test dust/water	Salt/glycerin	Lime/water	Salt/organic solvent
Hydrocyclone geometry				
Cyclone size (m)	0.0445	0.1016	0.0445	0.0100
Cyclone length (m)	0.4150	0.8382	0.4150	0.0800
Vortex finder diameter (m)	Vary	0.0254	0.0140	0.0021
Vortex finder insertion depth (m)	Vary	0.0445	0.0165	0.0083
Apex (m)	Vary	0.0127	0.0032	0.0024
Inlet diameter (m)	–	0.0381	–	0.0021
Inlet height (m)	Vary	–	0.0100	–
Inlet width (m)	Vary	–	0.0080	–
Cone angle (°)	6.8	12.0	6.8	6.0
Material properties				
Solid density (kg/m^3)	2770	2207	2557	2160
Liquid density (kg/m^3)	997	1268	1031	1170
Liquid viscosity (Pa s)	0.0010	0.0040	0.0013	0.0012

some plant operation data. The pilot hydrocyclone tests were conducted with slurries made of test dust and water. Three sets of plant data were used, salt in glycerin, lime in water, and salt in an organic solvent. The geometry of the hydrocyclone used in each case and the properties of materials involved are shown in Table 3.

For all the data series, the pressure drop across the cyclone feed and overflow were recorded and the volume flow rates of feed, overflow and underflow were measured. Samples of feed, overflow, and underflow were collected for measuring solid concentrations and particle size distributions. For the reliability of measurement, multiple samples were taken and the averaged values were used.

The correct sample analyses were key to the success of model comparisons. The materials involved in these four systems all behave differently, some contain large crystals and some have very fine particles. One system was even temperature sensitive. Therefore, the sample analyses were quite tedious and required different techniques for different systems. The majority of the time in this work was spent in ensuring the good data quality.

The properties of interest in hydrocyclone simulations are the pressure drop, particle separation efficiency, and the flow split (underflow to feed ratio). These data allow the calculation of the solid concentration and particle size distribution in underflow and overflow. All the data obtained are tabulated in Tables 4 and 5.

4.1. Pressure drop

Pressure drop is the first design parameter for all cyclone applications. All the models studied in this work predict pressure drop across the cyclone. These calculated values were compared with the pressure drop measured from the operating cyclones. The comparisons were tabulated and the sums of the squared deviations were also illustrated (Tables 4 and 5).

The results show that the model performance is system dependent. Mueller's model worked well for the test dust/water system but turned out to have very poor prediction on plant systems. The simplest model is the Krebs model. It does not appear to be accurate for all test dust runs but predicts extremely well for the plant systems. Up to this point, it can be seen that model prediction without some operation data verification is dangerous. A model may work well for certain systems but erroneous results can occur for other systems.

4.2. Cut size

The cut size is defined as the size of particles which have 50% chances of being separated to the underflow. The cut size is calculated directly in models of Bohnet, Schubert/Neesse, Plitt, Svarovsky, and Krebs. The cut size for the Braun's and Mueller's models as well as test data were obtained from the reduced grade efficiency curves.

For practical considerations, all models seemed to work well for the test dust/water system but Braun's and Plitt's models had a little better overall performance. Larger discrepancies between the model prediction and measurement were observed for the plant hydrocyclones system. Occasionally, one model may predict a cut size close to the measurement but in general the performance was poor. The poor performance may be due to the difficulties in getting the exact dimensions of the operating cyclones in the plant. For some models, the correct cyclone dimensions are very important for the calculation.

4.3. Reduced grade efficiency

Grade efficiency is the separation efficiency of particles with a particular particle size. All the solids reported to the underflow are considered separated. Since the feed splits into underflow and overflow in a hydrocyclone, the flow splitting itself provides a 'guaranteed' separation efficiency. If the

Table 4
Model comparison for test dust/water system

System	Test dust/water								
Run no.	1	2	3	4	5	6	7	8	–
Vortex finder (m)	0.0140	0.0140	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	–
Apex (m)	0.0032	0.0022	0.0032	0.0032	0.0022	0.0022	0.0032	0.0032	–
Feed rate (m^3/h)	3.1580	3.3609	1.4334	1.7475	1.4211	1.7159	1.4790	1.7460	–
Overflow rate (m^3/h)	3.0800	3.3259	1.2827	1.5778	1.3398	1.6264	1.3310	1.5800	–
Underflow rate (m^3/h)	0.0780	0.0350	0.1507	0.1697	0.0813	0.0895	0.1480	0.1660	–
Feed concentration (vol. %)	0.50	0.31	0.47	0.46	0.45	0.41	4.66	4.64	–
Overflow concentration (vol. %)	0.23	0.22	0.19	0.18	0.21	0.19	2.16	2.00	–
Underflow concentration (vol. %)	9.30	9.50	2.85	3.07	4.51	4.32	27.22	29.68	–
Comparison of model predictions for Δp									$\sum R^2$
Measured (bar)	2.00	2.00	2.00	3.00	2.00	3.00	2.00	3.00	0.00
Bohnet (bar)	3.29	3.75	1.24	1.98	1.15	1.79	1.28	1.88	10.30
Braun (bar)	3.29	3.75	1.24	1.98	1.15	1.79	1.28	1.88	10.30
Mueller (bar)	2.70	3.12	1.87	2.84	1.86	2.78	2.00	2.84	1.88
Schubert/Neese (bar)	3.26	3.68	3.76	5.01	3.31	4.82	3.85	5.35	25.52
Plitt (bar)	2.36	2.70	1.78	2.53	1.87	2.62	1.92	2.58	1.23
Svarovsky (bar)	1.89	2.16	0.36	0.54	0.35	0.52	0.35	0.49	26.67
Krebs (bar)	2.11	2.39	0.43	0.65	0.43	0.62	0.46	0.64	24.22
Comparison of model predictions for cut size									$\sum R^2$
Measured (μm)	9.80	9.70	6.60	5.95	7.60	7.95	7.85	6.80	0.00
Bohnet (μm)	13.61	13.20	10.86	9.84	10.91	9.93	10.69	9.84	92.23
Braun (μm)	8.95	9.50	8.45	7.49	8.95	7.90	9.75	8.80	15.99
Mueller (μm)	5.85	5.65	5.45	4.90	5.70	5.05	5.95	5.40	52.02
Schubert/Neese (μm)	15.26	14.24	11.43	10.38	12.96	11.97	12.79	11.84	188.07
Plitt (μm)	10.84	13.63	6.80	6.21	8.89	8.15	8.73	8.08	20.75
Svarovsky (μm)	9.35	9.67	12.12	10.98	13.33	12.06	15.14	13.89	209.11
Krebs (μm)	5.46	5.28	8.49	7.60	8.53	7.67	9.40	8.56	51.11
Comparison of model predictions for grade efficiency and particle size distribution									$\sum$
Bohnet	–	–	–	–	–	–	–	–	–
Braun	1	1	3	2	2	2	3	3	17
Mueller	3	3	2	2	2	3	3	3	21
Schubert/Neese	3	3	4	3	3	3	4	4	27
Plitt	2	3	1	1	2	2	5	5	21
Svarovsky	–	–	–	–	–	–	–	–	–
Krebs	4	4	3	2	2	1	2	2	20
Comparison of model predictions for underflow coacentration									$\sum R^2$
Measured (vol. %)	9.30	9.50	2.85	3.07	4.51	4.32	27.22	29.68	0.00
Bohnet (vol. %)	–	–	–	–	–	–	–	–	
Braun (vol. %)	9.17	9.34	2.34	2.50	3.72	3.98	23.03	24.78	0.43
Mueller (vol. %)	10.53	13.89	2.70	3.05	4.03	4.66	25.32	29.19	0.25
Schubert/Neese (vol. %)	6.64	5.40	2.04	2.16	3.10	3.23	20.17	21.44	1.46
Plitt (vol. %)	8.05	5.51	2.62	2.81	3.95	3.99	24.92	26.51	0.33
Svarovsky (vol. %)	–	–	–	–	–	–	–	–	–
Krebs (vol. %)	11.33	115.27	2.41	2.73	3.99	4.13	24.05	25.71	0.64

separation efficiency due to the flow splitting is subtracted, the resulting separation efficiency is called the reduced grade efficiency. The separation efficiencies calculated by models are actually the reduced efficiency. In Schubert/Neese's, Plitt's and Krebs' models, correlations are offered to calculate the reduced grade efficiency from the cut size. In Braun's and Mueller's models, the reduced grade efficiencies were calculated with the model predicted particle size distribution and the measured underflow and overflow rates.

Since the reduced grade efficiency is not a single number, the model comparisons are done with charts. Due to the space limitation, only the reduced grade efficiency chart for run no. 1 is shown (Fig. 2). For all the other data set, the comparison is represented with numerical numbers in Tables 4 and 5. A number of '1' is given to the model which

Table 5
Model comparison for plant systems

System	Salt/glycerin	Lime/water	Salt/organic solvent		
Run no.	9	10	11	12	
Feed rate (m^3/h)	13.6270	2.6230	0.2910	0.2430	–
Overflow rate (m^3/h)	8.2450	2.5440	0.1300	0.0900	–
Underflow rate (m^3/h)	5.3830	0.0790	0.16201	0.1520	–
Feed concentration (vol. %)	31.10	1.70	4.45	12.42	–
Overflow concentration (vol. %)	18.50	0.93	0.01	0.04	–
Underflow concentration (vol. %)	50.30	23.2	8.01	19.72	–
Comparison of model predictions for Δp					$\sum R^2$
Measured (bar)	3.45	1.40	1.24	1.24	0.00
Bohnet (bar)	0.29	2.00	1.83	5.10	25.57
Braun (bar)	0.29	2.00	1.83	5.10	25.57
Mueller (bar)	1.98	1.85	14.35	9.67	245.18
Schubert/Neese (bar)	2.52	2.37	N/A	N/A	1.80
Plitt (bar)	2.01	1.71	4.48	4.49	23.18
Svarovsky (bar)	0.81	1.23	6.13	3.57	36.31
Krebs (bar)	3.80	1.45	1.40	1.04	0.19
Comparison of model predictions for cut size					$\sum R^2$
Measured (μm)	105.00	25.40	13.00	N/A	0.00
Bohnet (μm)	54.80	18.65	4.15	N/A	2643.93
Braun (μm)	135.00	13.50	3.98	N/A	1122.97
Mueller (μm)	N/A	8.60	2.55	N/A	391.44
Schubert/Neese (μm)	231.60	22.17	N/A	N/A	16037.99
Plitt (μm)	205.20	15.76	3.30	N/A	10227.06
Svarovsky (μm)	143.90	13.68	3.19	N/A	1746.80
Krebs (μm)	76.70	7.80	2.78	N/A	1215.10
Comparison of model predictions for grade efficiency and particle size distribution					
Bohnet	–	–	–	–	–
Braun	3	3	3	3	12
Mueller	4	4	3	3	14
Schubert/Neese	5	1	–	–	6
Plitt	2	5	5	15	
Svarovsky	–	–	–	–	–
Krebs	3	4	3	2	12
Comparison of model predictions for underflow concentration					$\sum R^2$
Measured (vol. %)	50.30	23.26	8.01	19.72	0.00
Bohnet (vol. %)	–	–	–	–	–
Braun (vol. %)	45.13	29.29	8.01	19.49	0.63
Mueller (vol. %)	37.34	34.97	8.01	19.69	3.05
Schubert/Neese (vol. %)	27.13	23.91	–	–	5.37
Plitt (vol. %)	42.78	27.53	7.76	17.65	0.79
Svarovsky (vol. %)	–	–	–	–	–
Krebs (vol. %)	61.13	37.04	8.01	19.74	3.07

shows the best fit to the measured data and the larger the number the worse the data fitting.

Again, a strong dependency of model performance on the system evaluated can be seen. For example, Braun's model worked very well for the first two runs of test dust/water system but not as good as Krebs or Plitt's models in other runs. A number of '5' on Tables 4 and 5 represent a really bad fit. In general, Braun's, Mueller's and Krebs' models are more reliable in grade efficiency and grade efficiency predictions.

4.4. Particle size distribution

The solutions of Braun's and Mueller's models provide the particle size distribution of underflow and overflow. In other models, the flow splits are required to calculate the particle size distribution from the reduced grade efficiency. An example of the simulated overflow and underflow particle size distribution for the salt/glycerin sysem are shown in Figs. 3 and 4. All models seemed to do pretty well in predicting the particle size distribution. If only the particle size

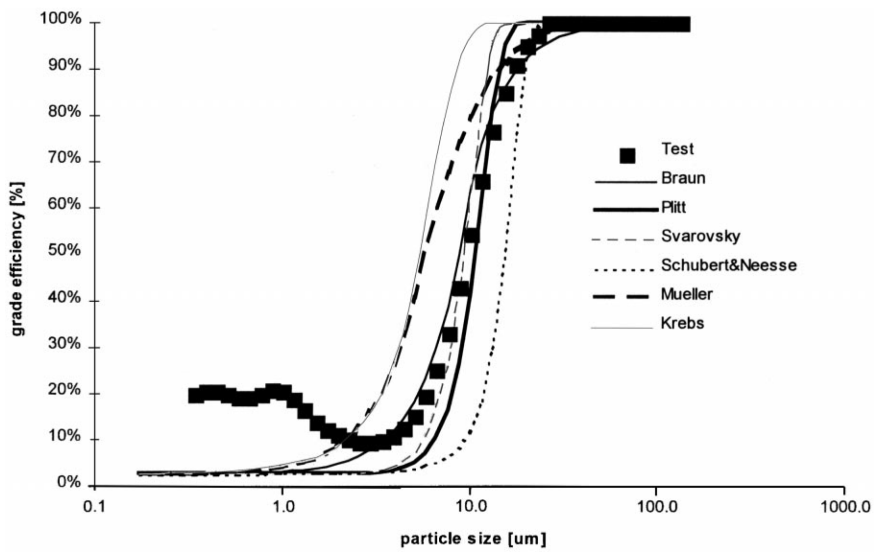

Fig. 2. Grade efficiency comparison for run no. 1.

distribution is examined, one may conclude that the models are very effective. However, once the pressure drop, grade efficiency and concentrations are considered, limitations in models can be realized. Models verified with particle size distributions only need to be treated with caution.

4.5. Flow split

The flow split ratio between the underflow and overflow is required for the calculation between the grade efficiency and particle size distribution. Among the models studied, only Schubert/Neesse, Plitt and Svarovsky offered predictions for the flow split and the predictions were not accurate for the cases studied in this work. Therefore, the measured flow rates were used for this study.

The lack of capability to predict the flow split ratio is the major deficiency for all models. Without the correct prediction of the flow ratio, the hydrocyclone simulations are not very meaningful.

4.6. Underflow and overflow concentration, and solid flow rates

Concentrations and solid flow can be calculated from the above discussed data. Braun's model seems to have a little better overall performance. However, the best model for each

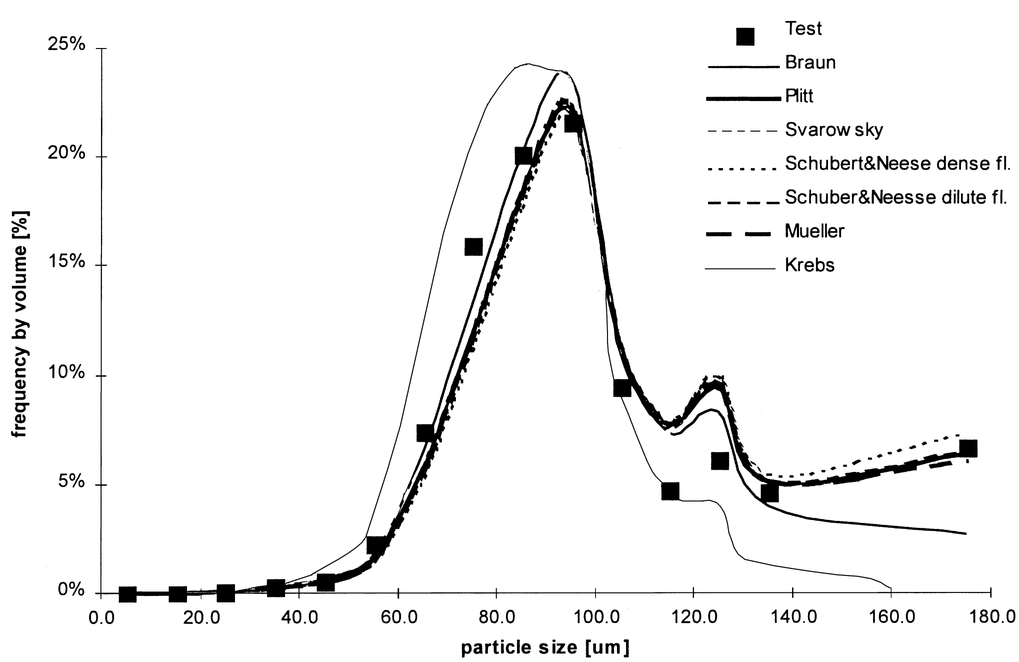

Fig. 3. Particle size distribution in the overflow for salt/glycerin system.

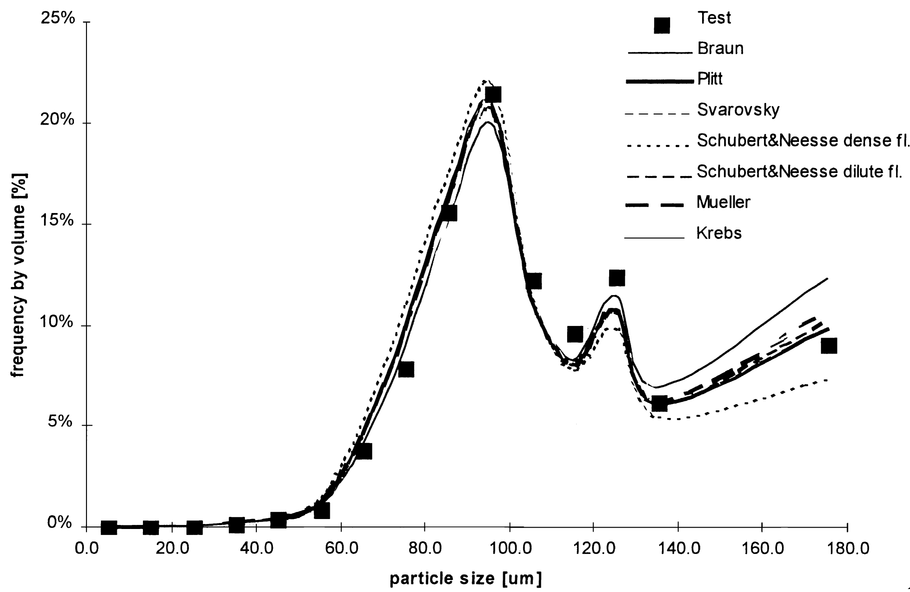

Fig. 4. Particle size distribution in the underflow for salt/glycerin system.

system is again varying. Test data need to be available to determine which model is the best choice.

5. Discussion

It can be seen that none of the models made good predictions for every set of data. Under different operating conditions it was a different model which could be considered as the best fit for the experimental data.

It also can be seen that no models can be considered as the best model if both pressure drop and separation performance are compared. A model may have good prediction on separation but perform poorly on predicting pressure drop. Braun's model made good grade efficiency prediction, but the calculation of pressure drop was not very good. The pressure drops were best predicted by Krebs' and Plitt's models.

Braun's and Mueller's models are theoretical models with some empirical correlations. The calculations of these correlations are not easy and sometimes involve assumptions and uncertainties. For example, the friction factors used for calculating the tangential velocity in a cyclone is not easy to get by an industrial user, the factors used in Mueller's model are based on experimental data obtained from tests with cyclones running air, water and oil [7]. In Braun's model the formula for rough pipes from Colebrook [13] was used and the coefficient of roughness of the wall was set as a constant (1 μm). These coefficients will not be the same for all systems. For the calculation of pressure drop in Braun's model (same as Bohnet's model), a constant friction was used. This friction coefficient may not be the same for the real conditions. Both models also include correlations to calculate tangential velocity, suspension viscosity and turbulent exchange coefficient. These predictions came from others authors and involved a bit of uncertainties and system dependent parameters. Therefore, although these models are theoretically sound but the uncertainties of some key parameters make the prediction of hydrocyclone performance difficult.

Schbert and Neesse considered a homogenous turbulence field and force field for mathematical simplifications. This assumption may not be representative for the real conditions in a hydrocyclone. Also a constant value which is used for laminar flow was used in the grade efficiency calculation. The field in a cyclone is turbulent most of the time and other values may be more appropriate.

Bohnet calculates the size of particles which cannot be separated because of a balance of forces. In a real separation all particles go to overflow or underflow. Also the friction coefficients used for the calculation of the tangential velocity were set as a constant value and the wall roughness was not taken into account.

During the experiments, an air core could be seen which influenced the flow inside of a cyclone. Only Braun took this air core into account in the calculation of the turbulent exchange coefficient. Other models didn't consider this effect.

In the model by Svarovsky, Rietma's optimum hydrocyclone proportions were used. The real proportions of hydrocyclones evaluated were not necessary close to the values suggested by Rietma.

Plitt's and Krebs' models were experimentally based. The coefficients used for calculations are obtained by fitting the models with experimental data. These parameters may not be appropriate once dealing with systems outside the domain of their experimental database. However, these parameters allow the user to adjust the simulation according to the real data. A distribution formula (also called sharpness of separation) is also used in Plitt's and Krebs' models for grade efficiency calculation. Different distribution formula can lead to very different results. Without actual data, it is difficult to determine the reliability of the simulation.

6. Conclusions

From this study, it was realized that a good simulation of hydrocyclone operations involves the calculation of pressure drop, cut size, grade efficiency, and the flow split (underflow to feed or overflow to feed ratio). It is still impossible to have one model which can describes all the above mentioned parameters satisfactorily.

Due to the complexity of hydrocyclone operations, most of the existing models actually are a combination of a group of models, and each of these ‘submodels’ describes a certain property in a cyclone operation. With these different considerations, assumptions and adjustable parameters, it is possible to select a combination of parameters to fit a particular set of hydrocyclone data very well. However, this best combination of parameters may not necessary be suitable for another system or even the same system operated under different conditions.

The complex nature of the two-phase flow and particulate system make it difficult to develop a single perfect model to describe all systems well. However, models can still be a good tool for estimating hydrocyclone performance as long as the models are applied in the right domain.

It is recommended based on the results of this work that some data should be obtained to select an appropriate model for calculations. Any model predictions without experimental data should be treated cautiously.

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