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Performance evaluation of water-injection cyclone treating a synthetic mixture

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ABSTRACT

The effect of change in operating variables i.e., vortex finder diameter, spigot diameter and water injection rate on different performance numbers is studied in water-injection cyclone treating a synthetic mixture of atomized ferro-silicon and ground silica sand. Suitable empirical models relating the operating variables and fines (below 25 microns) recovery, ferro-silicon and silica recoveries in the overflow product and the separation efficiency at 25 microns size are developed. At comparable levels of operating throughput, the performance numbers obtained in a 100mm water-injection cyclone and a 100mm normal hydrocyclone are discussed.

An overall fines recovery of 85.6% was obtained in the overflow product of water-injection cyclone whereas in a normal hydrocyclone the combined fines recovery in the overflow product was 46.2%. Similarly the ferro-silicon recovery at fines below 25 microns in the overflow product from water-injection cyclone was 55.5% while that of hydrocyclone was only 9.8%. Also, silica recovery at fines below 25 microns in the overflow product of a water-injection cyclone was 98.6% in comparison to 82.1% in a normal hydrocyclone. Separation efficiency values obtained between coarse and fine products at 25 microns in the overflow product of water-injection cyclone and hydrocyclone were 83.5% and 45.8% respectively which indicates sharper classification in water-injection cyclone.

***Keywords** : Water-Injection, Empirical models, Separation efficiency, Feed water report to underflow.*

INTRODUCTION

The popularity of hydrocyclones over mechanical classifiers is due to their simplicity in operation, high throughput, low maintenance, less floor space requirement etc. During classification in a hydrocyclone, a certain amount of fines report to underflow product. This is attributed to the fact that even in the efficiently operated cyclones, some portion of feed water reports in to the underflow carrying all size material in an equivalent proportion[1]. Thus in closed circuit grinding where cyclones are operated as classifiers, some portion of already ground fines are sent back for unnecessary grinding. This will not only result in additional consumption of grinding energy, but also results in production of slimes which may in turn result in metal losses in tails due to their extreme fineness.

Improvement in classification efficiency of hydrocyclones for a given cut size can be brought by techniques like classification in series of cyclones and by hydraulic water-injection system at some height above the spigot in a normal hydrocyclone.

The classification in series is usually carried out in two ways either by treating the overflow or by treating the underflow of the primary cyclone in a secondary cyclone. The treatment of the underflow of a primary cyclone in a secondary cyclone reduces the fines reporting into underflow. This was industrially demonstrated at Rakha Copper Concentrator, India[2] . The arrangement reduced the report of fines in the coarse product and also reduced the circulating load of the ball mill. However, the system needed additional operational costs due to additional pumping systems, extra maintenance and is usually sensitive to small fluctuations in the plant operation.

Water-Injection Cyclone

Water-Injection cyclone (Fig.1) can be visualised as a normal hydrocyclone with a cylindrical water injection pot just above the apex. Water is jacketed in between outer solid cylindrical portion and an inner cylindrical portion provided with tangential inlet holes at equal distances on the periphery. The jacketed water injects tangentially into the underflow from the walls at some height above the underflow outlet. The injected water passes transversely through the underflow slurry. In this process, the feed water reporting with the underflow will be replaced by injected water. Thus the underflow solids will be relatively free of fines.

Application of water-injection cyclone was first reported by Dahlstrom for desliming mined product[3]. Later, the water washing system was patented in The United States of America in 1964. Kelsall and Holmes[4] demonstrated better sharpness of classification, in a 3" cyclone wherein 48% of the -10 micron sand in the feed reporting to underflow in normal operation was reduced to 11.5% on water injection. They also showed that the re-circulating load in a ball mill working in a closed circuit with a 24" cyclone was reduced from 350% to 160%. Bradley[5] reported the application of this technique in the paper industry to reduce loss of good fibre with the rejected dirt. Tests, using coal, were carried out by Firth et.al.,[6] on a modified hydrocyclone with water injection facility. This study revealed that the cyclone performance initially improves with increase in water injection rate and then deteriorates. In a recent study by Imre and Holzwarth[7] it was reported that the Krebs Water-Injection Cyclone otherwise known as cyclo-wash has some application in hydrate washing in alumina industry. More recently, Patil and Rao[8] have reported the work carried out on the classification behaviour of water-injection cyclone treating silica as feed sample. The study revealed some information on some of the variables treating a single mineral sample.

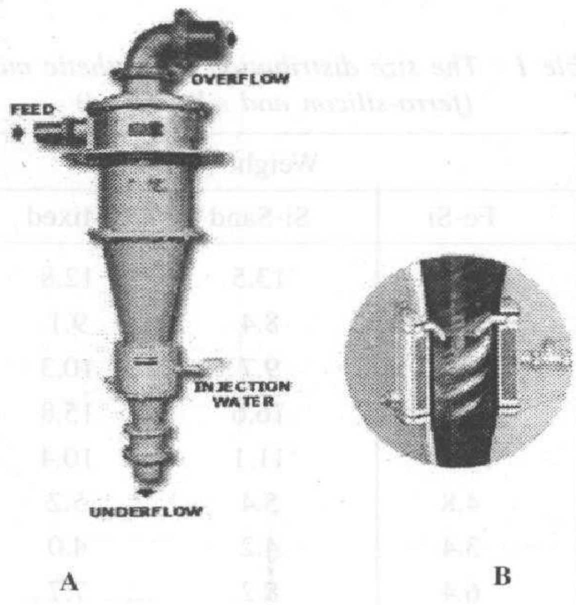

Fig. 1 : (A) Krebs water-injection cyclone (B) Seondary cyclonic action inside the injection pot (taken from website krebsengineers.com)

Thus in the present study an attempt has been made to evaluate the performance of a 100mm cyclowash also called as water- injection cyclone by treating a synthetic mixture of atomised ferro-silicon and ground silica sand. The effect of operating variables like vortex finder diameter, combination of truncated cone diameter and spigot diameter and injection water rate on the classification behaviour was evaluated. For comparison of the results obtained with water-injection cyclone, a set of experiments was also carried out in a normal 100mm hydrocyclone. The recovery of overall fines below 25 microns, ferro-silicon and silica recoveries in the fraction below 25 microns obtained and the separation efficiency at 25 microns cut size were taken as the performance parameters. At comparable levels of operating throughput, the performance parameters obtained with water-injection cyclone and a normal hydrocyclone were compared.

EXPERIMENTAL

Feed Material

The feed sample used in the test work was prepared by mixing 100 kg of atomised ferro-silicon and 300 kg of processed and ground silica sand. The size distribution of ferro-silicon and silica sand was individually carried out by Alpine wet sieve shaker is presented in Table 1. The table also reveals information on the individual and cumulative data passing on the combined synthetic mixture (feed)

Table 1 : The size distribution of synthetic mixture (ferro-silicon and silica sand)

Size	Weight (%)			Cum.Wt.
	Fe-Si	Si-Sand	Mixed	Pass.(%)
+212	10.8	13.5	12.8	100
212*150	11.1	8.4	9.1	87.2
150*100	11.8	9.7	10.3	78.1
100*75	13.3	16.6	15.8	67.9
75*53	8.5	11.1	10.4	52.1
53*45	4.8	5.4	5.2	41.6
45*38	3.4	4.2	4.0	36.4
38*25	6.4	8.2	7.7	32.4
-25	30.0	22.9	24.7	24.7

The table indicates that ferro-silicon has 30% of material in the form of fines below 25 microns and the ground silica has 23% of fines below 25 microns. Overall the mixture contained 24.7% of fines below 25 microns.

Test-rig

The experiments were carried out on a 100 mm diameter hydrocyclone and on a 100 mm diameter water-injection cyclone procured from Krebs Engineers.

The schematic diagram of test rig used for experimental work on a water-injection cyclone is presented in Fig. 2.

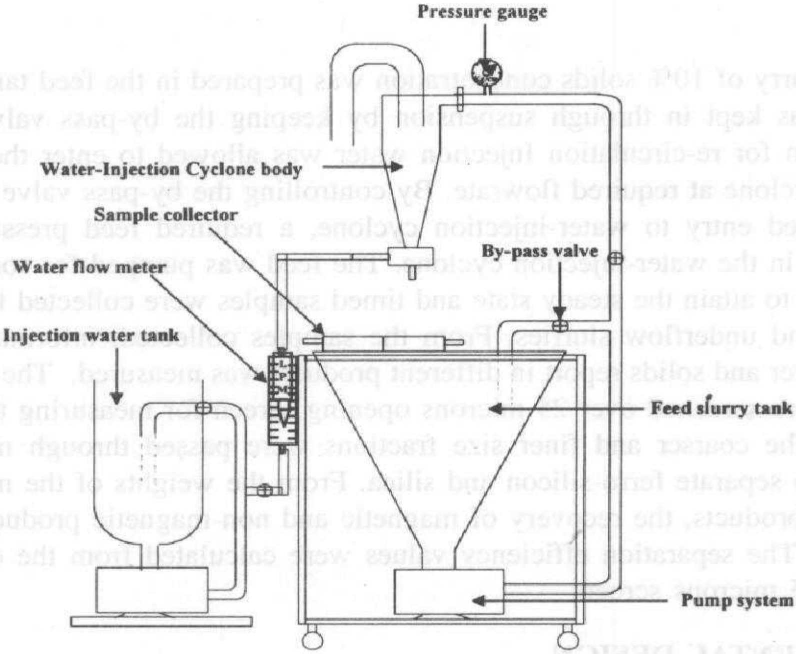

Fig. 2 : Schematic diagram of the water-injection cyclone test rig

The test rig consists of a feed tank of 200 liters capacity mounted on a stable platform. The bottom of the tank is connected to a centrifugal pump with rubber lined impeller to minimise the abrasion of the solid particles. The pump was driven by a 3 phase, 5.5 KW motor. The outlet of the pump was connected to the feed inlet of the hycyclone/water-injection cyclone and the line was connected to a control valve. A diaphragm type pressure gauge was fitted near the feed inlet of the separator. A by-pass pipe with a control valve was connected to the pump outlet line to obtain the required feed pressure. The required separator (hydrocyclone/water-injection cyclone) was fitted above the slurry tank.

During the experimental work with hydrocyclone, the overflow and underflow products were allowed to continuously discharge in to the tank and were re-circulated. A sample collection device moved on rails was above the feed tank enabled the collection of overflow and underflow slurries simultaneously.

The same test rig used for experimentation with hydrocyclone was also used for test work on water-injection cyclone with an additional 150 liters stainless steel tank to store water required for injection purposes. While carrying out test work with water-injection cyclone, the product slurries were not re-circulated back to feed tank as they got diluted with the injected water. Timed samples from both the products were simultaneously collected from both the streams.

Procedure

Feed slurry of 10% solids concentration was prepared in the feed tank. The material was kept in through suspension by keeping the by-pass valve completely open for re-circulation Injection water was allowed to enter the water-injection cyclone at required flowrate. By controlling the by-pass valve and the valve at feed entry to water-injection cyclone, a required feed pressure was maintained in the water-injection cyclone. The feed was pumped for some time for cyclone to attain the steady state and timed samples were collected from the overflow and underflow slurries. From the samples collected, information regarding water and solids report in different products was measured. The product samples were screened over 25 microns opening screen for measuring the fines recovery. The coarser and finer size fractions were passed through magnetic separator to separate ferro-silicon and silica. From the weights of the magnetic separation products, the recovery of magnetic and non-magnetic products were calculated. The separation efficiency values were calculated from the data obtained at 25 microns screen.

EXPERIMENTAL DESIGN

A set of twelve experiments was designed for the test work on water-injection cyclone by changing the vortex finder diameter (VFD), a combination of truncated cone diameter and spigot diameter (TCD-SPD) and water injection rate. The vortex finder diameter was varied at two levels i.e., 25.4mm and 38.0 mm. Similarly the spigot diameter was varied at 16.0 mm and 22.3 mm. Water injection rate was studied at three different levels 20 lpm, 35 lpm and 50 lpm at all the possible combinations of the vortex finder and apex diameters. For convenience in the experimentation, the feed pressure to cyclone was maintained constant at 0.562 kg/cm^2 and feed solids was maintained constant at 10% by weight. Truncated cones i.e., with diameters 19.0mm, 25.4mm corresponding to the spigot diameters of 22.25mm and 26.97mm respectively were fitted above the injection pot.

As a comparative study, another set of six experiments was carried out on the Kreb's 100mm hydrocyclone by changing important variables like vortex finder diameter (VFD), spigot diameter (SPD) and feed pressure (FP).

RESULTS AND DISCUSSION

The results obtained on the test work with water-injection cyclone were utilised for generating different performance numbers. The effects of change in the operating conditions on the water distribution, on solids throughput and split, feed water report to underflow and its effects on the solids distribution characteristics were discussed as follows:

Water Split

The relation between the total water i.e., feed water + injected water, and the water reported into the overflow is presented in Fig. 3. It can be observed from the data that there is a linear relationship between the total water and the water reported into the overflow. It can be observed from the figure, that over a range of operating conditions, the major variable influencing the water distribution to overflow is the spigot diameter. This is similar to the findings by Linch and Rao[8] in a normal hydrocyclone, Suresh et.al.[9] in a water-only cyclone and Patil and Rao[10] in a water-injection cyclone treating a mono-mineralic (sand) as feed.

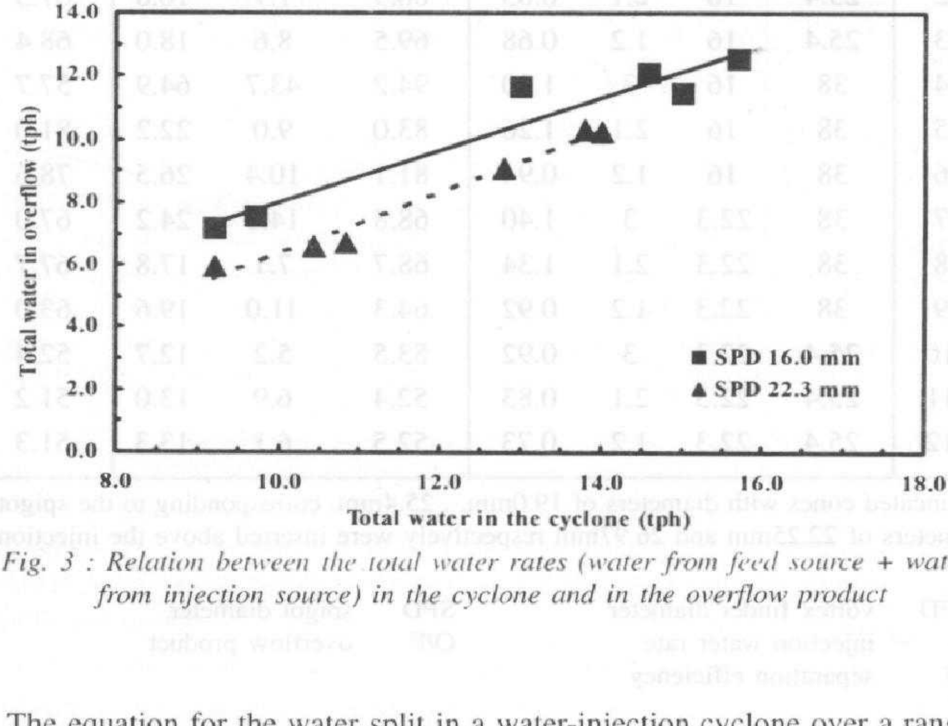

Fig. 3 : Relation between the total water rates (water from feed source + water from injection source) in the cyclone and in the overflow product

The equation for the water split in a water-injection cyclone over a range of operating conditions is as follows

WOF =0.876*WF-0.216*SPD +2.57 ... (1)

WOF = Water in the overflow expressed in tph.

WF = Water in the feed expressed in tph.

SPD = Spigot diameter expressed in mm.

Solids Distribution

The solids throughput of the cyclone, recovery of overall fines below 25 microns, recoveries of ferro-silicon and silica in fines below 25 microns and the separation efficiency of the unit at 25 microns size obtained at different operating conditions are presented in Table 2.

Table 2 : The experimental conditions and test results obtained in a 4" Water-injection cyclone

E.No.	VFD	*SPD	WI	Sol.Th.	O/F Recovery (%)			SE (%)
	mm.	mm.	lpm.	(tph)	-25 mic	Fe-Si	Silica	25 mic.
1	25.4	16	3	1.28	85.6	8.3	22.2	83.5
2	25.4	16	2.1	0.83	68.9	7.7	16.8	67.5
3	25.4	16	1.2	0.68	69.5	8.6	18.0	68.4
4	38	16	3	1.30	94.2	43.7	64.9	57.7
5	38	16	2.1	1.26	83.0	9.0	22.2	81.0
6	38	16	1.2	0.94	81.1	10.4	26.5	78.6
7	38	22.3	3	1.40	68.8	14.1	24.2	67.0
8	38	22.3	2.1	1.34	68.7	7.1	17.8	67.7
9	38	22.3	1.2	0.92	64.3	11.0	19.6	63.0
10	25.4	22.3	3	0.92	53.5	5.2	12.7	52.4
11	25.4	22.3	2.1	0.83	52.4	6.9	13.0	51.2
12	25.4	22.3	1.2	0.73	52.5	6.1	13.3	51.3

*Truncated cones with diameters of 19.0mm. , 25.4mm. corresponding to the spigot diameters of 22.25mm and 26.97mm respectively were inserted above the injection pot

VFD vortex finder diameter
SPD spigot diameter
IR injection water rate
O/F overflow product
SE separation efficiency

Effect of variables on the recovery of overall fines below 25 microns in the overflow:

The relation between the water-injection rate and the fines report at different combinations of vortex finder diameter and spigot diameter is presented in Fig. 4 (A). It can be observed from the figure that there are two sets of data obtained at two different spigot diameters. At smaller spigot diameter, an increase in injection water rate is associated with major improvement in fines recovery where as at bigger spigot diameter an increase in injection water rate marginally increased the fines recovery in the overflow product.

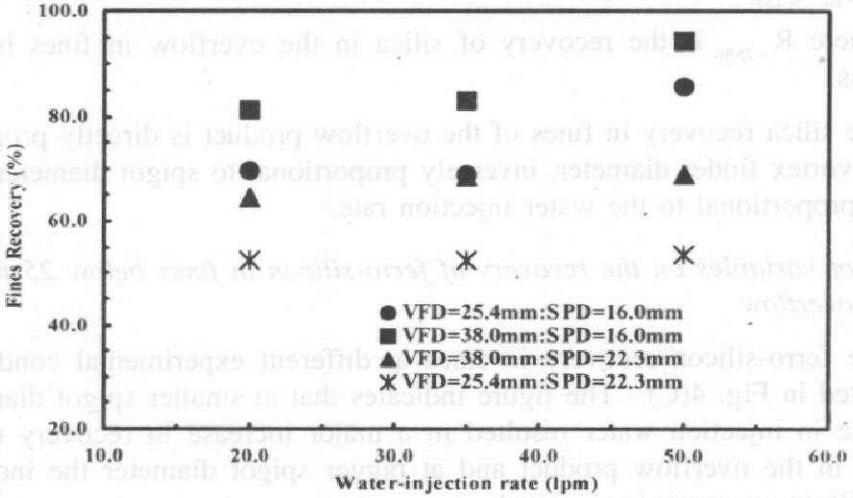

Fig. 4(A) : Relation between variables and the recovery of fines below 25 microns

It can be observed from Table 2 that fines recovery into the overflow is directly proportional to the vortex finder diameter, inversely proportional to spigot diameter and directly proportional to the water injection rate.

The equation relating the operating variables and the overall recovery of fines below 25 microns is as follows

$$Log_{10}R_{-25} = 0.014VFD - 0.046SPD + 0.074IR + 0.046 \quad (R^2 = 0.927) \qquad ... (2)$$

Where R_{-25} is the percentage recovery of fines below 25 microns in the overflow product

Effect of variables on the recovery of silica in fines below 25 microns in the overflow

The relation between the water-injection rate and the silica report at fines at different experimental conditions shown in Fig. 4 (B). The figure indicates that at smaller spigot diameter an increase in injection water rate is associated with major improvement in the fines silica recovery and other set of data obtained at bigger spigot indicate a marginal increase in the fine silica recovery in the overflow product.

The equation for the silica recovery in fines in the overflow product is as follows

$$Log_{10}R_{-25Si} = 0.010VFD-0.357SPD+0.036IR+4.711 \quad (R^2 = 0.928) \quad ... (3)$$

Where R_{-25Si} is the recovery of silica in the overflow in fines below 25 microns.

The silica recovery in fines of the overflow product is directly proportional to the vortex finder diameter, inversely proportional to spigot diameter and directly proportional to the water injection rate.

Effect of variables on the recovery of ferro-silicon in fines below 25 microns in the overflow

The ferro-silicon recovery in fines at different experimental conditions is presented in Fig. 4(C). The figure indicates that at smaller spigot diameter an increase in injection water resulted in a major increase in recovery of ferro-silicon in the overflow product and at bigger spigot diameter the increase in ferro-silicon recovery is marginal.

The equation for fine ferro-silicon recovery in the overflow product is as follows :

$$Log_{10}R_{-25FeSi} = 0.097VFD-0.148SPD+0.663IR+0.393 \quad (R^2 = 0.886) \quad ... (4)$$

Where $R_{-25FeSi}$ is the recovery of silica in the overflow in fines below 25 microns.

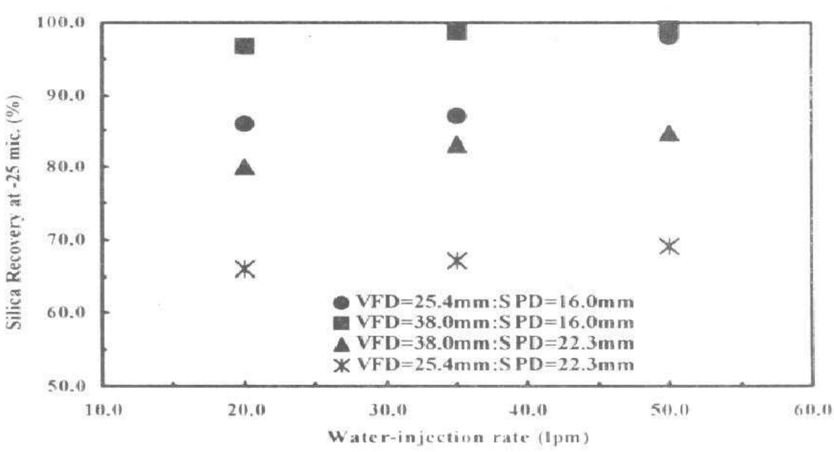

Fig. 4(B) : Relation between variables and the recovery of silica in fines below 25 microns

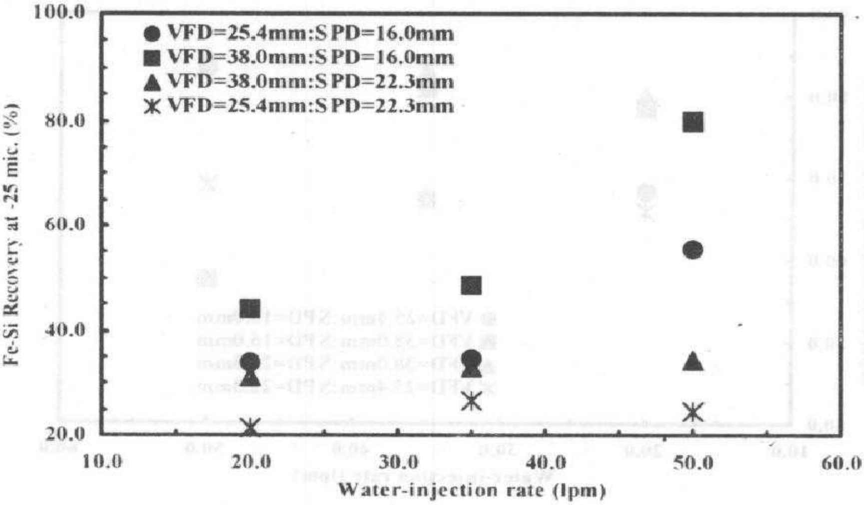

Fig. 4(C) : Relation between variables and the recovery of ferro silicon in fines below 25 microns

The fine ferro-silicon recovery in the overflow product is directly proportional to the vortex finder diameter, inversely proportional to spigot diameter and directly proportional to the water injection rate.

Effect of variables on separation efficiency at a cut size of 25 microns:

The separation efficiency number in the present context is defined as the difference of the recovery of finer and coarser fractions at 25 microns size in the overflow product

SE_{25} = *Recovery of fines below 25 microns in the overflow - Recovery of coarse material above 25 microns in the overflow* ... (5)

Fig. 4 (D) indicates the change in separation efficiency with injection rate at different operating conditions. The separation efficiency values followed a linear relationship at bigger spigot diameter. At a combination of smaller diameter spigot and at bigger diameter vortex finder a drop in the separation efficiency at 50 lpm water injection rate was observed. This can be explained by increased amount of coarser fraction in the cyclone overflow due to restricted underflow. Though the recoveries of ferro-silicon and silica increased at this condition, the decrease in separation efficiency is due to flushing of coarser particles into the overflow product. However, at smaller diameter spigot and smaller diameter vortex finder diameter, a sharp increase in separation efficiency with the increase in injection water rate can be observed.

Log10SE = 0.013VFD -0.043SPD+0.062IR+4.510 $(R^2 = 0.914)$ ... (6)

Where SE is the Separation Efficiency (%)

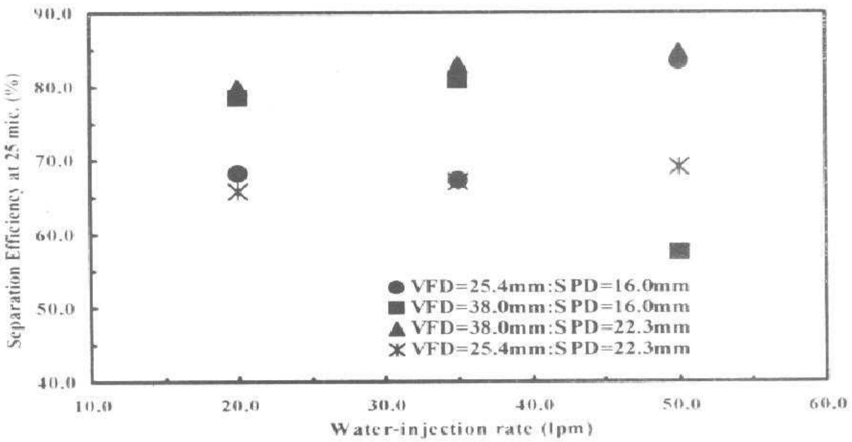

Fig. 4(D) : Relation between operating variables and the separation efficiency at 25 microns

Relation between Feed Water and Solids Report into Underflow (WIR_f)

The recovery of fines at different operating conditions can be related to the feed water report into the underflow. In the present study, assuming that the injection water has completely replaced an equal amount of feed water reporting into the underflow, a new index has been developed. The index here onwards termed as WIR_f, is the percentage ratio of the difference between the underflow water and the injection water rate and the feed water.

$$WIR_f = 100*(\text{Underflow water report} - \text{Injection water})/\text{feed water} \quad \dots (7)$$

The relation between the WIR_f and the recoveries of fines below 25 microns, ferro-silicon and silica recoveries into the overflow product at fines below 25 microns size and the separation efficiencies at 25 microns are presented in Fig. 5(A) to 5(D). Two different kinds of relationships can be observed from the figures. The data obtained at smaller spigot diameter indicated a quadratic relationship i.e., with decreasing WIR_f till a particular value, the fines recovery, ferro-silicon recovery, silica recovery and separation efficiencies increase and then decrease with further decrease in WIR_f. The data obtained at bigger spigot diameter has a linear relationship i.e., with increasing WIR_f, the fines recovery, ferro-silicon recovery, silica recovery and separation efficiency decrease. It can also be observed that the data points at smaller spigot diameter are mostly above the data points at bigger spigot diameter.

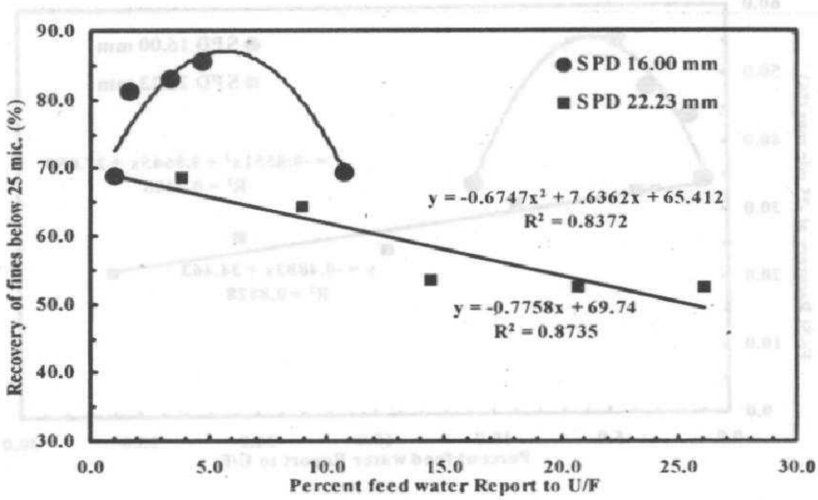

Fig. 5(A) : Relation between the feed water report to underflow and the recovery of fines below 25 microns

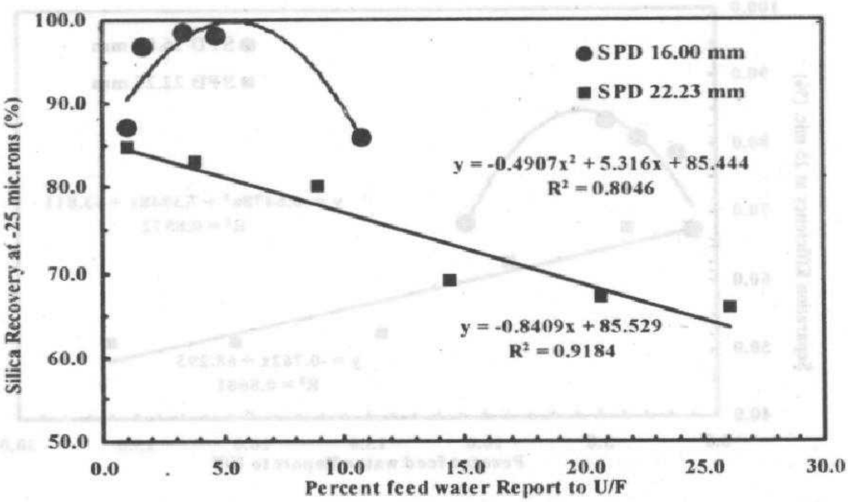

Fig. 5(B) : Relation between the feed water report to underflow and the recovery of silica in fines below 25 microns

Comparative Classification Study in Water-injection Cyclone and Hydrocyclone

For comparison of the performance of water-injection cyclone with a normal hydrocyclone, data on the classification performance of a 100mm hydrocyclone treating the synthetic mixture was generated over a range of operating conditions. The experimental conditions and test results obtained in a normal hydrocyclone (without water-injection assembly) are presented in Table 3.

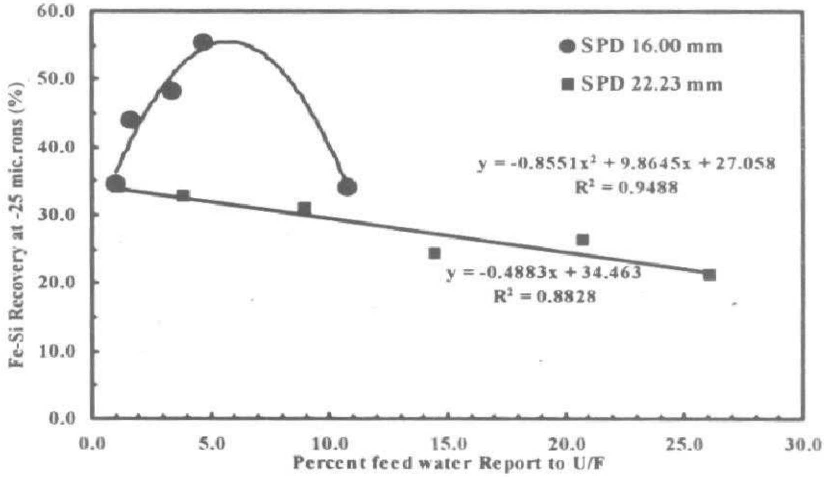

Fig. 5(C) : Relation between the feed water report to underflow and the recovery of ferro-silicon in fines below 25 microns

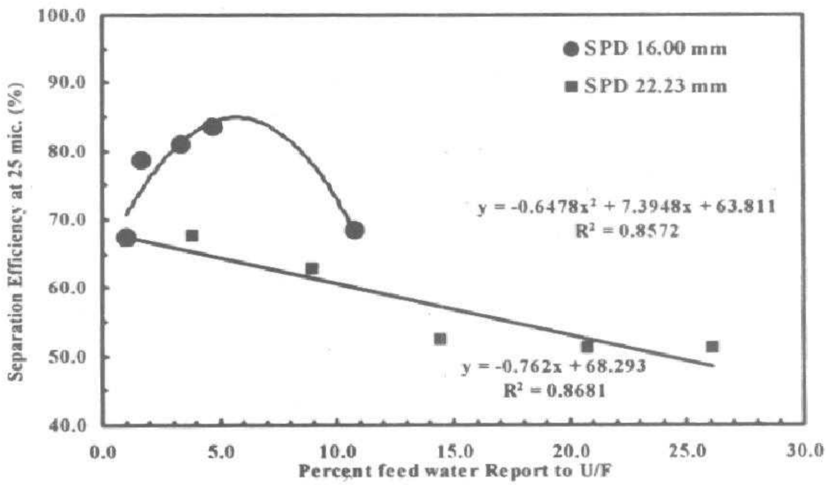

Fig. 5(D) : Relation between the feed water report to underflow and the separation efficiency at 25 microns

It is expected that for a given cyclone diameter, the operating throughput in a water injection cyclone system will be smaller than a normal hydrocyclone because of additional injection water. Thus in the present investigation the following performance data obtained in a water-injection cyclone and a hydrocyclone are compared at constant levels of operating throughputs.

- Recovery of fines below 25 microns in the overflow product

- Recovery of ferro-silicon in fines below 25 microns in the overflow
- Recovery silica in fines below 25 microns in the overflow
- Separation Efficiency values at 25 microns cut size

Table 3 : The experimental conditions and test results obtained in a 4" Hydrocyclone

E.No	VFD (mm)	SPD (mm)	Sol.Th. (tph)	O/F Recovery (%)			SE
				-25 mic.	Fe-Si	Silica	25 mic.
1	25.4	17.5	1.2	30.1	2.9	8.6	29.6
2	34.0	17.5	1.4	42.8	4.3	12.7	42.6
3	40.0	17.5	1.6	48.0	5.1	13.9	47.6
4	40.0	14.0	1.2	46.2	6.0	15.1	45.8
5	34.0	14.0	1.0	47.1	8.5	18.9	46.8
6	25.4	14.0	0.8	34.1	4.0	12.8	33.7

VFD is vortex finder diameter
SPD is spigot diameter
O/F is overflow product
SE is the separation efficiency

Recovery of fines below 25 microns in the overflow product:

The relation between the throughput and fines recovery in the overflow product is presented in Fig.6. The data points on hydrocyclone indicated that fines recovery in the overflow product varied between 34.1% to 42.8% at different operating throughputs. Higher fines recovery values i.e., between 52.2% to 85.6% were obtained in water-injection cyclone over hydrocyclone over a range of operating throughputs between 0.7tph. and 1.3 tph.

A maximum difference in fines recovery between water injection cyclone and hydrocyclone was observed around 1.3 tph. At this operating throughput, the fines recovery in a water injection cyclone was 85.6% whereas in a hydrocyclone the fines recovery at this throughput was 42.8%. Similarly at a capacity of 0.7 tph the fines recovery was 69.5% and 34.1% in water injection cyclone and in hydrocyclone respectively. This indicates that water injection cyclone resulted in higher fines recovery over a wide range of operating throughputs.

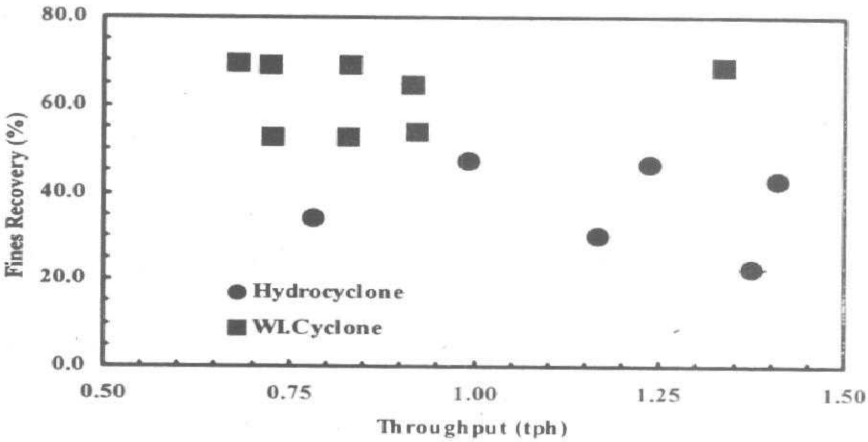

Fig. 6 : Relation between the solids throughput and the fines (below 25 microns) recovery in the overflow product

Recovery of silica in fines below 25 microns in the overflow product:

The relation between the throughput and the silica recovery in the overflow product at fines below 25 microns was presented in Fig. 7. It can also be observed that the data points on water-injection cyclone are above the data points obtained with hydrocyclone over a range of operating conditions from 0.7tph. to 1.3tph..

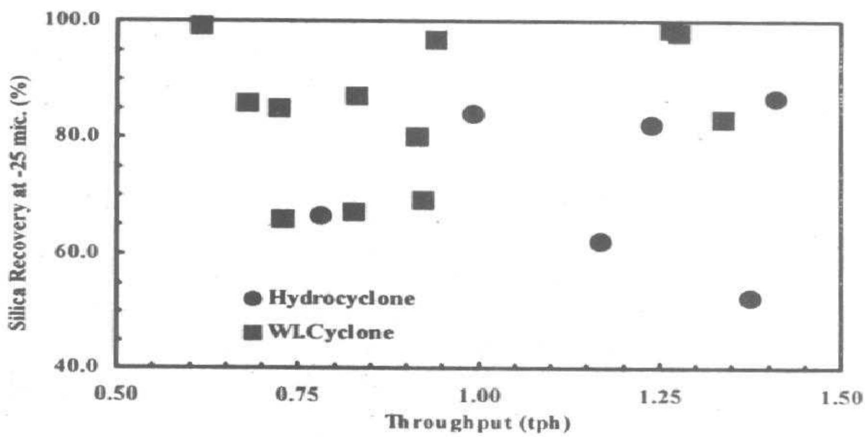

Fig. 7 : Relation between the solids throughput and thesilica recovery fines (below 25 microns) in the overflow product

At 0.7 tph throughput the silica recovery was 84.7% in water injection cyclone and in the hydrocyclone at 0.8 tph operating throughput the silica recovery was 66.5%. Similarly, at 1.3tph, silica recovery was 98.0% in a water-injection cyclone and at a comparable throughput, the silica recovery was 86.6% in hydrocyclone.

Recovery of ferro-silicon at fines below 25 microns in the overflow product:

It can also be observed from Fig. 8 that the ferro-silicon recovery values obtained in water-injection cyclone are higher than the data points obtained with hydrocyclone.

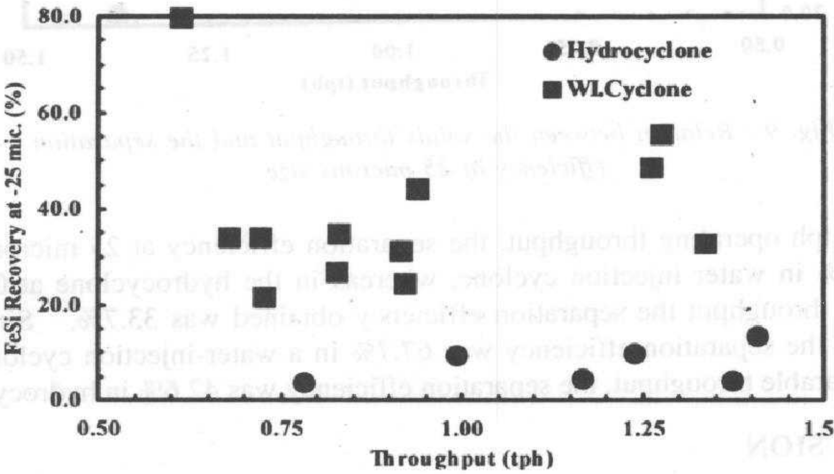

Fig. 8 : Relation between the solids throughput and ferro-silicon recovery at fines (below 25 microns) in the overflow product

For example in water-injection cyclone, the ferro-silicon recovery at 0.7tph operating throughput was 34.1% whereas in a hydrocyclone, at 0.8 tph operating throughput, the ferro-silicon recovery was 3.7%. Similarly, at 1.3 tph, ferro-silicon recovery was observed to be 55.5% in a water-injection cyclone and 13.4% in hydrocyclone.

Separation efficiency at 25 microns size in the overflow product:

The relation between the throughput the separation efficiency at 25 microns size in the overflow product is presented in Fig. 9. The data obtained with both hydrocyclone and water-injection cyclone indicated that the separation efficiencies increase over a range of operating conditions from 0.7 tph to 1.4 tph. It can also be observed that the data points of water-injection cyclone are above the data points obtained with hydrocyclone.

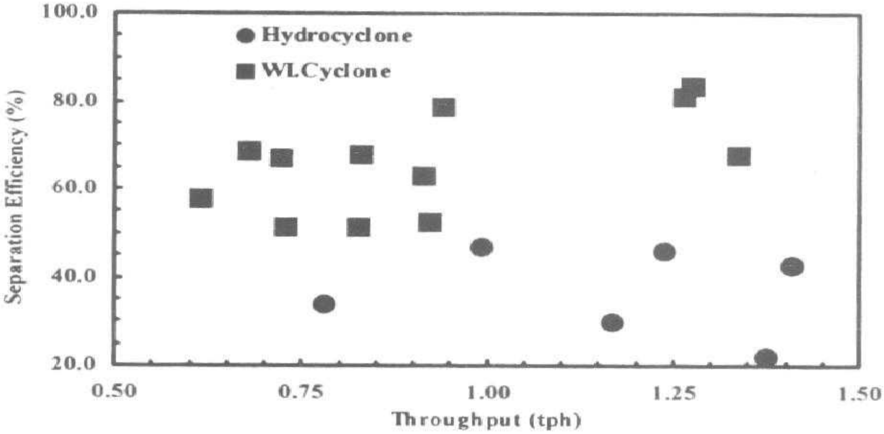

Fig. 9 : Relation between the solids throughput and the separation efficiency at 25 microns size

At 0.7tph operating throughput, the separation efficiency at 25 microns size was 68.4% in water injection cyclone, whereas in the hydrocyclone at 0.8 tph operating throughput the separation efficiency obtained was 33.7%. Similarly at 1.3 tph the separation efficiency was 67.7% in a water-injection cyclone and at a comparable throughput, the separation efficiency was 42.6% in hydrocyclone.

CONCLUSION

1. Comparative performance study on water-injection cyclone and a normal hydrocyclone indicated that recovery of fines below 25 microns in the overflow is more in water-injection cyclone.
2. The study revealed that over the entire range of operating throughputs the recovery of fines below 25 microns in the overflow product of a water-injection cyclone is higher than the recovery of fines in the overflow product of a hydrocyclone. For example, at 1.3 tph solids operating throughput the recovery of fines achieved in hydrocyclone is 42.8% and the fines recovery in water-injection cyclone is 85.6%
3. The increase in the fines recovery is mainly due to increase in the ferro-silicon recovery in the fines below 25 microns.
4. The total water report into the overflow product of water-injection cyclone is a function of total water in the cyclone body and the spigot opening. This is similar to the relation between the feed water rate, spigot opening and overflow water rate in a hydrocyclone

* The recovery of fines below 25 microns in the overflow is directly proportional to the vortex finder diameter and injection water rate and inversely proportional to the spigot diameter.

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