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PERFORMANCE CHARACTERIZATION OF WATER-ONLY CYCLONE FOR PROCESSING HIGH ASH INDIAN COAL

S. Hore*[1], S. K. Das[1], K. M. Godiwalla[1], K. K. Bhattacharya[2] and R. Singh[2]
[1]*Mathematical Modelling & Simulation Division,* [2]*Mineral Processing Division, National Metallurgical Laboratory (CSIR), Jamshedpur - 831007, India*

Abstract: In this study semi-empirical performance models have been employed to characterize the performance of water-only cyclone on the basis of experimental data modelling for fine coal cleaning. Experiments have been conducted in the laboratory on a 100 mm water only cyclone. High ash coals used for the experiments belong to the Patherdih and Munidih colliery in the Eastern part of India. Separation based on specific gravity was studied on Patherdih sample whereas size classification analysis has been carried out on Munidih sample. Washability studies on Patherdih sample have been undertaken to determine the specific gravity of effective separation for a desired coal quality. The Mayer curve has been employed to plot float-and-sink analysis from which the Tromp distribution curve is constructed. A reduced efficiency curve has been generated based on specific gravity as well as size classification analysis. Attempts have been made to describe the reduced efficiency curve by employing Rosin-Rammler and Logistic distribution function to characterize the performance of the cyclone. A simplified approach has been proposed to estimate the performance model parameters. Experiments were conducted by varying the operating parameters like spigot diameter, feed inlet pressure and percentage solids in the feed to study the sensitivity of operating conditions. The effect of operating variables on the performance of the cyclone in terms of classification function has been investigated. A graphical user interface (GUI) based user friendly software (HYDROSIM) has been developed based on semi-empirical models for calculating the cut-size (d_{50}) under various operating conditions.

Keywords: Coal washing, water-only cyclone, performance modelling, distribution function

1. INTRODUCTION

Coal plays central role in the economy of India. It accounts for 75 % [1, 2] of annual energy use. Whilst it is cheap and plentiful, the environmental and health effects of usage of coal are becoming more and more severe its usage grows at a rapid rate. Clean coal technologies have the potential to reduce emissions of the gases. Further, power plants that use fossil fuels to generate electricity currently face environmental regulations to restrict polutant releases to the air, water and land. The regulatory measures are stringent for controlling NO_x, SO_2 and fly ash contents in the emissions. Cleaner production and eco-efficiency are complimentary strategies, dealing with the use of minerals, materials, energy and water in many industries, in particular in processing and extraction of minerals, coal and metals.

India has some of the largest reserves of coal in the world (approx. 197 billion tons) [1, 2]. Coal deposits in India occur mostly in thick seams and at shallow depths. Non-coking coal reserves aggregate 172 billion tons (85%) while coking coal reserves are 29 billion tons (the remaining 15%). Indian coals have very high ash content as well as high inorganic matter content and have difficult washability characteristics. The ash contains primarily silica and alumina. Therefore, for Indian coals, fine crushing is essential for liberation of mineral matters [3] and hence fine coal cleaning process is getting more attention by process engineers.

Corresponding author; E-Mail: sh@nmlindia.org; Tel: 91-0657-2273038

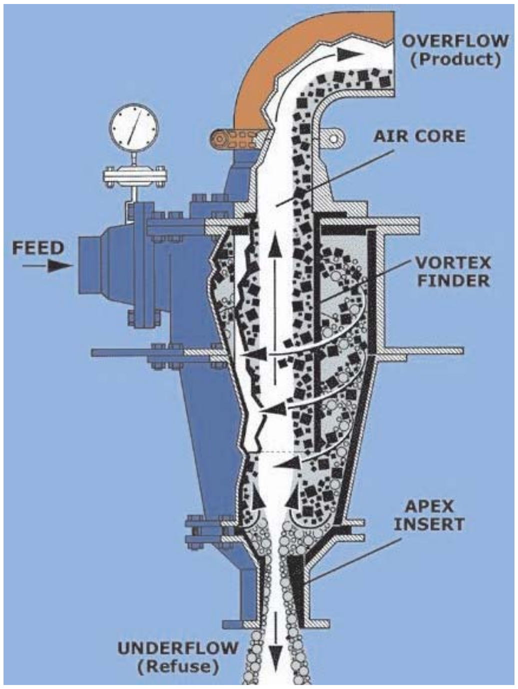

Fig. 1. Water - only cyclone

In recent years a number of new process technologies have emerged allowing even finer materials to be successfully processed. The application of cyclone separator for fine coal cleaning has been widely reported in the literature [4-8]. These studies have demonstrated the potential application of cyclones in coal preparation to clean fine coal where the specific gravity differential between coal and shale is small. The schematic of a water-only cyclone has been depicted in Fig. 1. The lighter particles (clean coal) are recovered from the overflow whereas heavier materials report to the underflow[9].

In the present study, investigations have been carried out pertaining to high ash coal from Patherdih and Munidih colliery from Eastern India using water-only cyclone. Experiments have been conducted in the laboratory on a 100 mm water-only cyclone. The clean coal product and the refuse of Patherdih sample have been subjected to washability studies to determine the specific gravity of separation for a specified coal quality. The Mayer curve has been generated to characterize float-and-sink analysis for predicting the cleaning properties of coal. The Tromp distribution curve has been constructed from float-and-sink washability data of clean coal and refuse to determine the specific gravity of separation with a given ash content. Classification analysis based on size was carried out for Munidih coal samples. A reduced efficiency curve has been obtained and attempts have been made to describe the behaviour using Rosin-Rammler and Logistic distribution function for estimating the cyclone performance. Model parameters of the reduced efficiency curve have been estimated by linearizing the model equations using logarithmatic transformation. The details of the experimental programme and the methodology adopted are discussed in the subsequent sections. A user-friendly, GUI-based software (Copyrighted) has been developed incorporating several semi-empirical models [10-12] to predict the cut-size of the cyclone for given geometry and operating conditions.

2. PERFORMANCE MODELLING OF THE WATER-ONLY CYCLONE

Attempts have been made to model cyclone operation both analytically and empirically. Development of high speed computers has been facilitated the numerical solution of the equations for fluid dynamics and thus rekindled on interest in theoretical modeling [13-16]. Despite of potential of theoretical models, they have not made a significant impact on the prediction of cyclone performance. Also such solutions are computationally intensive and time consuming. Computational fluid dynamics (CFD) modeling of cyclones is still in its infancy and faces formidable hurdles, not least of which is the computing power required, current-models typically take days or weeks to converge. On the other hand, empirical performance models of the cyclone have received considerable attention for practical application [11,17,18].

Empirical cyclone models are based on the observation that the probability of a particle reporting to one of the product streams is dependant upon the particle settling characteristics like size and specific gravity. The classification action of the cyclone is determined by the net effect of the two competing forces that act on every particle - the outward centrifugal force and the inward drag force. On the basis of equilibrium orbit hypothesis [19] any particle that experiences an equilibrium between the drag and centrifugal forces inside the cyclone will have an equal chance to exit through either the underflow or the overflow because they will tend to circulate on a circular orbit inside the cyclone until randomly impact with other particles.

For a homogeneous coal the result of these competing forces is that the fine particles report with the bulk of water to the overflow product while a relatively high density product containing the coarser particles is discharged as cyclone underflow. In homogeneous coal all particles have a substantially uniform density implying that separation is based on size alone. Heterogeneous coals contain significant quantities of particles with different densities and thus density effect in separation become important. In the present investigation separation based on specific gravity as well as size has been considered, and attempts have been made to describe the reduced efficiency curve using a Rosin-Rammler type of distribution function for estimating the performance.

3. EXPERIMENTAL INVESTIGATIONS

3.1 Experiments with water-only cyclone

Experiments on a water only cyclone have been conducted in the laboratory using Patherdih and Munidih coal of Eastern India. The cyclone diameter and vortex finder diameter were 0.1 m and 0.025 m respectively. A 0.01 m diameter spigot was fitted with the cyclone. A given amount of solids and water were mixed in the feed tank to achieve solids of 5% by weight in the feed pulp. The feed slurry was pumped at the inlet pressure 0.1 bar. Samples from both the overflow and underflow slurry streams were collected simultaneously for a fixed interval of time. The slurry and solid weights of the products were measured and solid samples after drying were used for size analysis. The experiment was repeated for 15% solids and also conducted for 0.02 m spigot diameter and 0.5 bar feed inlet pressure in various combinations. For Patherdih sample washability studies were conducted to determine the gravity of separation. Different operating variables and the yield and ash results obtained with Munidih coal sample are presented in Table I. Table II presents the overall wt% and ash% of cyclone overflow and underflow from water-only cyclone treated with Patherdih coal sample.

Table I. Experimental variables and results for Munidih coal using water-only cyclone*							
Expt. No.	Pulp density %	Feed inlet pressure bar	Apex diameter m	Yield		Ash	
				Overflow, %	Underflow %	Overflow %	Underflow %
1	5	0.1	0.01	80.40	19.60	18.01	38.91
2	15	0.1	0.01	84.50	15.50	18.50	39.10
3	5	0.5	0.01	80.10	19.90	17.87	38.05
4	15	0.5	0.01	81.00	19.00	17.86	39.64
5	5	0.1	0.02	54.40	45.60	17.67	27.17
6	15	0.1	0.02	53.40	46.60	18.24	26.31
7	5	0.5	0.02	46.30	53.70	17.47	25.91
* Cyclone diameter 0.1 m, vortex finder diameter 0.025m							

3.2 Washability studies of coal samples

Table II. Size analysis of cumulative overflow and underflow for Patherdih coal			
Product	Weight Kg	Weight %	Ash %
Cyclone overflow	1.27	60.24	24.42
Cyclone underflow	0.84	39.76	45.18
Total	2.10	100.00	32.67

Washability analysis for Patherdih coal samples using an organic liquid Bromoform with a specific gravity from 1.4 to 2.0 have been conducted in the laboratory. The dry weight of each fraction has been determined and each has been analyzed for ash content. The reconstituted washability of original sample developed from washability of sizes of cumulative overflow and cumulative underflow has been presented in Table III.

Table III. Re-constituted washability data (sink-float) of Patherdih coal

	Original		1.4F		1.5 F		1.6 F		1.7 F		1.8 F		2.0 F		2.0 S	
	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %	Wt. %	Ash %
+48#	17.12	24.22	4.75	6.18	9.66	11.93	11.71	14.09	13.46	16.74	11.87	20.43	12.83	22.39	17.11	25.25
-48+100#	38.14	33.17	14.61	5.18	20.77	7.97	23.74	10.20	25.94	12.23	28.38	14.50	30.67	17.64	38.11	33.09
-100+200#	19.60	29.51	6.24	7.12	9.15	9.14	11.32	11.62	13.25	14.31	15.98	17.65	16.89	19.72	19.58	29.28
-200+325#	9.88	38.51	1.82	8.63	2.49	9.96	3.56	12.53	4.40	14.75	4.95	16.39	6.37	22.03	9.90	42.33
-325 #	15.25	48.88	48.88	0.00	1.27	12.05	1.95	16.11	4.64	21.91	4.99	22.56	6.78	27.92	15.29	48.55
	100.0	33.26	33.26	6.00	43.35	9.48	52.27	11.86	61.69	14.61	66.18	17.19	73.53	20.26	99.99	33.71

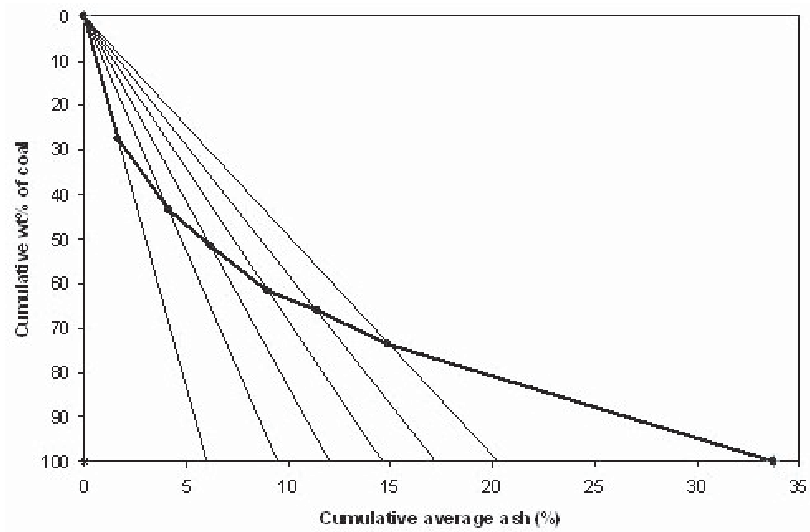

Fig. 2. Mayer curve from float-sink analysis of Patherdih coal (From Table III)

Table IV. Typical recovery data of % clean coal from Mayer's curve (Patherdih coal)

Average ash of clean coal product (%)	Recovery of clean coal product Y_C (%)	Recovery of refuse Yr(%)	Average ash of refuse (%)
8	34	66	46.94
10	45	55	53.09
14	56	44	58.77
17	66	34	66.12

3.3 Construction of Mayer curve

The Mayer curve, known as the M-curve, provides a useful tool for float-and-sink analysis to predict the results of cleaning properties of coal. The M-curve has been constructed by plotting both the cumulative weight percent on the ordinate scale and the cumulative average ash percent on the abscissa scale (Fig 2), the values of which are taken from Table III. Diagonal lines are drawn from the origin to intersect the cumulative average ash axis at each cumulative ash value from float-and-sink analysis. Each cumulative ash value is then plotted on its respective diagonal at the intersection of the corresponding cumulative ordinate. The M-curve is drawn through these points. The Mayer curve provides some predictive capability to estimate the cumulative yield (weight-percent) for a given cumulative ash percentage.

In analyzing a two-product separation, the usual procedure is to select the desired ash content for the clean coal. Then the yields of coal and refuse can be determined graphically. If the ash value of clean coal is selected as 8%, a line is drawn from the origin to that value on the ash axis. The point at which the line intersects M-curve gives the yield of clean coal. The various ash values for the clean coal and refuse are presented in Table IV.

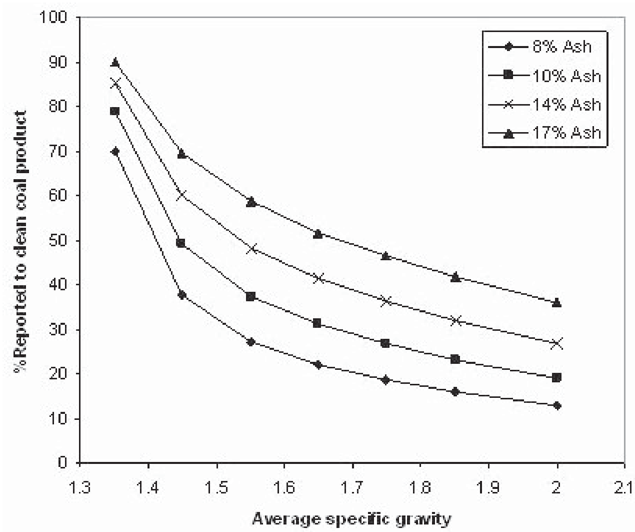

Fig. 3. Tromp distribution curve for float on water-only cyclone treated with Patherdiah coal (From Table V)

3.4 Performance distribution function

The performance of water-only cyclone is characterized by a distribution function (also called a partition curve). The distribution curve is a plot of the weight percent of feed reporting to clean coal (overflow) as a function of specific gravity [20]. An important performance parameter, the specific gravity of separation is estimated from this curve. The distribution curve facilitates prediction of the ash content of the clean coal and refuse products, as well as the yield of clean coal. Therefore, the distribution curve should be generated as accurately as possible for a given coal cleaning device to characterize the performance.

To determine the distribution curve three sets of coal analytical data are required, namely (1) recovery of clean coal, (2) float-and-sink washability analysis of the clean coal product, and float-and-sink washability analysis of the refuse. The result of float-and-sink analysis presented in Table V has been used for generating the Tromp distribution curve [21]. Figure 3 shows the distribution curve for various ash percentages.

The specific gravity of separation, SG_{50}, is defined as the value of specific gravity corresponding to 50% yield. It is the point of separation where a particle has an equal probability of appearing in the clean coal or in the refuse. In the present investigation the specific gravity of separation (SG_{50}) has been calculated using a Lagrange interpolating polynomial to the experimental data. The Lagrange polynomial equations used in this analysis are as follows.

$$P(x) = \sum_{j=1}^{n} P_j(x) \quad (1)$$

Where

$$P_j(x) = y_j \prod_{k=1, k \neq j}^{n} \frac{x - x_k}{x_j - x_k} \quad (2)$$

Table V. Float-and-sink washability yields and distribution data for Patherdih coal sample

Av. Sp. Gr.	Clean coal product			Refuse			Reconstituted feed coal	
	Sink & Float results of clean coal	Wt.% as % Feed coal	Distribution factor, d %	Sink & Float results of reject	Wt.% as % of Feed reject	Distribution factor, d %		d* %
For 8% ash								
	Wt.%	=B*YC	(Yield)	Wt.%	=E*Yr	%	Wt.%	%
A	B	C	D	E	F	G	H	I
		=B*0.34	=C/H		=E*0.66	=F/H	=C+F	=D+G
1.35	49.25	16.74	69.74	11.01	7.27	30.26	24.01	100
1.45	20.46	6.96	37.78	17.36	11.46	62.22	18.41	100
1.55	8.45	2.87	27.27	11.61	7.66	72.73	10.54	100
1.65	4.92	1.67	22.09	8.94	5.90	77.91	7.57	100
1.75	3.24	1.10	18.65	7.28	4.80	81.35	5.91	100
1.85	3.60	1.22	15.94	9.78	6.45	84.06	7.68	100
2.00	9.78	3.33	12.91	34.00	22.44	87.09	25.77	100
SG_{50} = 1.4								
For 10% ash								
		=B*0.45	=C/H		=E*0.55	=F/H	=C+F	=D+G
1.35	49.25	22.16	78.54	11.01	6.06	21.46	28.22	100
1.45	20.46	9.21	49.09	17.36	9.55	50.91	18.76	100
1.55	8.45	3.80	37.32	11.61	6.39	62.68	10.19	100
1.65	4.92	2.21	31.05	8.94	4.92	68.95	7.13	100
1.75	3.24	1.46	26.69	7.28	4.00	73.31	5.46	100
1.85	3.60	1.62	23.15	9.78	5.38	76.85	7.00	100
2.00	9.78	4.40	19.05	34.00	18.70	80.95	23.10	100
SG_{50} = 1.45								
For 14% ash								
		=B*0.56	=C/H		=E*0.44	=F/H	=C+F	=D+G
1.35	49.25	27.58	85.06	11.01	4.84	14.94	32.42	100
1.45	20.46	11.46	60.00	17.36	7.64	40.00	19.10	100
1.55	8.45	4.73	48.09	11.61	5.11	51.91	9.84	100
1.65	4.92	2.76	41.19	8.94	3.93	58.81	6.69	100
1.75	3.24	1.81	36.16	7.28	3.20	63.84	5.02	100
1.85	3.60	2.02	31.90	9.78	4.30	68.10	6.32	100
2.00	9.78	5.48	26.80	34.00	14.96	73.20	20.44	100
SG_{50} =1.52								
For 17% ash								
		=B*0.66	=C/H		=E*0.34	=F/H	=C+F	=D+G
1.35	49.25	32.50	89.67	11.01	3.74	10.33	36.25	100
1.45	20.46	13.50	69.58	17.36	5.90	30.42	19.41	100
1.55	8.45	5.58	58.55	11.61	3.95	41.45	9.52	100
1.65	4.92	3.25	51.65	8.94	3.04	48.35	6.29	100
1.75	3.24	2.14	46.35	7.28	2.48	53.65	4.61	100
1.85	3.60	2.38	41.68	9.78	3.33	58.32	5.70	100
2.00	9.78	6.45	35.83	34.00	11.56	64.17	18.01	100
SG_{50} =1.54								

* Distribution factor

In the above equation, P(x) is the polynomial of degree ≤ (n-1) that passes through the n points $(x_1, y_1 = f(x_1))$, $(x_2, y_2 = f(x_2))$,.., $(x_n, y_n = f(x_n))$. In the Lagrange interpolating polynomial, x_j's represent reduced efficiency and y_j's are corresponding yields.

3.5 Reduced efficiency curve

A reduced partition curve can be generated by plotting the weight percent of feed reporting to clean coal, against the reduced specific gravity which is defined as the ratio of specific gravity to the specific gravity of separation, i.e. SG/SG_{50} [20]. The reduced efficiency curve is invariant with design (vortex finder and spigot) and operating variables (feed density and pressure). This curve is dependent on the cyclone size and the nature of the feed material only [22].

3.6 Separation by size classification

Performance of the cyclone is characterized by establishing a functional relationship between percentage of each particle size in the feed that reports to the product stream and particle size. The cut point of the cyclone is defined as the size of the particle that has a 50% chance of leaving in either the underflow or overflow. This is normally represented by the symbol d_{50}. The sharpness of the classification depends on the slope of the central section of the partition curve. The efficiency is higher when the slope is closer to the vertical [23]. The reduced partition curve can be obtained by plotting the weight percent of feed reporting to clean coal, against the geometric mean size of the size fraction divided by the separation size (d_{50}).

4. MODELLING OF DATA

The concept of reduced efficiency curve processing coal is highly useful since it provides a methodology by which a large amount of experimental data can be summarized and used for predictions. A number of useful empirical distribution functions are available to represent the reduced partition curve. The most commonly used are Rosin-Rammler, Exponential Sum and Logistic functions [19].

1. Rosin-Rammler

$$y = 100\left[1 - \exp\left(-\alpha x^{\beta}\right)\right] \tag{3}$$

2. Exponential Sum

$$y = 100\left[\frac{\exp(\beta x) - 1}{\exp(\beta x) + \exp(\beta) - 2}\right] \tag{4}$$

3. Logistic

$$y = 100\left[\frac{1}{1 + x^{-\beta}}\right] \tag{5}$$

where, x is the ratio of SG/SG_{50} and y is the corresponding performance indicator. α and β are the model parameters which can be estimated from the experimental results. β is a measure of the sharpness of separation.

4.1 Parameter estimation

Fitting of experimental data to the model equations of reduced efficiency curve necessitates estimation of α and β for the process. Least square method can be applied to determine the parameters α and β after some simplification of the model equations.

Substituting $y' = \frac{y}{100}$

Equation (3) can be written in the following form:

$$y' = 1 - \exp(-\alpha x^{\beta})$$

Or,

$$\frac{1}{(1-y')} = \exp(\alpha x^{\beta})$$

This can be further linearized using its equivalent logarithmic form:

$$\ln\left[\ln\left\{\frac{1}{(1-y')}\right\}\right] = \ln\alpha + \beta \ln x \tag{6}$$

Similarly equations (4) and (5) can be linearized as follows:

$$\ln\left(\frac{y'}{1-y'}\right) = \ln\left[\frac{\exp(\beta x) - 1}{\exp(\beta) - 1}\right] \tag{7}$$

$$\ln\left(\frac{1-y'}{y'}\right) = \beta \ln x \tag{8}$$

4.2 Numerical implementation and software development

Semi-empirical performance models [10-12] have been implemented in a computer software (designated as HYDROSIM) for calculating d_{50} based on various operation and design parameters. The software embodies several semi-empirical models, namely, Bradley, Lilge, Dahlstrom, Hass, Yoshika and Hotta, Plitt, De Gelder and Rietema,. The Plitt's model has the provision for calculating d_{50} considering with and without feed size effect and viscosity. The user needs to enter required design and operating parameters which are the inputs for the selected model. The output is displayed in terms of d_{50} values on the graphic screen. The software provides a useful tool to conduct parametric sensitivity analysis to evaluate the effect of various design parameters such as cyclone diameter, feed inlet diameter, vortex finder diameter, spigot diameter etc. and operating parameters such as total feed flow rate, volume fraction solids in the feed on the performance of the cyclone. The effect of various operating parameters on the performance can be visualized

Table VI. Results used to plot the reduced effciency curves using Rosin-Rammler distribution function for Patherdih coal sample

8% Ash (α = 0.66, β = -5.02, Correlation Coefficient = 0.94)			**14% Ash** (α = 0.85, β = -4.29, Correlation coeffcient = 0.96)		
Reduced	Yield of clean coal		Reduced	Yield of clean coal	
sp.gr	Exp.	Predicted	sp.gr	Exp.	Predicted
0.96	69.74	55.30	0.89	85.06	75.66
1.03	37.78	43.02	0.95	60.00	64.66
1.10	27.27	33.13	1.02	48.09	54.22
1.18	22.09	25.48	1.09	41.19	44.98
1.25	18.65	19.66	1.15	36.16	37.14
1.32	15.94	15.26	1.22	31.90	30.63
1.43	12.91	10.59	1.32	26.80	23.03
10% Ash (α = 0.79, β = -4.8, Correlation coefficient = 0.95			**17% Ash** (α = 1.06, β = -3.84,Correlation coeffcient = 0.97)		
0.93	78.54	66.88	0.88	89.67	82.81
1.00	49.09	54.35	0.94	69.58	73.77
1.07	37.32	43.41	1.01	58.55	64.50
1.14	31.05	34.41	1.07	51.65	55.72
1.21	26.69	27.24	1.14	46.35	47.79
1.28	23.15	21.61	1.20	41.68	40.85
1.38	19.05	15.42	1.30	35.83	32.24

graphically. For Munidih and Patherdih coals it has been found that for the given operating conditions Plitt's model with feed size effect provides a better compatibility for characterization of the performance than rest of the models under consideration.

The software is fully menu driven with graphical user interface (GUI) facility. The GUI has been developed using Visual Basic 6.0. The executable version of the code runs on a PC operating under Windows environment.

5. RESULTS AND DISCUSSION

Equations (6-8) yield a linear relationship between the logarithm of the efficiency and the reduced specific gravity. The least square linear fitting of the experimental data through equations (6-8) will therefore provide initial values for α and β. The data pertaining to the reduced efficiency curve for Patherdih coal samples with corresponding model parameters for both Rosin-Rammler and Logistic distribution are depicted in Tables (VI & VII). Correlation coefficients generated by fitting Rosin-Rammler and Logistic distribution functions to Patherdih coal data using least square principle is also cited. It has been observed that the Exponential distribution function exhibits a very poor correlation with the experimental data and therefore has been ignored for further analysis. Figures (4a-4d) show the goodness of fit of the Rosin-Rammler and Logistic distribution with regard to Patherdih coal data. It has been found that for lower ash content both Rosin-Rammler and Logistic distribution functions fit well but the deviation enhances with higher ash content of

Table VII. Results used to plot the reduced effciency curves using Logistic distribution function for Patherdih coal sample

8% Ash (β = 6.26, Correlation Coefficient = 0.93)			**14% Ash** (β = 4.84, Correlation coeffcient = 0.88)		
Reduced	Yield of clean coal		Reduced	Yield of clean coal	
sp.gr	Exp.	Predicted	sp.gr	Exp.	Predicted
0.96	69.74	56.00	0.89	85.06	63.97
1.03	37.78	44.86	0.95	60.00	55.68
1.10	27.27	34.89	1.02	48.09	47.64
1.18	22.09	26.60	1.09	41.19	40.20
1.25	18.65	20.05	1.15	36.16	33.58
1.32	15.94	15.04	1.22	31.90	27.87
1.43	12.91	9.80	1.32	26.80	20.94
10% Ash (β = 4.8, Correlation coefficient = 0.91			**17% Ash** (β = 4.0,Correlation coeffcient = 0.60)		
0.93	78.54	58.17	0.88	89.67	62.87
1.00	49.09	49.67	0.94	69.58	55.99
1.07	37.32	41.74	1.01	58.55	49.35
1.14	31.05	34.67	1.07	51.65	43.14
1.21	26.69	28.58	1.14	46.35	37.49
1.28	23.15	23.46	1.20	41.68	32.44
1.38	19.05	17.41	1.30	35.83	26.01

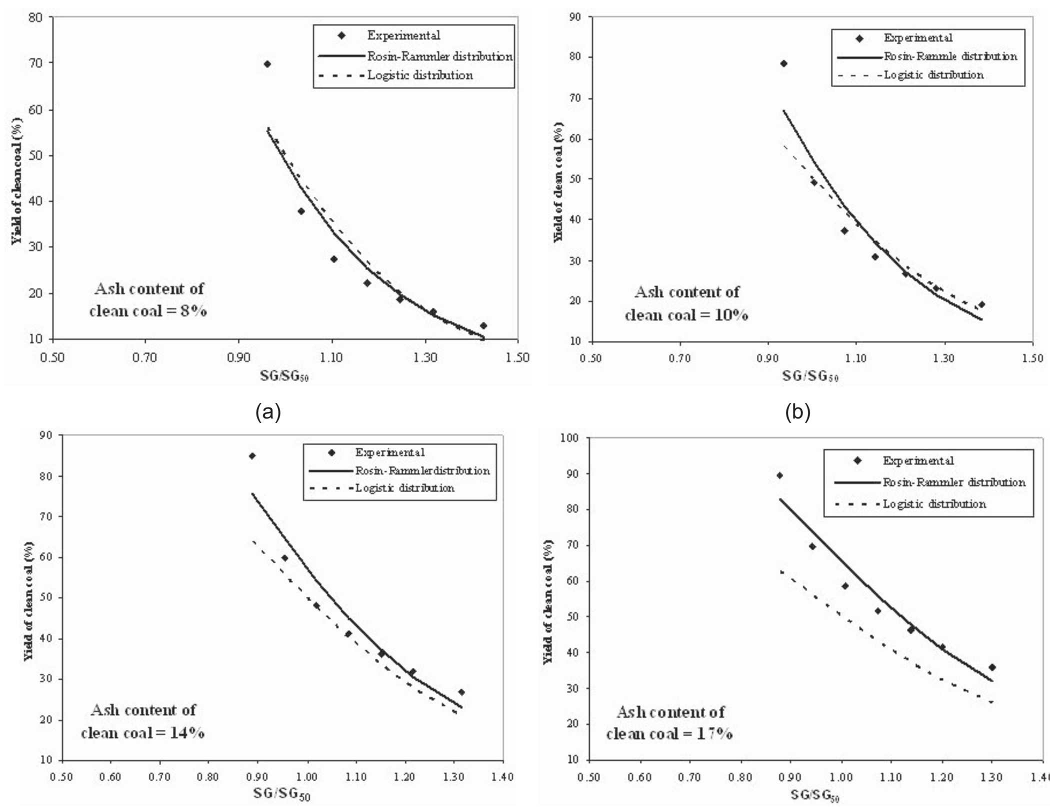

Fig. 4. Experimental and predicted reduced efficiency curves for Patherdih coal : (a) 8% ash, (b) 10% ash, (c) 14% ash and (d) 17% ash. (From Tables VI and VII)

Table VIII. Particle size analysis of Mundidih coal sample using water-only cyclone

Expt. No.	Average Size	d_{50}	Yield to overflow Experimental	Rosin-Rammler distribution Predicted	Logistic distribuion Predicted
2		129.5		α = 0.61, β = -2.69, Corr. Coefficient = 1.00	β = 3.5, Corr. coefficient = 1.00
	375.00		1.33	3.41	2.36
	300.00		4.70	6.13	5.02
	275.00		7.50	7.69	6.69
	250.00		12.39	9.82	9.09
	225.00		17.00	12.82	12.64
	175.00		27.00	23.65	25.85
	150.00		40.00	33.54	37.42
	111.50		60.00	59.64	62.80
	72.00		89.71	94.72	88.64
	55.00		96.21	99.77	95.24
	30.00		97.09	100.00	99.41
	15.00		98.09	100.00	99.95
	7.50		98.72	100.00	100.00
	2.50		100.00	100.00	100.00
3		84.0		α = 0.61, β = -1.99, Corr. coefficient = 1.00	β = 2.5, Corr. coefficient = 1.00
	375.00		0.59	3.03	2.32
	300.00		4.68	4.68	3.98
	275.00		5.60	5.55	4.90
	250.00		7.80	6.67	6.14
	225.00		8.20	8.16	7.85
	175.00		12.04	13.11	13.77
	150.00		20.93	17.39	19.01
	111.50		32.00	29.17	33.00
	72.00		60.00	56.16	59.52
	55.00		75.00	75.60	74.24
	30.00		96.48	99.11	92.92
	15.00		98.77	100.00	98.67
	7.50		98.55	100.00	99.76
	2.50		97.37	100.00	99.98
4		72.00		α = 0.61, β = -1.99, Corr. coefficient = 0.99	β = 2.8, Corr. coefficient = 0.99
	375.00		0.80	2.25	0.97
	300.00		1.86	3.48	1.81
	275.00		2.62	4.13	2.29
	250.00		5.22	4.97	2.97
	225.00		8.65	6.09	3.95
	175.00		10.00	9.84	7.68
	150.00		16.59	13.13	11.35
	111.50		28.00	22.43	22.71
	72.00		50.00	45.48	50.00
	55.00		64.00	64.54	68.01
	30.00		83.06	96.87	92.07
	15.00		95.30	100.00	98.78
	7.50		97.22	100.00	99.82
	2.50		98.75	100.00	99.99

Table VIII. Particle size analysis of Munidih coal sample using water-only cyclone (contd.)									
							375.00		
Expt. No.	Average size	d_{50}	Yield to overflow Experimental	Predicted	Values of constants	Correlation coefficient	Predicted	Values of constants	Correlation coefficient
6	375.00	46.0	0.65	1.01	α = 0.55	1.00	0.72	β = 2.8	1.00
	300.00		0.86	1.54	β = -1.99		1.20		
	275.00		1.06	1.82			1.47		
	250.00		2.50	2.18			1.84		
	225.00		4.00	2.65			2.34		
	175.00		4.80	4.24			4.15		
	150.00		5.28	5.64			5.85		
	111.50		11.76	9.70			11.10		
	72.00		25.00	20.89			25.87		
	55.00		40.00	32.35			39.65		
	30.00		75.00	70.96			73.19		
	15.00		92.95	99.01			93.30		
	7.50		92.51	100.00			98.61		
	2.50		89.06	100.00			99.89		

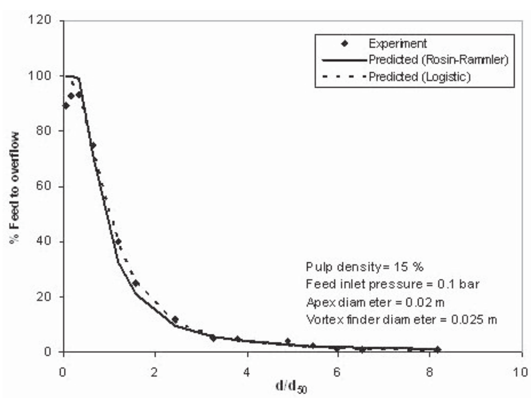

Fig. 5. Experimental and predicted reduced efficiency curve for Munidih coal (From Table VIII)

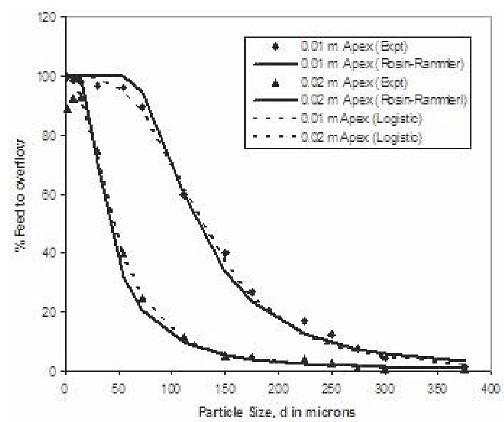

Fig. 6. Partition curves for two different apex diameters for Munidiah coal (From Table VIII)

coal. Consequently, Rosin - Rammler distribution shows a better fit than Logistic distribution function. Experimental results are indicated by discrete points and the continuous and broken lines show the predictions.

Particle size analysis of Munidih coal sample has been presented in Table VIII. The partition curve for Munidih coal generated from the experimental data is shown in Fig 5. Corrected partition curves have been generated by superimposing theoretical classification functions (Rosin-Rammler and Logistic) on the experimental data. In this case, the parameter 'x' in equations (3-8) represents the ratio of d/d_{50} where, d is the average particle size. It has been found that in the case of size classification analysis, the performance of cyclone can be reasonably characterized using both Rosin-Rammler and Logistic distribution functions.

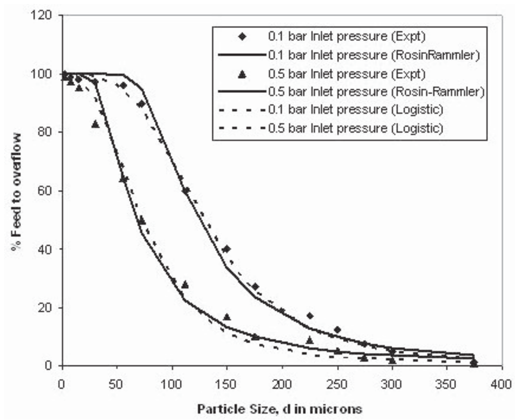

Fig. 7. Partition curves depicting two different feed inlet pressures for Munidih coal (From Table VIII)

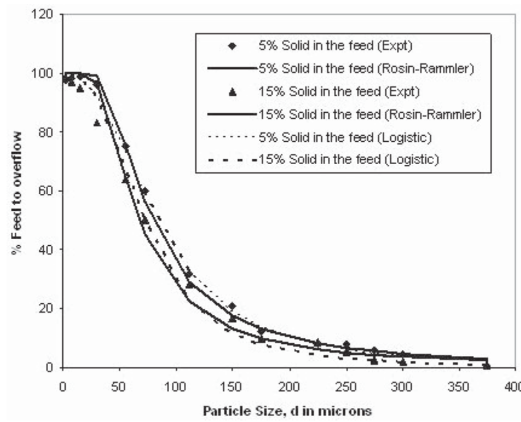

Fig. 8. Partition curves for variation in the percentage solids in the feed for Munidih coal (from Table VIII)

Figures (6-8) show the sensitivity in quantitative terms, the effect of variations in apex diameter, feed inlet pressure and percentage of solids in the feed on the yield and performance of the cyclone. In the figures, markers represent the experimental data and the solid and broken lines represent the predicted values using Rosin-Rammler and Logistic type equation for different operating conditions. It may be observed that the sharpness index increases with an increase in the pressure and apex diameter whereas d_{50} decreases. Also from Figure 8 it can be noted that changing the pulp density does not affect the cyclone performance significantly.

The observed depletion in d_{50} with increase in apex diameter may be attributed to the fact that any increase in the apex diameter enhances the volumetric flow rate in the downward direction. Consequently, the d_{50} value diminishes which may adversely impair the performance. Lower values of d_{50} with increasing feed inlet pressure (higher throughput) may also be explained as a consequence of higher centrifugal action leading to accumulation of more number of particles in the vicinity of the wall and increased likelihood of particles to report to the underflow. The trends are found to be consistent with regard to operational parameters.

6. CONCLUSION

Experimental investigations have been conducted using water-only cyclone for characterization of Patherdih and Munidih coal sample. Experimental data has been utilized to construct Mayer curve, Tromp distribution curve and reduced efficiency curve. The Mayer curve provides an efficient tool to establish further correlation for yield and ash content of the coal. Tromp distribution curve provides functional correlation between yield and average specific gravity.

Performance of water only cyclone for washing high ash coal has been attempted using modelling of data analysis. It is observed that the Rosin-Rammler and Logistic distribution can be employed to reasonably represent the performance of water-only cyclone in terms of size classification as well as specific gravity separation. The model parameters have been calculated by transforming the governing model equations in equivalent logarithmic form and subsequently least square technique has been applied. After estimating the model parameters the performance of the cyclone for variations in operating conditions can be quantified. Parametric sensitivity analysis has been carried out with respect to apex diameter, percentage solids in feed and feed inlet pressure to quantify the yield (recovery to overflow). The broad trend of the sensitivity analysis provides a realistic assessment of the effect of operating parameters on the overall yield. It is observed that, the water-only cyclone is one of the appropriate unit operations for effectively cleaning high ash coal fines. However, for efficient washing of coals at a plant scale necessitates multistage operation with feedback philosophy.

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