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# Processing of coal fines in a water-only cyclone

A.K. Majumder [a,*], J.P. Barnwal [b]

[a] Department of Mining Engineering, Indian Institute of Technology, Kharagpur 721302, India
[b] Advanced Materials and Processes Research Institute, Hoshangabad Road, Bhopal 462 026, India

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ABSTRACT

It is reported in the literature that a water-only cyclone (WOC), a centrifugal gravity concentrator, is an alternative to froth flotation to treat coal fines (below 0.5 mm). This unit overcomes the inherent limitations of froth flotation and the dense–medium cyclone techniques as it requires no chemicals or artificial medium. The literature dealing with WOC performance to treat coal fines is also limited and as a result it is not well established how the design variables affect the performance of a WOC while treating coal fines. Therefore, an attempt has been made to develop regression models based on factorial design of experiments to quantify the effects of major design variables of a WOC on the beneficiation characteristics of a typical coal fine sample. Further attempts have been made to provide possible explanations on the observed trends of the data based on simple hydrodynamic analyses.



## 1. Introduction

Froth flotation is commonly used to process coal fines below 0.5 mm. However, due to environmental hazards and the use of costly chemical reagents, it is imperative to identify an alternative technique to process coal fines. The water-only cyclone (WOC) is a centrifugal gravity concentrator that uses water as the medium of separation and is also termed as an autogenous cyclone or auto-medium cyclone. The principle of operation of a WOC differs from a normal conventional cyclone because of its geometry. It has a wide angle conical bottom, a long cylindrical portion and a long vortex finder extending along the length of the cylindrical portion. As it does not involve a medium recovery circuit as needed with a dense-medium cyclone (DMC), the process is simple and environmentally friendly.

The wide cone angle is believed to build up an autogenous bed of particles along the conical section of the cyclone [1–3]. This bed prevents particles from moving unimpeded, and “hindered-settling” conditions prevail [4]. The long cylindrical portion increases the average retention time of particles inside the cyclone to enable better separation.

Kim and Klima [5] reported that the performance of a WOC is greatly influenced by changes in both geometry and operating conditions. However, literature dealing with the quantitative prediction on the performance of a WOC at various operating conditions to process various coal fines is limited. A research project was, therefore, undertaken to quantify the effects of various design and process variables of a WOC on the separation characteristics of various coal fines. In this paper, an attempt has been made to study the effects of various design variables of a laboratory model (76 mm diameter) WOC to process a typical coal fine sample collected from an Indian coal preparation plant.

## 2. Feed sample preparation and characterization

Around one ton of coal fines (below 0.5 mm) sample was collected from the fine coal circuit of Patherdih coal preparation plant of Jharia coalfields, India for the present test work. The entire sample was first dried in an oven for 24 h to remove surface moisture. After proper sampling, using a rotating type sampling device, the representative samples were kept in 50 kg bags for further studies. After repeated sampling, around 500 g of representative samples were taken out from a 50 kg bag for the conventional float–sink studies. The float–sink data are presented in Table 1.

It is evident from the table that the coal fines are liberated enough to make gravity separation effective. The feed ash content of the coal fines is 36.13%. Approximately 30% of the feed coal is heavier than 1.8 specific gravity having a high ash content of around 80%.

## 3. Selection of test variables

From the literature review on the WOC, it is observed that vortex finder diameter (VFD), vortex finder length (VFL), cone angle (CA), spigot diameter (SPD), pulp density (PD) and feed inlet

* Corresponding author. Tel.: +91 3222 281838.
*E-mail addresses:* arunmajumder@hotmail.com, majumder1965@gmail.com, arunmajumder@hotmail.com (A.K. Majumder).

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**Table 1**
Float–sink data of patherdih coal fines.

| Specific gravity | Direct | | Cumulative | |
|---|---|---|---|---|
| Range | Wt.% | Ash % | Wt % | Ash % |
| Float 1.3 | 11.14 | 3.75 | 11.14 | 3.75 |
| 1.3–1.4 | 16.69 | 5.43 | 27.83 | 4.76 |
| 1.4–1.5 | 14.80 | 8.73 | 42.63 | 6.58 |
| 1.5–1.6 | 14.28 | 12.90 | 56.91 | 9.78 |
| 1.6–1.7 | 7.09 | 15.40 | 64.00 | 13.18 |
| 1.7–1.8 | 6.17 | 17.52 | 70.17 | 15.59 |
| 1.8 Sink | 29.83 | 79.91 | 100.00 | 36.13 |

pressure (FIP) are important variables. To study the effects of all the above-mentioned variables was beyond the scope of this work. However, as mentioned earlier, the use of a wide cone angle and a long vortex finder make a WOC geometrically different from a DMC. It is also difficult to correctly evaluate the performance of any cyclone-type device without studying the effects of either VFD or SPD. Therefore, for the present study only VFL, VFD and CA were chosen as variable parameters, whereas the PD, FIP and SPD were kept at constant levels of 10% by weight, 0.7 kgf/cm$^2$ and 20 mm, respectively.

## 4. Experimental procedure

A 76 mm cylindrical diameter WOC made of stainless steel was used. A closed circuit test rig, consisting of a slurry pump and a by-pass line was used for carrying out the experiments. Slurry feed rate to the separator and the pressure at the inlet could be adjusted using the by-pass valve. A heavy duty stirrer was fitted horizontally at the bottom level of the slurry tank to keep the slurry in uniform suspension.

Before carrying out an experiment, pre-determined quantities of feed coal and water were mixed in the slurry tank to maintain the desired feed slurry concentration of 10%. Initially, slurry was pumped through the separator by keeping the by-pass valve fully open, and subsequently, the opening of the valve was adjusted to obtain a feed inlet pressure of 0.7 kgf/cm$^2$. The system was then allowed to run for a few minutes to attain a steady state. The steady-state condition was believed to be achieved as soon as the slurry flow rates through the overflow and underflow were found to be constant. The overflow and underflow streams were then collected for a known period of time, and the respective slurry weights were recorded. The slurry samples were weighed and dried to determine the solids weight. Representative samples of the products were then analyzed for ash content.

## 5. Statistical design of experiments

The use of a statistical design of experiment helps in understanding the effects of individual variables and also the effects of interactions between the variables [6]. To generate maximum information using minimum number of experiments, a factorial design of type $p^n$ was used where $n$ is the number of variables and $p$ is the number of levels. For each variable two levels were chosen for this study. Three base level experiments were also carried out to establish the repeatability of the experimental data. Altogether eleven tests were performed. The design matrix and experimental results are presented in Table 2.

The standard deviations calculated at the 95% confidence level for the three base level experiments for the clean coal yield and ash are 1.2% and 0.73%, respectively. As the values of the standard deviations of the repeat experiments are marginal, the reliability of the other experimental data presented in Table 2 is established.

**Table 2**
Actual and coded values of the variables.

| Experiment number | Experimental conditions | | | Clean coal | |
|---|---|---|---|---|---|
| | VFL ($X_1$) | VFD ($X_2$) | CA ($X_3$) | Yield % ($Y_1$) | Ash % ($Y_2$) |
| 1 | 128 | 33 | 105 | 50.75 | 21.56 |
| 2 | 134 | 33 | 105 | 54.98 | 23.23 |
| 3 | 128 | 37 | 105 | 71.86 | 25.97 |
| 4 | 134 | 37 | 105 | 76.03 | 27.24 |
| 5 | 128 | 33 | 143 | 59.54 | 24.45 |
| 6 | 134 | 33 | 143 | 64.39 | 26.53 |
| 7 | 128 | 37 | 143 | 80.46 | 28.20 |
| 8 | 134 | 37 | 143 | 86.30 | 28.28 |
| *Base level experiments* | | | | | |
| 9 | 131 | 35 | 124 | 71.49 | 26.53 |
| 10 | 131 | 35 | 124 | 72.68 | 27.20 |
| 11 | 131 | 35 | 124 | 72.19 | 26.61 |

VFL, vortex finder length in mm; VFD, vortex finder diameter in mm; CA, cone angle in degrees.

It may be observed from Table 2 that the lowest ash content of clean coal (21.56%) was achieved at experiment number 1 with a yield of 50.75%. Although the ash reduction of this coal fine sample from a feed ash content of 36.13% in a single-stage WOC is quite remarkable but 21.56% ash of clean coal is higher than the specified limit of 17–18% ash content by the metallurgical industries of India. Based on the washability data from Table 1, it may be observed that at 21.56% ash content of clean coal the likely yield should be around 78%, which means that around 27% of likely clean coal has been lost in tailings. To understand the effects of the selected variables on the ash content and yield of clean coal, an attempt has been made to develop regression models.

## 6. Development of regression models

Using the design matrix and the experimental data presented in Table 2 and following the standard formulae given in any related text book, the final regression equation for the clean coal yield, $Y_1$, becomes

$$Y_1 = 68.04 + 2.38X_1 + 10.62X_2 + 4.63X_3 + 0.12X_1X_2 + 0.28X_1X_3 + 0.08X_2X_3 + 0.13X_1X_2X_3 \quad (1)$$

where $X_1$–$X_3$ are defined in Table 2.

Similarly the regression equation for the clean coal ash content, $Y_2$, becomes

$$Y_2 = 25.68 + 0.64X_1 + 1.74X_2 + 1.18X_3 - 0.3X_1X_2 - 0.1X_1X_3 - 0.37X_2X_3 - 0.2X_1X_2X_3 \quad (2)$$

In order to check the validity of the proposed equations within the range of the variables selected, a few random experiments were also carried out following the afore-mentioned methodology. The respective experimental conditions and the comparison between the actual and the model predicted data are presented in Table 3.

It is evident from Table 3 that the proposed equations predict the actual clean coal yield and ash content within average errors of 2.7% and 5.6%, respectively. Therefore, it may be considered that the proposed regression Eqs. (1) and (2) are valid to predict the yield and ash content of clean coal within the range of the variables selected.

## 7. Significant observations and discussion

From Eqs. (1) and (2) it may be observed that the influences of all the individual variables on the yield and ash content of clean