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INVESTIGATION OF SEPARATION PERFORMANCE OF DENSE MEDIUM CYCLONE USING COMPUTER SIMULATION

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Abstract: Dense medium coal processing technology has been widely used in coal preparation industries in the world since it is the most accurate and efficient coal preparation process to obtain clean coal with a highest possible yield. Separation of coal and impurities using this technology is based on density differences. In literature, a number of mathematical models exist for dense medium cyclones. One of the most widely used model in the coal industry was developed by Mineral Technologies, Inc. This model consists of the equation which predicts the operating performance of a well maintained dense medium separator for a given cyclone geometry (including cyclone diameter) and separation density. In this study, MODSIM© (education/demo version) dense medium cyclone model was applied to coal preparation plant owned by Soma Uyar Mining Co. As a result, the float-sink test results at separation density of the dense medium cyclone were predicted.

Keywords: *coal, dense medium cyclone, washability, float-sink test*

Introduction

Coal has a very important place in the world's energy production compared to other fossil fuel sources such as oil and natural gas which are consumed rapidly. In the future, coal reserves will play an important role in energy production; therefore there is a need to have the most effective utilization and evaluation methods to obtain fine-grained high quality coal products (Das et al. 2013).

There are several common coal slurry beneficiation methods, namely centrifugal separation (hydrocyclone classifier-separator and centrifugal separator), wet gravity separation (Reichert spiral separator), and physicochemical method (flotation) (Lutynski et al. 2014).

Computer usage in all areas of industry has been increasing quickly during the last 30 years. Therefore, mining activities also need certain developments in computer software to assist coal processing operations.

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There are two simulation packages developed only for the use by coal preparation. The first one, COPREP (Gottfried et al. 1982), was developed by the U.S. Department of Energy and the University of Pennsylvania. The second software, SHSP (Carmola et al. 1983), was prepared by Exxon Research and Engineering Company. SHSP consisted of modules in earlier version while in later version consisted of coal preparation plant units. While COPREP was firstly designed for mainframe computers, SHSP was directly designed for computer control of plants.

The simulation packages such as MODSIM©, Utah MODSIM©, SimPlant, JKSimHet, GSIM, SPOC, CAMP, MINDRES, and USIM-PAC are generally prepared for mineral processing operations. The features of these packages are given in several studies (Sastry et al. 1985, Napier-Munn et al. 1992).

The float-sink test is a routine exercise, especially, in coal preparation and mineral processing plants to evaluate and cross-check the washability characteristics of coal and minerals. Data obtained from the float–sink tests are used to form a set of washability curves which are then used to assess the degree of difficulty of gravity separation of the feed and to provide qualitative or quantitative data for the products of the separation at a selected relative density (Burt 1984; Osborne 1988).

Katti et al. (1997) showed that gravity separation processes have been used in the mineral industry to separate particles under the action of hydrodynamic and gravitational forces. Although these equipments are extensively used for tonnage processing in coal industry, their uses have been now extended to waste treatment such as separation of valuable metallic matter from slag. However, these processes never run at their best due to lack of understanding of the process and the underlying principles of separation. Even though trial runs and pilot tests are conducted for efficient operation, these tests are often time consuming and expensive. Against this background, Katti et al. (1997) indicated that the capabilities of numerical simulation can give a better understanding of the process with a view to improve its performance. Data from different coal washeries are collected to simulate the behavior of the plants. A result of simulation utilizing jigging for coal washing was found to be in good agreement with the plant data. The same coal is also treated in other gravity separation processes in order to decide upon a particular washing circuit.

In this perspective, the aim of this study is to obtain the amount of clean coal and the percentage of ash beneficiated at different separation densities in dense medium cyclone at Soma Uyar Coal Co. and to simulate the results using MODSIM© software (education/demo version). For this purpose, first, the float-sink tests for the samples obtained from dense medium cyclone unit of Soma Uyar Coal Co. (Manisa, Turkey) were performed. The samples were taken from a separation device (Dense Medium Cyclone) at different time intervals. Then, the Tromp distribution curves were plotted for the dense medium cyclone from the float-sink test data of the products (clean coal and waste), and the feed and amount of clean coal and percentage of ash were determined at each separation density. Finally, the results obtained from these studies were simulated using MODSIM© (education/demo version) data.

Materials and experimental

Materials

The proximate analysis of the coal samples used for the experiments and simulation is presented in Table 1.

Table 1. Proximate analysis values of coal samples used

Coal	Total Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	Net Calorific Value (kJ/kg)
Unit	15.60	29.95	35.74	18.71	13565.23

Experimental

Float-sink tests

A series of the float-sink tests was performed for the samples maintaining a ratio of densities of about 1.3–1.8 g/cm^3. The samples were first separately subjected to size analysis to ensure the accuracy of the float-sink tests. A small head sample was collected from each size fraction for determining the ash values of the samples to cross-check the accuracy of subsequent float-sink tests. Zinc chloride was used as the heavy medium. Each size-density fraction was then subjected to ash content determination. In addition, the average density was determined for the final sink product of the coal samples using density buckets. The ash percentage for each coal samples was determined by using the ISO 1171 procedure.

MODSIM

MODSIM© is a simulator that calculates detailed mass balance for any ore and coal processing plant. Other special particle properties that are specific to particular systems can also be considered such as calorific value, volatile matter, pyritic sulfur, organic sulfur and ash content for coal. Additionally, sometimes very subtle particle properties such as shape and surface characteristics have important influences on the behavior of some of the unit operations of mineral processing. MODSIM© can accommodate all of these particulate properties.

The main unit operations of ore dressing include size-reduction (crushing and grinding), classification on the basis of size of particles, concentration operations that separate particles according to their mineralogical composition, and solid-liquid separations. MODSIM© provides a close perspective among the standard models for these operations (King 2001).

The use of the partition curve is the most widely used method to describe the operation of any gravity separation unit and the generalized partition function was described in connection with dense media separators. It is always possible to describe the operation of any gravity separator by means of a partition function even if the partition function itself depends on the nature of the feed material as is always the case for gravity separators. In fact, the partition curve determined on an operating unit can be used to diagnose the operation. Ideally, partition functions should produce steep symmetric curves that show no short circuiting, and hence asymptote to the limits 1.0 and 0.0 at $\rho = 0$ and $\rho = 1$, respectively. Deviating from the ideal can be attributed to various design and operational inadequacies. Leonard and co-investigators (1979) provided a convenient tabulation of causes for poor partition functions in a variety for coal washing units. Although the partition curve is an excellent diagnostic tool, it is not entirely satisfactory for simulation because of the difficulty of predicting the partition curve for any particular item of equipment (Leonard IV et al. 1983).

The procedure of Gottfried and Jacobsen (1977) attempted to address this problem. The generalized partition curve is estimated in terms of a target density of separation for the proposed unit. The target density is the ρ_{50} point on the partition curve plotted for the sample. This point is in fact fixed by the density behavior of the material in the separator and by the density of feed. In any gravity separation operation, the partition function on a density basis varied in a systematic manner through the variations in ρ_{50} and the imperfection for each density fraction.

The relative density is the ratio of density to average density in the feed and the cut point for any density at the relative cut point for the feed material. Once the target density and the average density in the feed are known, the cut point and imperfection for each density can be obtained from the Tromp distribution curve. These can be used with any appropriate generalized partition function such as the exponential sum and logistic functions. An appropriate amount of short-circuiting to either floats or sinks can also be preferred if it is anticipated that this kind of inefficiency will be present in the equipment. MODSIM© provides the generalized Gottfried and Jacobsen (1977) method as an alternative model for most gravity separators.

Osborne (1988) recommends that the variation of the *écart probable moyen* (EPM, also known as the separation efficiency) with density, equipment size, and separation density should be computed using a series of factors based on Eq. 1.

$$\text{EPM} = f_1 \cdot f_2 \cdot f_3 \cdot E_s \tag{1}$$

where f_1 is a factor accounting for the variation of *EPM* with density, f_2 is a factor accounting for variation of EPM with equipment size, and f_3 is a manufacturer's guarantee factor usually in the range 1.1 to 1.2. E_s is a standard function representing the variation of *EPM* with separation density for each type of equipment. E_s for various types of coal washing equipment are calculated using the following equations:

Dense-medium cyclone: $$E_s = 0.027\rho_{50} - 0.01 \tag{2}$$

Dynawhirlpool: $$E_s = 0.15\rho_{50} - 0.16 \tag{3}$$

Dense-medium bath: $$E_s = 0.047\,\rho_{50} - 0.05 \tag{4}$$

Baum jig: $E_s=0.78(\rho_{50}\ (\rho_{50}-1)\ 0.01)$ (5)

Water-only cyclone: $E_s=0.33\ \rho_{50}-0.31$ (6)

Shaking table and spiral concentrator: $E_s=\rho_{50}-1$ (7)

For dense-medium cyclones f_1 varies from 2 to 0.75 as particle size varies from 0.5 mm to 10 mm. For dense-medium vessels f_1 varies from 0.5 for coarse coal to 1.4 for fine coal.

The clean coal quantity and ash content were investigated in a unit of the plant by estimating, at the same separation density which was determined at different times, the Tromp distribution curves using the MODSIM© simulator (Fig. 1). The Tromp distribution curve was plotted to determine the washability performance of the dense medium cyclone that is operated by Soma Uyar Coal Co.

Firstly, the washability data were obtained from the coal sample to be beneficiated in the dense medium cyclone. After this, float-sink test data, which allow identification of the coal sample, were entered into MODSIM©, and finally the selection of model and parameters was performed. The selection of models for the separation densities defined from the drawn Tromp distribution curve allow to predict the amount of clean coal and ash content in MODSIM©.

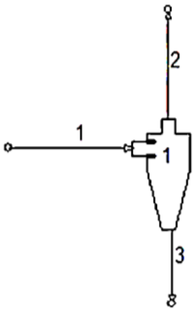

Fig. 1. Dense Medium Separator instrumentation diagram
in MODSIM© (MODSIM™ 3.6.22-education/demo version)

Results and Discussion

Float-sink tests

A washability curve was used to determine the response of an ore to gravity separation. These curves allow prediction of the mass and assay of float and sink including the anticipated recovery at any predetermined density of separation and the ease or difficulty of the separation proposed. Alternatively, the curves can be used to determine the density of separation required to achieve a desired weight split, product assay, recovery etc. (Burt 1984). In this context, the float-sink tests were carried out for the samples and the results are seen in Fig 2.

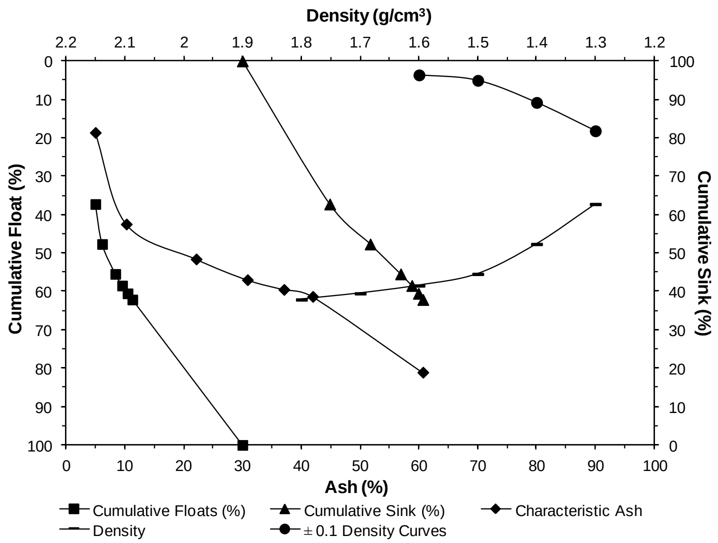

Fig. 2. Float-sink curves for –18+0.5 mm size fraction

The explanations for lines seen in Fig. 2 are as follows.

Cumulative float-sink curves

The cumulative percent assay for floats or sink products is plotted against the cumulative percent weight of floats (or sink) for each density of separation. These curves indicate both the assay of floats (or sink) which is the result at a particular density of the separation. They are used in conjunction with the density curve to predict the percent weights and assay of two products of separation at any particular density. Alternatively, the reverse procedure can be used to determine the required density of separation for any desired assay in the concentrate or tailings (Burt 1984).

Characteristic ash curve

Plotting the actual determined assays for each fraction against the average cumulative % weight sinks or floats for each density gives a curve which indicates the position of the values, and hence the general character of the material in relation to separation. The curve is actually drawn by plotting the determined assay of each density fraction against the cumulative percent weight of the previous fraction plus one half of the percent weight of the fraction in question. This is done because the assay refers to the whole of the weighing between the two densities. The curve, therefore, should coincide with the cumulative percent assay of floats curve (lowest assay) at zero percent cumulative weight floats. Similarly, it should coincide with the cumulative percent assay sinks curve (highest assay) at zero percent cumulative weight sink (Burt 1984).

±0.1 density curves

While the characteristic assay curve gives a qualitative indication of the ease or difficulty of separation, this is not sufficient for the prediction of the performance of gravity process (Burt 1984). As a result of amount of the mid product ratio, the ash characteristic and ±0.1 density curve (Fig. 2) was obtained from the float-sink tests performed at the particle size fraction of -18+0.5 mm. According to these results, the coal has difficult washing feature. The average value of coal ash, which is around 30%, was obtained from the cumulative float and sink curves. According to the characteristic ash curve, it was determined that the quantity of middling is more than the amount of clean coal. The most suitable washing density was appeared as 1.6 g/cm^3 from ±0.1 density curve. From these results, it is understood that this coal has to be processed in heavy-media separation.

Performance of dense medium cyclone

When material has been treated in a gravity process, sequential heavy liquid tests are carried out on each of the two products (concentrate and tail) separately. From the knowledge of the weight composition of the two products and the data from float-sink tests, it is then possible to reconstruct the theoretical results of float-sink tests on the head sample of material. It is essential that both products are treated at the same densities and over the same range as each other to avoid complicated and inaccurate interpolations. From the results of these tests, there are various performance criteria that can be derived to assess separation performance. With help of distribution factors, which has been taken from performance known washing unit, it might be possible to guess washing results of minerals (Leonard 1979; Burt 1984; Osborne 1988).

The amount of clean coal and shale after the operation was determined. The operating performance was calculated in a dense medium cyclone of the Uyar Coal Co. The Tromp distribution curves drawn from float-sink data of the obtained products are shown in Fig. 3.

Determination of clean coal property with Tromp distribution curves

The separation performance of a coal washing device depends on its structure, operating conditions, separation medium, feed amount, ash of coal, and coal particle size. The Tromp distribution curve shape depends rather on the feeding material properties than the separation sensitivity of the used device. The Tromp distribution curve was plotted using the samples taken at different time periods for the same washing device, and the results are shown in Fig. 4. The results showed that the separation density for the same sample varies for different washing conditions applied in the same washing device. The dense medium cyclone of Soma Uyar Coal Co. was used in the investigations. As can be seen from the Fig. 4, the changes of the amount of clean coal and ash are time-dependent in the applied dense medium cyclone.

In the time-dependent measurements, the performance of the dense medium cyclone (as seen in Fig. 4.) was changing. These changes in the device were not caused by mechanical problems. In this plant, the performance of the dense medium cyclone was adversely affected by changes in the shift hours, lunchtime and meal breaks. Additionally, the separation densities of the dense medium in the separator also changed.

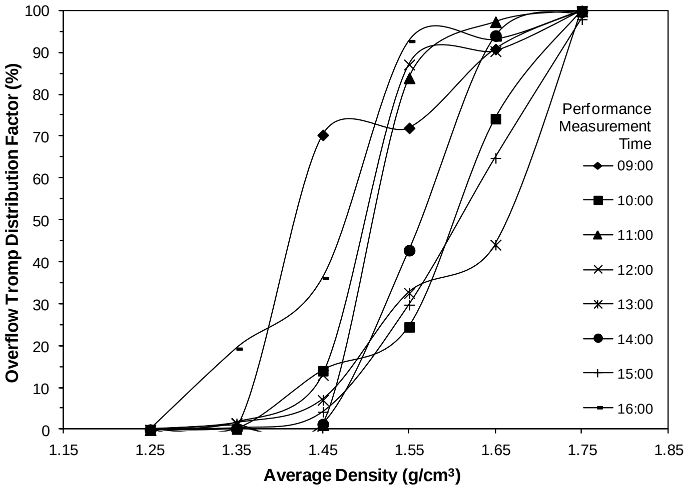

Fig. 3. Tromp distribution curves for separation at different time

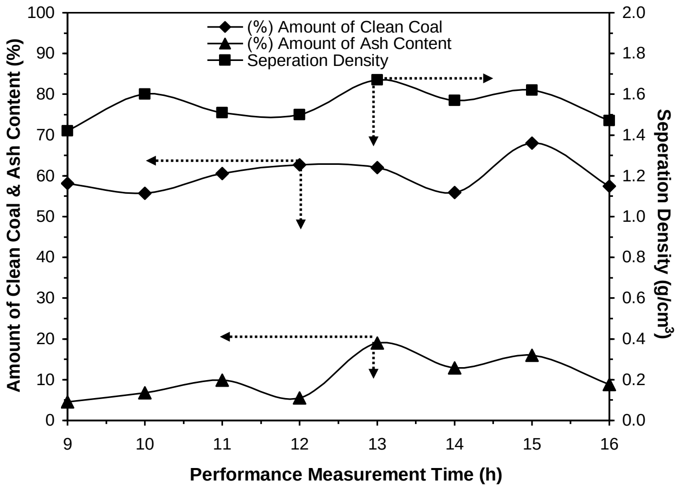

Fig. 4. Ash content and amount of clean coal depending on separation density of the dense medium in Soma Uyar Coal Co. cyclone as a function of time

MODSIM©

A comparison of the simulation results to that of the industrial scale of the dense medium cyclone for the samples is seen in Figs. 5 and 6. As seen in Figs. 5 and 6, real-time and artificial approach made by MODSIM© compared with at relatively low densities showed similar trends, but showed different results at relatively high separation densities. This can be attributed to the batch tests used in the flotation unit where there was a lot of interaction with the fluid. In the complex material with heavy liquid, the effect of water showed considerable difference. Hence, the results were different at relatively high densities. Mean while, the ash content of the samples obtained from industrial coal plant and MODSIM© showed similar patterns because the coal fed to dense medium cyclone showed no big change. On the other hand, the amount of clean coal was different as seen in Fig. 6. The reason for this is to move of clean coal into waste due to higher washing density.

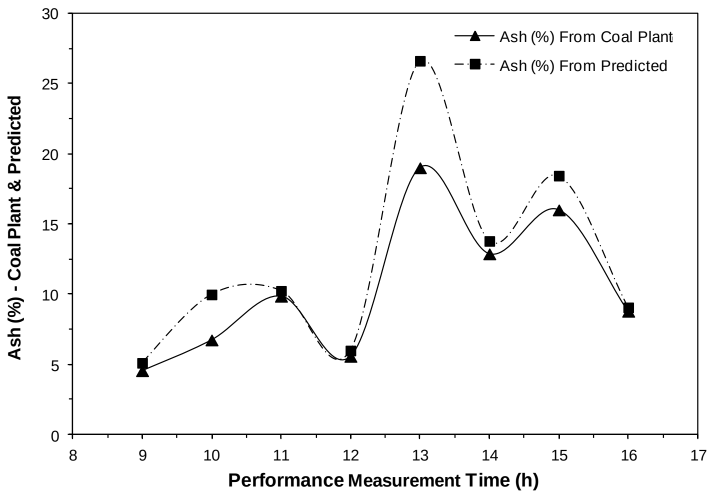

Fig. 5. Comparison of ash values obtained from MODSIM© and coal plant

In this study, the simulation results with MODSIM© appears to coincide with the real plant data. Although previous simulation results using MODSIM© (Katti et al. 1997) showed good results, the simulation results obtained from this study is not satisfactory because of some factors. For example, sedimentation behavior of coarse coal particles in heavy medium is different respect to fine coal particles. Additionally, in coal beneficiation plants, because the fed coal and the separation density change too much within a short time, predictions can be emerged badly.

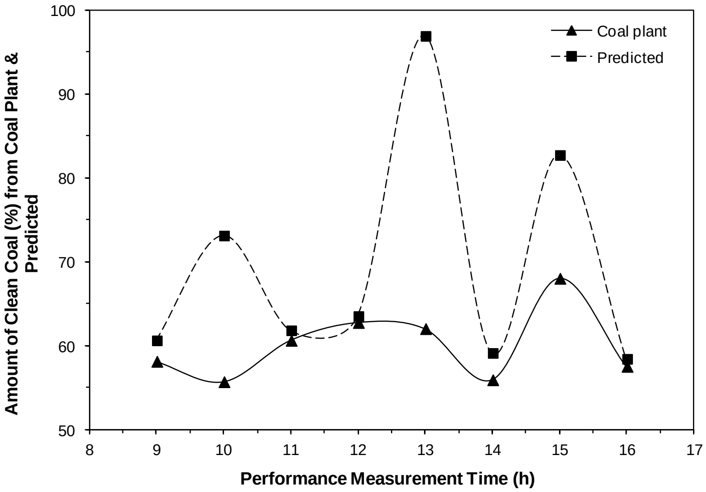

Fig. 6. Comparison of amount of clean coal obtained from MODSIM© and coal plant

MODSIM© has been not developed and used so far to quantify the flow and particle fields in the industrial dense medium cyclone at different medium properties in order to understand the effect of medium properties such as the medium density, magnetite type, and non-magnetic content on DMC's performance. The findings are summarized as follows:

1. As the density of feed medium increases, the operational head and the medium split remain constant. The off-set increases but the *Ep* is relatively insensitive to density of medium feed. The pressures drop significantly increases with the increasing in feed medium density, resulting in a high inward pressure gradient force on particles and reduced separating efficiencies.

2. The operating head and the medium split decrease, and the density change increases as the magnetite particles become coarser (from ultrafine to medium grade). The off-set increases and *Ep* increases slightly for coarse particles and remains almost constant for fine particles as the magnetite particles become coarser. The separation performance in the cylindrical section is insensitive to magnetite particle size. However, since the magnetite segregates near the spigot, the local pressure gradient, medium density and viscosity all increase, which leads to a higher density change. The difference between the pressures gradient force and the centrifugal force becomes large in this area and the particles there have more opportunities to move into the upward bulk flow, resulting in a higher off-set and *Ep*.

Conclusions

In dense medium cyclone clay minerals of coal often change the separation density of the device. Therefore, magnetite has to be added to the cyclone to maintain certain separation density. However, this results in continuous variation of separation density due to the addition of indefinite amount of magnetite over a long period of time. As a result, the device performance is affected negatively in terms of operating cost and product quality. Problems associated with dense medium cyclones are attributed to manual control of the device since the observed variation in the separation density occurs during the breaks between shifts. Therefore, computerized control of the device should be performed in order to maintain a stable separation density.

In this study, it was found that there are differences between clean coal and ash content values obtained from the plant and the predicted values. The model used in MODSIM© software package showed differences between the data obtained from industrial plants and laboratory studies. The adaptation to the automation system is easy and reliable with the help of the software program packages such as MODSIM©.

By analyzing the performance of the existing dense media separation plant, it was found that improvements could be made with better process control. The models developed in this work could be used for controlling dense medium beneficiation plant in future.

Acknowledgments

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