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Simulation of industrial gravity separation processes using a general purpose simulator

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ABSTRACT

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 use has 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. For efficient operation it is desirable that trial runs and pilot tests are conducted but these are often time consuming and expensive. Against this background, this paper attempts to show the capabilities of numerical simulation to gain a better understanding of the process with a view to improve its performance. Data from different coal washeries are collected to simulate the behaviour of the plants. Results of simulation utilizing jigging for coal washing is 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.

INTRODUCTION

Jig offers economic advantages over the heavy media and other gravity separators owing to its simple design features and operational advantages. According to a recently published plant census, 37% of the plants that process coal rely on jigs as primary cleaning devices[1]. In India, due to difficult washing characteristics of coal, heavy media separators are preferred over jigs. However, over the years there has been a lot of research and development work done to popularize jigs. In particular, jigs can now handle, more than before, tonnage material with minimum space requirement and treat wide range of sizes with reasonable efficiency. With a better understanding of the jigging process and with the help of automatic control techniques, coal processing by means of jigs may become viable.

Coal processing through jigs also rests on pure economic considerations. Recently Coal India Ltd. revised the prices for grade C and medium coking coals that will have severe impact on the industry. It is estimated that in the power and steel sectors the increase would be of the order of Rupees 25 and 10 crores respectively. Therefore, atleast in the power sector where the coal is supplied with very little preparation, it is felt that there is a need for finding cheaper means of coal cleaning. This will reduce the wear in the boiler house and cut down bulk transportation leading to a cost optimization. Ghosh *et.al.*[2] report that the overall ash in the final product can be brought down by 7 to 8 units through deshaling.

There has been a renewed research interest to understand the basic mechanism of stratification of particles in jigs. While some investigators have studied plunger type jigs, others have focused their attention on the air pulsated jigs. Baum and Batac jigs are of the latter variety. In Baum jigs the air chamber is located at the side of the jig bed while in the Batac jigs it is located underneath the bed plate. A mixture of feed coal, shale, and middlings is supported on the perforated bed plate. An upward pulsation of water dilates the bed and subsequently a downward suction of water enables stratification of coal bed as per specific gravity under the action of hydrodynamic and gravity forces. This simplified picture is well taken to understand the principle but the actual performance of the jig is far more complex.

A variety of equipment is available as heavy media separators. Chance cone, as the name suggests is a conical vessel that is used extensively for primary cleaning as in Jamadoba, Bihar. The separation principle is similar to a float-sink method. Sand is used in suspension by injecting water and stirring by means of paddles to achieve a medium of desired specific gravity. The feed is introduced from top at one end and lighter material overflows from the other end. The heavy shale sinks to the bottom. Equipments are designed based on the interplay of centrifugal and gravity forces as in the case of a heavy media cyclone in order to improve the efficiency of separation.

It is evident from the foregoing that a wide variety of jigs as well as other heavy media separators are available by different manufacturers. While it is well known that HMS performs better with hard-to-wash coals, there is also a wide spread belief that jigs are going to be introduced in the coal cleaning circuits sooner than later. In this light, Sarkar [3], has summarized the performance of jigs and their status of usage in India. As stated by him "... Jigs also hold good potential for large scale application in India for the deshaling of sized or non-sized non coking coal..." In a coal cleaning plant often there is a choice available between incorporating either a jig or a HMS in the circuit. This entails a major planning in terms of pilot scale research costing a lot of revenue. In this paper the aforesaid problem is tackled by using a very popular simulator known as MODSIM ©[4]. The purpose of this paper is, however, not so much as to decide upon conclusively as to the usage of jig as it is to demonstrate the utility of a general purpose simulator.

SIMULATOR STRUCTURE

The simulator structure for a processing plant in its simplest form may be described as shown in Fig. 1. Input data with respect to important properties of material being processed is fed to the simulator. These data are processed according to a flowsheet, for which the unit models making up the flowsheet are available. What results at the end of the simulation is a complete characterization of each and individual streams with respect to specified material properties and flow rates of individual component phases. In addition, other important global performance indicators such as power drawn, total flow rate etc., are computed. Design data are also the outcome of the simulation to assess the capital cost involved.

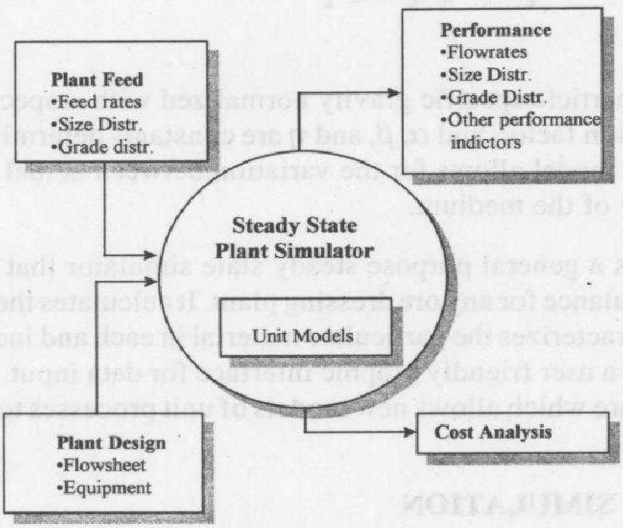

Fig. 1 : Elements of a general purpose simulator.

Mineral processing plant simulator analyses various types of unit operations that can be categorized into three major groups, namely,

* Separation units

* Size reduction units

* Solid-liquid separation units

The unit modules in any simulator are linked together by an executive program. Material flows in accordance with the flowsheet structure and all the units are connected by means of flow streams. The material in a flow stream is processed by one or the other of the above three units. For example, the model of a jig must calculate the partition function based on which particles of different specific gravities and sizes be separated into different product streams. The partition function will depend on the type of ore and its size and specific gravity distribution. The calculated product stream properties are passed on by the simulator as feed to the next unit in the flowsheet. Eventually, the material is tracked completely through the plant and all the process streams are thus defined.

The success of a simulator lies in the accuracy of the mathematical models of the unit operations. MODSIM uses some of the proven and recent models available in literature. For example, in case of jigging and heavy media separation a modified form of a model proposed by Lynch[4] is used. Here, the partition function curve is approximated as follows:

$$f(x) = \beta + (\eta - \beta)\frac{e^{\alpha.x} - 1}{e^{\alpha.x} + e^{\alpha} - 2} \qquad \dots (1)$$

where x is the particle specific gravity normalized with respect to the cut point, $f(x)$ is the partition factor, and α, β, and η are constants determined from the feed properties. The model allows for the variation between actual cut point and the specific gravity of the medium.

MODSIM is a general purpose steady state simulator that can calculate the detailed mass balance for any ore dressing plant. It calculates the composition and completely characterizes the particulate material in each and individual stream of the plant. It has a user friendly graphic interface for data input. It has a complete modular structure which allows new models of unit processes to be added into the simulator.

METHOD OF SIMULATION

There are various ways by means of which a processing plant can be simulated. MODSIM uses a sequential modular approach. In this approach each individual processing unit is represented by separate mathematical model called "unit modules". The unit modules are connected by data sets that represent material flowing streams between the unit modules. Flow of material constitutes solids and liquid. While the liquid is usually water, the solids are particles with size and mineral matter distributions. Thus each particle has a unique set of physical properties. MODSIM uses size and grade as two basic independent properties of the particles and depending on the processing need any other property may also be utilized.

Size and grade of particles are specified in discrete classes and this leads to hundreds of variables describing a stream within a flowsheet. For even few streams there are thousands of equations to be solved. In absence of recycle streams, sequential calculations can be done from the known feed streams, through the units, to the product stream. However, there are always recycle streams that complicate the calculations. MODSIM adopts the most efficient strategy for such calculations. In the calculation procedure, first flowsheet is rendered acyclic by appropriate tearing. Basically, tearing is the step where some streams are torn open to break all the recycling loops. The tear streams are chosen such that the iterative calculation procedure converges as efficiently as possible. MODISM incorporates excellent loop finding and tearing algorithms.

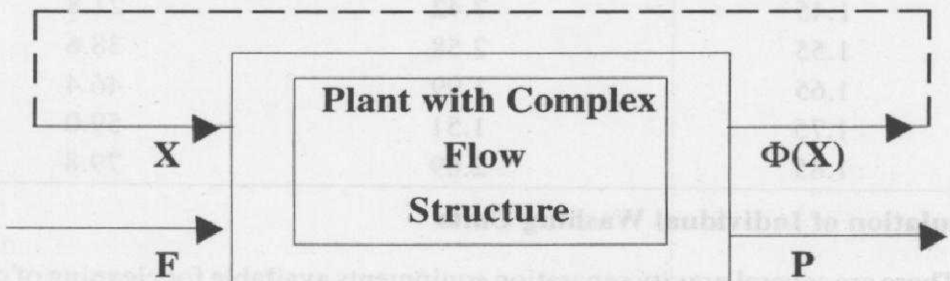

Fig. 2 : Schematic representation of system variables.

An iterative solution scheme is often used for simultaneous solution of equations. This can be explained in reference to Fig. 2. Here X is the vector of all estimated variables in all tear streams, $\Phi(X)$ is the vector of all calculated variables in all tear streams. F and P are the feed and product variable vectors respectively. Vectorially, the solution to this system is to find X' that satisfies the following equation :

$$X' = \Phi(X') \qquad \dots \quad (2)$$

In an iterative method, previous values of X and $F(X)$ are utilized to determine next set of X values. This procedure can be represented as

$$X^{k+1} = G(X^k) \qquad K = 0, 1, 2 \dots\dots \qquad \dots \quad (3)$$

where $G(X)$ is a function of X and $\Phi(X)$ and k is the iteration index. Various methods of iterative solution procedures are available. MODSIM uses the most efficient algorithms available to ensure fast convergence.

SIMULATION RESULTS

MODSIM has been used to simulate the performance of individual coal washing units as well as integrated coal cleaning plants. Performance of individual units is compared by means of simulation for a fixed type of coal. The same processing units are again compared in an integrated coal cleaning plant. In both cases the objective is to ascertain the effectiveness of one equipment over the other by means of simulation.

Table 1 : Specific gravity analysis of a typical easy-to-wash coal

Specific Gravity	Wt. (%)	Ash (%)
1.25	67.7	3.7
1.35	16.11	12.8
1.45	7.42	21.8
1.55	2.58	38.6
1.65	1.99	46.4
1.75	1.51	59.0
1.85	2.69	79.8

Simulation of Individual Washing Units

There are several gravity separation equipments available for cleaning of coal. Jigs and heavy media separators are the ones that are most commonly used for cleaning of coal. In this simulation two types of gravity concentration equipments are considered: Baum jig and drum separator. The feed to these equipments is a typical easy-to-wash type coal. The specific gravity analysis of this coal is given in Table 1. The ash content of this coal is 11.08%. At first, a jig is simulated with this coal. The result of simulation is compared with the plant data[6] and it is presented in Fig. 3 in form of performance curves. It is clear from this figure that MODSIM is able to simulate the behavior of this unit quite closely except towards the lower specific gravity range. This jig separates coal at a cut point of 1.50. Although the theoretical yield for this coal, at 6.69% ash in the product is 90.9%, the actual yield turns out to be 87.7%. MODSIM also provides other information pertinent to individual flow streams. This information is given in Table 2.

Table 2 : Output data for washing unit – Baum jig

STREAM TYPE	SOLID FLOW t/hr	WATER FLOW m^3/hr	% SOLIDS	SOLIDS YIELD %	REC. OF Comb	GRADE OF Comb	REC. OF Ash	GRADE OF Ash
Feed	41.80	167.18	20.00	100.00	100.00	88.90	100.00	11.08
Conc.	36.65	146.56	20.00	87.68	92.02	93.29	52.92	6.69
Tails	5.16	20.62	20.00	12.33	7.98	57.54	47.08	42.29

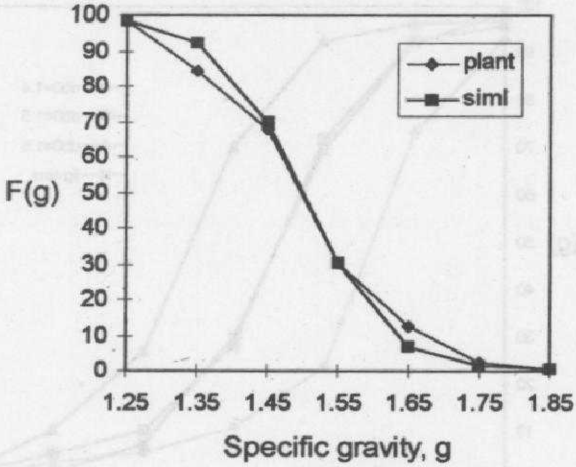

Fig. 3 : Comparison of partition behavior of a jig : plant vs. simulated data.

In another simulation, the performance of the Baum jig is compared with that of a drum separator. The same type of coal is used here and the flow rate in the feed stream is also kept the same as before. The results of simulation are shown in Fig. 4. It is observed in this figure that the performance of the jig and the drum separator is quite similar. In other words, the partition curves for these units are almost identical. In order to select a particular unit process one has to perform a careful cost analysis of these individual units.

For further analysis of the performance of these units, the cut point of separation is varied in case of the drum separator. As the cut point is varied, the performance curve is shifted. It is observed in Fig. 4 that on increasing the cut point the partition curve is shifted to the right. This allows a higher yield because, according to the partition curve, more material reports to the concentrate stream at a higher cut point for all values of specific gravity. However, this decreases the combustible recovery in the concentrate stream or an increase in the overall ash in the concentrate. The situation is just reversed by decreasing the cut point from 1.6 to 1.4. It may be noted that the best compromise between the grade and yield is achieved at a cut point of 1.5.

It has been observed by means of simulation that for an easy-to-wash type coal, such as the one employed here, use of jig may be advantageous over other gravity separation units owing to its simple operational features and other economic advantages. However, as the coal quality changes to that of difficult-to-wash type the above argument may not be quite true. In order to elucidate this point further, a typical coal washing plant is considered for simulation where both types of coal are used.

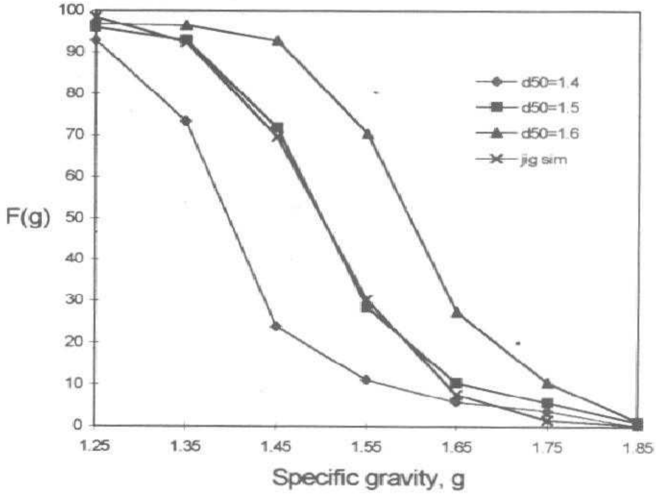

Fig. 4 : Performance of two gravity separation units : Baum jig and drum separator.

Simulation of Coal Washing Plant

A typical coal preparation plant as shown in Fig. 5 is considered for simulation. This plant uses a jig or a Chance cone as the preliminary washing unit. With a two stage heavy medium cyclone, this plant produces three product streams: concentrate, middlings and tailings. Typically, the ROM coal is screened where the fine fraction which is not amenable to gravity separation is sent for flotation. Since the objective here is to assess the performance of gravity separation units alone, the flotation part of the circuit is not simulated. However, MODSIM is quite capable of simulating the entire plant.

The performance of this plant circuit is analyzed with three different types of raw coal data. As before, one is expected to feed data pertaining to both particle size and grade distributions. MODSIM gives a choice of specifying data with respect to the specific gravity distribution as the same for all size classes. In reality, this is not the case. In all the simulations reported here, the specific gravity distribution is kept the same for all size classes. Nevertheless, this is as accurate a simulation as one would like to get in absence of detailed float sink data.

The three types of coal used in the simulations have marked difference in their washability characteristics. The float-sink analysis data of these three different types of coal are given in Table 2 [7-8]. This plant is simulated at a feed rate of 600 tons/hr. Simulations are carried out with these coals in two parts: First, the Baum

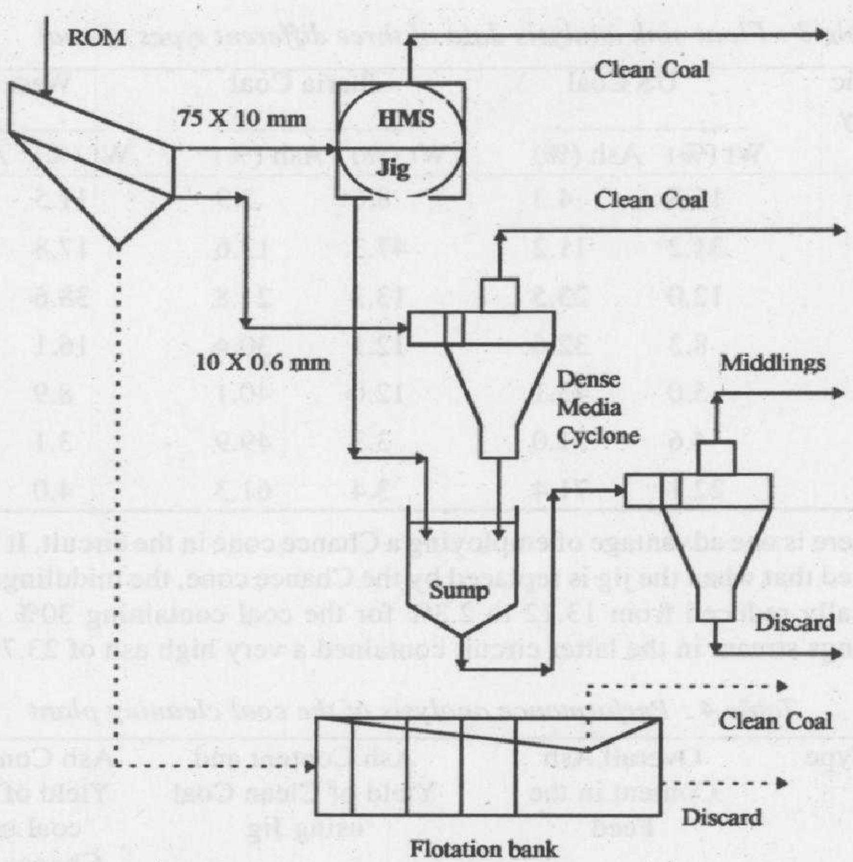

Fig. 5 : A typical coal washing flow sheet with two stage dense medium cyclones.

jig is used in the circuit as the preliminary cleaning device, and second, the same is replaced by Chance cone. In both cases the feed to the circuit is kept the same.

The overall plant yield and ash percentage of clean coal is given in Table 4. It is observed that for the coal having higher ash percentage, i.e., for the US coal, the Chance cone separator performs better. The overall yield of the plant is higher and the ash percentage of clean coal is lesser when compared to the Baum jig under similar conditions. For the West Bokaro coal, it seams, the Baum jig would perform better even though the ash percentage of clean coal from this circuit is slightly higher as compared to the one employing a Chance cone. This is due to the fact that for both circuits the yields are comparable with a very little difference in the ash content in the coal. Again, the advantage of using a Baum jig as preliminary washing unit for such coal lies purely in its cost effectiveness and ease of operation.

Table 3 : Float-sink analysis data of three different types of coal

Specific Gravity	US Coal		Jharia Coal		West Bokaro	
	Wt (%)	Ash (%)	Wt (%)	Ash (%)	Wt (%)	Ash (%)
1.25	16.8	4.3	8.6	3.9	11.5	4.5
1.35	31.2	11.2	47.3	12.6	17.8	9.4
1.45	12.0	23.5	13.3	21.8	38.6	20.2
1.55	8.3	32.6	12.1	30.4	16.1	29.8
1.65	5.0	43.1	12.0	40.1	8.9	40.4
1.75	4.6	51.0	3.3	49.9	3.1	50.1
Sink	22.1	71.4	3.4	61.3	4.0	60.5

There is one advantage of employing a Chance cone in the circuit. It has been observed that when the jig is replaced by the Chance cone, the middlings yield is drastically reduced from 13.12 to 2.3% for the coal containing 30% ash. The middlings stream in the latter circuit contained a very high ash of 23.7%.

Table 4 : Performance analysis of the coal cleaning plant

Coal Type	Overall Ash Content in the Feed	Ash Content and Yield of Clean Coal using Jig		Ash Content & Yield of Clean coal using Chance Cone	
US	30.0	12.26	54.05	13.13	63.29
Jharia	21.4	15.38	68.35	14.81	73.05
West Bokaro	21.3	13.13	53.41	12.00	57.10

DISCUSSION

The use of MODSIM as a general purpose mineral processing plant simulator is discussed. It is applied to simulate gravity separation units. The important observations based on simulation results are as follows:

* Performance of individual coal cleaning units such as jig and drum separator is quite comparable for a typical easy-to-wash coal. However, a jig may be preferred in such cases owing to the advantages that it offers in terms tonnage processing and ease of operation.

* In an integrated plant the performance of the circuit again depends on the

quality of the coal and the tonnage being processed. Three types of coal are employed for simulating a typical coal washing plant. It has been shown that of the three types of coal used here, the West Bokaro coal is most suitable for jigging practice.

* There has been always a problem with regard to the amount and grade of middlings generated in a coal preparation plant. It has been observed that with the use of a Chance cone the total yield of the middlings stream with a high ash content is reduced.

The full utility of MODSIM is far from what is described in this paper. It is particularly useful to improve the performance of a running plant through simulation. Space does not permit us to present all the data that are generated through simulation. For example the simulation results pertaining to calorific value, volatile matter, organic sulfur, etc. are omitted. In addition, other data that are of importance from a design standpoint are also not discussed here. It is in this regard MODSIM is perhaps one of the most versatile and user-friendly software package available for routine plant data analysis and simulation.

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