Mathematical modelling for optimization of mineral processing operations

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Synopsis

The use of temperature measurements for unusual applications in the analysis and control of column flotation and milling is discussed. This is followed by a review of some of the authors current research in the application of the discrete element method to the modelling of particulate processes, specifically milling, fluidized beds and chute flow.

Introduction

In this paper we focus on the use of a variable, which is generally underexploited in the mineral processing world: temperature. Very little mention of it is made in texts dealing with milling or flotation, for example. However, the unique characteristics of temperature, that

- it is an indicator of the energy content of the material concerned, and
- it can be very easily, cheaply and accurately measured

impart to it roles which, if recognized, can lead to important insights into process behaviour, and possibly substantial improvements in our ability to control and optimize these processes.

It is of interest to inquire what is the unique contribution of chemical engineering in the processing of minerals and materials. A unifying aspect of all processes is the presense and unique behaviour of particles. The typical graduate chemical engineer is presumably more than familiar with basic transfer processes (momentum, mass and heat), thermodynamics, reactor design, control, etc. Generally an ability to apply these skills to particulate systems will be emphasized. The importance of the particle disciplines is emphasized when one glances at the contents pages of volume 2 of the Coulson and Richardson[1] series. In the latter half of this paper we therefore review some recent work on the application of discrete element modelling (DEM) to the modelling of milling, fluidized beds and chutes.

Analysis and control of flotation columns

Fortuitous results[2] arose from a research programme aimed at developing a measurement of interface level for flotation columns. The method involved the measurement of temperature at a number of locations in the froth phase spanning the range of froth heights to be used in the column.. The method relied on sharp changes in temperature at the interface, caused by the fact that the wash water used in the plant was at 4ºC while the feed slurry was near 20ºC. The method worked well, providing measurements of level, which were much more accurate than those provided by a pneumatic method. However, the temperature probes were too delicate for the application and a conductivity-based method superceded the temperature method.

It is worth pointing out that a simple analysis of the behaviour of the froth phase shows that the froth washing inefficiency defined as the ratio: (water in the concentrate originating from the feed slurry)/ (total water in the concentrate–from the feed and the wash water) is given by

$$W_{fc} / W_c = \left(T_c - T_w\right) / \left(T_f - T_w\right) \qquad [1]$$

where T_f, T_w and T_c are the temperatures of the feed, wash water and concentrate, respectively. These can easily be measured and the ratio is a measure of the effectiveness with which the feed water (and its associated entrained gangue particles) has been replaced by the wash water (a low value implies effective washing).

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Firstly, interesting results were obtained from an analysis of the temperature profiles in the froth phase. They revealed the distributed nature of the mixing process in the froth phase, as shown in Figure 1. Temperature profiles are shown at two different locations in the froth phase.

The profile sensed by probe 2 shows a much colder froth than that sensed by probe 1, indicating that the froth washing process near probe 2 was much more effective. Presumably the wash water addition mechanism was due for an overhaul. The effect of a step increase in the wash water rate on the froth temperature profiles is shown in Figure 2 and reveals how the wash water effectiveness increases after the change.

Secondly, a neat correlation between the reduced temperature of the concentrate and the grade of the concentrate was obtained, as shown in Figure 3. A cheap and rapidly responding measure of concentrate grade is made available by simple temperature measurements.

Analysis and control of milling

The focus of this project[3,4] involved the development of a technique aimed at improving the current methods of continuous optimization and control of a grinding circuit. An online dynamic energy balance has been designed around the discharge sump, and is used to calculate the mill discharge density. This density is approximately representative of the load viscosity, and can be successfully used to optimize mill operation.

The viscosity of the slurry in the mill affects most of the parameters within the mill, and also has a large effect on the dynamic behaviour of the load. The density of the load is directly affected due to the relationship between viscosity, percent solids and hold-up. For a fixed load volume, an increase in the slurry viscosity will increase the mass and hence affect the power. It is thus possible to observe and control changes in the load condition by observing the mill discharge viscosity.

Aside from its effect on mill load behaviour and density, the viscosity of the slurry has a strong influence on the

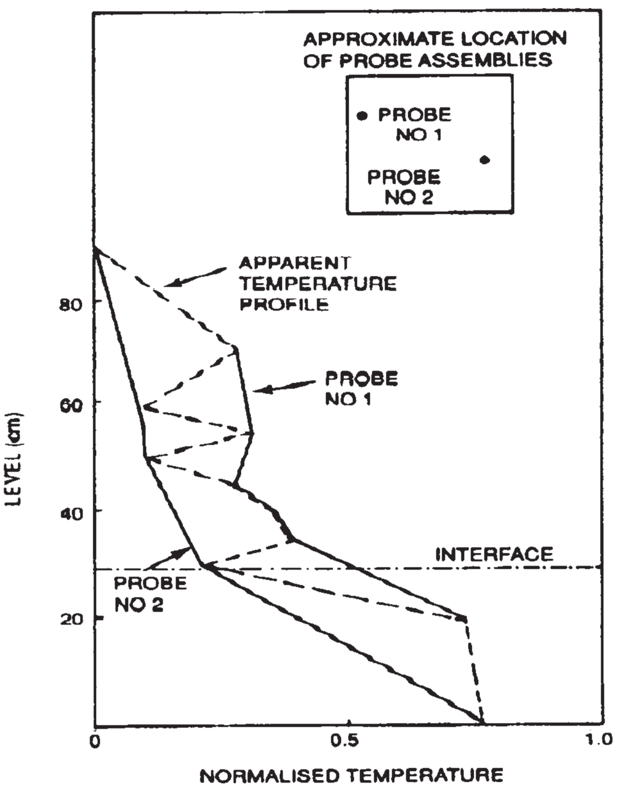

Figure 1—Effect of position of temperature probes on temperature profile in the froth phase of the flotation column

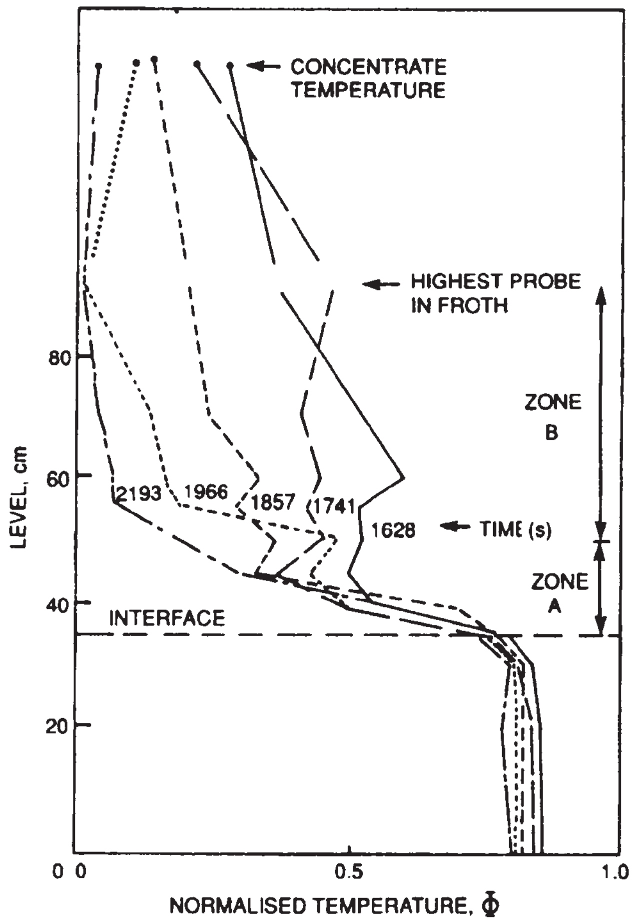

Figure 2—Effect of an increase in wash water rate on temperature profiles in the froth phase

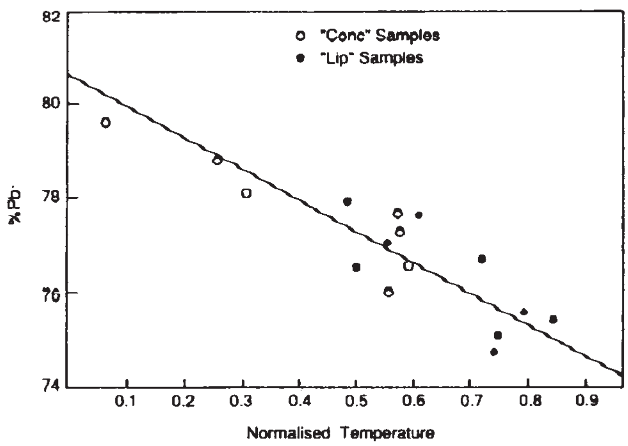

Figure 3—Correlation of the %Pb in the concentrate from the column with reduced temperature

grinding performance of the mill media. An excessively high viscosity implies a thick slurry inside the mill. The slurry effectively separates the grinding media such that the grinding performance decreases. This results in a higher amount of solids reporting to the cyclone underflow and hence a larger recirculating load. On the other hand, when the viscosity is too low, the grinding media are allowed to come into direct contact and result in excessive wear and wastage of the 'attrition capacity' of the mill.

Continuous monitoring of the mill circuit and its operating conditions requires the best-suited measurements that will describe the system and its dynamic behaviour. A variety of measurements can be used either directly for state assessment or to determine other useful parameters from the process models. Excellent work on viscosity measurement has been done by Shi[5] who formulated a model to accurately predict slurry viscosities using a rotating bobbin viscometer. However, reliable control of mill slurry viscosity has not yet been successfully implemented. Online viscometers are still not yet robust enough to cope with the harsh conditions typical of a milling environment. Control of the mill discharge per cent solids is therefore the closest technique available for controlling the mill load rheology. Robust measurement of slurry viscosity remains a tantalizing and worthwhile goal.

The grinding circuit

The experimental data was obtained from AngloGold's Mponeng gold plant, situated in the West Wits region near Carletonville, South Africa. The entire grinding circuit consists of three identical SAG mills running in parallel. Each mill circuit is closed by a hydrocyclone. The optimizing control system (OCS) installed on the plant was calculating only a discharge density for Mill No.1 using a mass balance principle when the energy balance study was initiated. The energy balance was therefore applied to Mill 1 for the purpose of comparing the discharge densities from the two models.

Figure 4 illustrates the circuit for Mill 1. The energy balance is concerned with measurements around the discharge sump only. The sump and its properties, however, cannot be isolated as they are intricately related to changes in this highly dynamic circuit. Four main control strategies dominate the circuit. The mill discharge density is controlled by the manipulation of the mill feed water flow. The mill feed belt controls the mill mass. Sump dilution water flow controls the sump volume.

Two pumps are used to pump the slurry from the sump to the cyclone. The variable speed second pump is used to maintain the specified inlet pressure to the cyclone.

The temperatures of all of the inlet and outlet streams are required for the energy balance. PT100 temperature probes were installed at the mill discharge stream, the sump dilution water and the sump underflow. The cyclone overflow temperature was also measured to ascertain whether or not a significant amount of energy is gained or lost between the sump outlet and the cyclone overflow. The slurry gains energy via pumping, pipe friction, etc. The slurry also loses energy via conduction/convection to the environment. A net gain or loss would therefore be very difficult to quantify mathematically, and so the temperature of the cyclone overflow was measured to allow an assessment to be made. A comparison of the cyclone overflow and the sump discharge temperatures provides an idea as to whether the net energy change from the sump to the cyclone is positive or negative. The reliability and variance of the two temperatures provide the energy balance model with a choice of input, as one of the measurements may ensure better model performance. Another factor influencing the measurement of the cyclone overflow temperature is that the environment for probe insertion is favourable compared to the sump discharge. The life of the cyclone overflow probe would therefore extend beyond that of a probe that is subjected to the highly turbulent conditions in the sump.

The energy balance

The energy balance is based on mass and energy flows in the system, thus making it possible to calculate the per cent solids of the mill discharge.

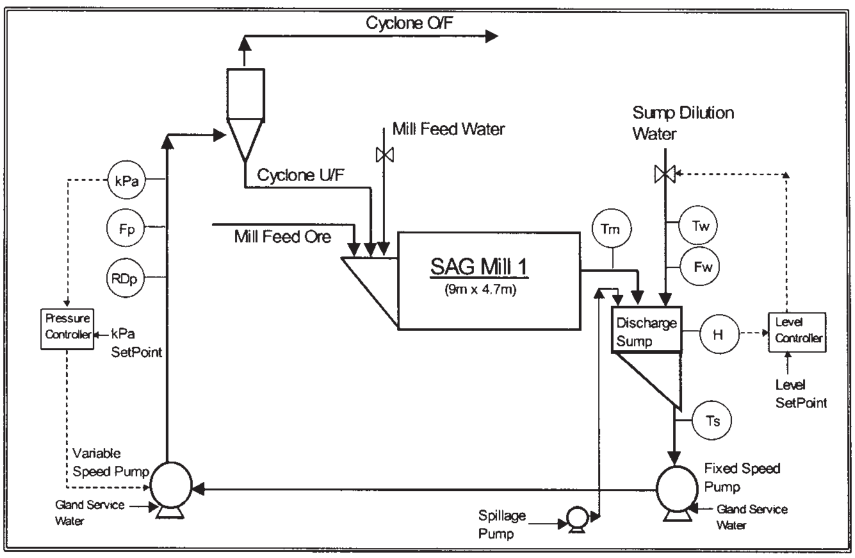

Figure 4—Mponeng milling circuit

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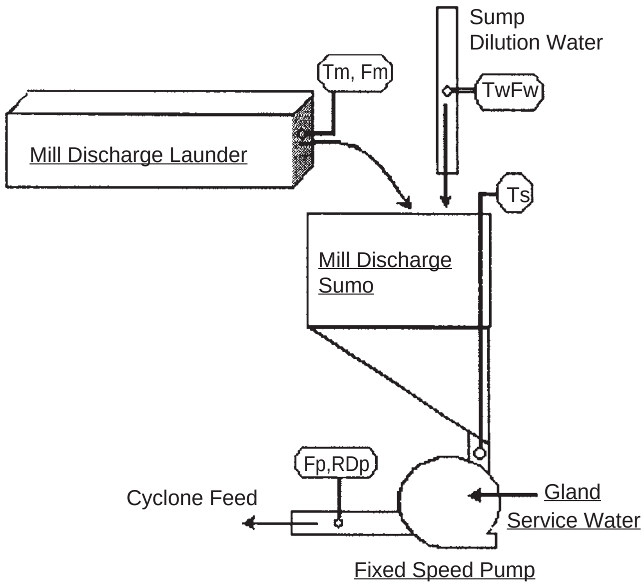

Figure 5—Sump schematic

The dynamic energy balance around the sump, as shown in Figure 5, is as follows:

[energy into the sump] = [energy leaving the sump] + [energy accumulated in the sump] MJ/hr.

$$F_{m[Solids]} \cdot \psi_{[Solids]} \cdot T_m + F_{m[Water]} \cdot \psi_{[Water]} \cdot T_m + F_w \cdot \psi_{[Water]} \cdot T_w = F_{s[Solids]} \cdot \psi_{[Solids]} \cdot T_s + F_{s[Water]} \cdot \psi_{[Water]} \cdot T_s + dE_{sump} / dt \qquad [2]$$

The symbols are defined as:

$\psi_{[Water]}$ – specific heat capacity of pure water
$\psi_{[Solids]}$ – specific heat capacity of quartzite
$F_{m[Solids]}$ – mill discharge solids flowrate
$F_{m[Water]}$ – mill discharge water flowrate
T_m – mill discharge temperature
F_w – sump dilution water flowrate
T_w – sump dilution water temperature
$F_{s[Solids]}$ – sump underflow solids flowrate
$F_{s[Water]}$ – sump underflow water flowrate
T_s – sump underflow temperature
E_{sump} – energy of the sump contents

The inputs of the energy balance consist mainly of the specific heat constants and the measured process variables. The mass flowrate of the mill discharge, however, needs to be determined. This is done using a dynamic mass balance around the sump. The only 'unknown' value in the process is the flowrate of gland service water. The error introduced by ignoring this was found to be negligible, as the value of the gland service water is generally less than 1.3% of the total flowrate through the sump.

The energy balance should provide improved accuracy (over the mass balance) because flow and density meters are notorious for incurring significant measurement errors. Temperature probes possess higher levels of inherent accuracy and thereby decrease the total compounded error in the measurements and models. Temperature probes are far less prone to drift than density and flow meters, thus making them more reliable in the long-term.

In addition to the enhanced accuracy of the energy balance, the capital cost of the temperature probes is insignificant relative to the cost of the extra instrumentation required to perform the mass balance (in fact the energy balance allows one to dispense with one flowrate measurement).

A detailed discussion of all these issues and the various equations used in the model are beyond the scope of this paper; interested readers are encouraged to contact the first author by e-mail for a document which illustrates the use of the energy balance concept in more detail.

Results—application of the energy balance

In order to test the model's performance, the required input data was obtained from the industrial circuit. Manual samples were taken from the mill discharge to allow direct assessment of the accuracy of the model. The mill discharge was sampled over two hours while step changes were made to the mill feed water flowrate between the values of 10 and 90 t/h, which covers all of the typical values during normal operation. The residence time of the mill is approximately 10 minutes and the effects of a change in the mill feed water should therefore be allowed to manifest in the form of a dynamic change in the density of the slurry entering the sump. The sump has a mean residence time of approximately one minute. The step changes in mill feed water flowrate were therefore maintained for a minimum of twenty minutes before the next change was made. Enough time was thus allowed for the effects of the step change to be registered by the energy balance around the discharge sump.

Figure 6 clearly shows that the energy balance predicts the behaviour of the manually sampled densities very well if the offset is ignored. The standard deviation of the variance between the energy balance output and the manual samples is less than the deviation of the OCS RD calculation. The OCS uses a Kalman filtered mass balance to model the entire grinding circuit, thus producing a mill discharge density

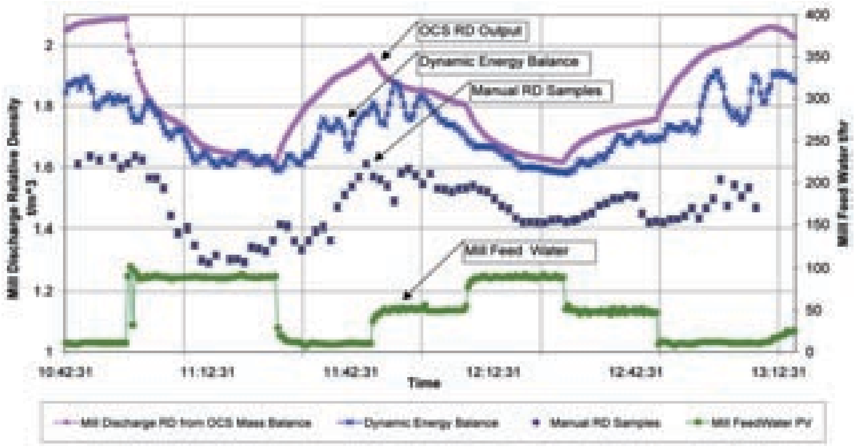

Figure 6—The energy balance density estimate compared with the mass balance and manual samples

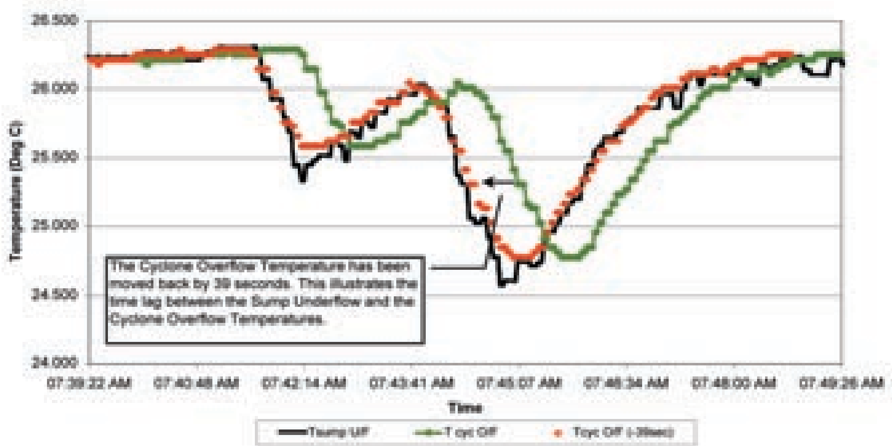

Figure 7—The Cyclone O/F and Sump U/F Temperature Responses

estimation. The energy balance outperforms the mass balance in its ability to account for the dynamic lag that the mill imposes on the change in the mill feed water flowrate. An offset does, however, exist between the energy balance and the manually sampled data. A large amount of confidence is placed in the manually sampled RD data, and calibration errors in flow or density must be the cause of this discrepancy.

As previously mentioned, the cyclone overflow temperature was measured to assess its use as a replacement for the sump temperature measurement. The cyclone overflow is in most cases easier to access and presents less of an abrasive environment to the temperature probe.

The sump temperature signal has a noisy-looking variance over very short time intervals. This is believed to be due to poor mixing in the sump, thereby resulting in poor representation of average sump temperature. The average temperature difference between the cyclone overflow and the sump was 0.1°C and indicates that there is a net positive gain in enthalpy of the stream (due to energy input by the pump) by the time it leaves the cyclone. Figure 7 shows the effect of a disturbance in the temperature of the sump contents. The average time lag between the two signals is 39 seconds. It is now possible to include the temperature difference and time lag into the dynamic model so that the cyclone overflow temperature can replace the sump underflow temperature.

Modelling the dynamics of the entire mill circuit

The above work was focused on modelling the behaviour of the mill discharge sump. A second project is now focused on the development of a Kalman filter based on an energy balance approach for the entire milling circuit.

Shortcomings of the mass-balances have been identified. Firstly, the mass-balance displays a large positive offset from the manually sampled discharge densities—as shown in Figure 6.

Secondly, the mass-balance assumes that the mill is perfectly mixed and therefore does not allow the control scheme to deal with the dynamic changes in the load appropriately. The new energy balance models are based on the ‘two-tank’ model for the mill load. The model assumes that a portion of the slurry in Tank 2 flows back into Tank 1, thereby allowing the model to cope with a variable amount of mixing (a large backflow implies the mill is essentially perfectly mixed, while no backflow implies that two mixers in series describes the mixing behaviour).

Online measurements will allow the determination of the appropriate amount of backflow. The temperature of Tank 2 will be assumed equal to the measured mill discharge temperature.

The temperature of all streams (slurry, rock and water) in the plant and ambient temperature will be measured. The energy of all of the streams entering and leaving the mill will therefore be accounted for. The energy loss via conduction and convection through the mill shell will be accounted for by quantifying the heat transfer coefficient of the shell allowing the models to account for convective loss.

The OCS© mass balance already computes many useful parameters, such as the fractional loading (ore, balls, water), the load RD, the discharge coefficient, etc. The energy balance is utilized to refine these estimations based on a mass-balance/energy balance combination. This system will then be capable of producing more meaningful parameters for state estimation. The Kalman filter (currently applied to the mass balance) observes the mill mass and power and other measurements such as the water and feed flowrates and the cyclone feed density, all of which are subject to significant errors (of the order of 5%). Kalman filtering will be applied to the energy balance in the same way to take advantage of the much more reliable information in the temperature measurements.

The energy balance has shown remarkable results and promises to be a useful application in the control of SAG mill circuits. A more detailed discussion of all these issues and the various equations used in the model is beyond the scope of this paper; interested readers are encouraged to contact the first author for a document which illustrates the use of the energy balance concept in more detail.

Discrete element method (DEM) modelling of particulate processes

We turn now to the modelling of the behaviour of particles (large—grinding balls—and small) using the DEM. The DEM was first introduced by Cundall and Strack[6] and has gradually developed to become a highly promising initiative in the simulation of particulate processes. The past decade has seen major strides in DEM development, for which the increase in the power and affordability of desktop computers has been critical.

DEM has been used in a wide range of applications:

Soils—stability, subsidence, creep, avalanching
Powders—mixing, flow
Fragmented and loose solids—chutes, bins, mills, block caving systems
Brittle solids—tunnels, dams, foundations, stone structures; rock fracture; fragmentation and heave in blasting
Other applications—fluidized beds (incorporating both continuum methods and DEM), ice fields.

The method has been shown to naturally reproduce macroscopic behaviour, which hitherto has required complicated explanations, such as the peculiarities of stress/strain behaviour and fracture in brittle solids, or the phenomenon of 'memory' in loaded soils.

Nature exhibits what has been called emergent behaviour: that simple relationships on the microscale lead to complex macroscopic behaviour. The fundamental laws of physics are simple and few in number, but the behaviour of matter in the large is extremely complex. Standard mesh-based codes solve equations derived for continuous rather than discrete systems and have had remarkable success when the equations, or constitutive relationships, have been known, and have been known to apply to the material being investigated. One has only to consider the success of computational fluid dynamics (CFD) codes, which solve the Navier-Stokes equations for fluids, or of large deformation hydrocodes, with their dozens of material models, which enable them to model shock effects in a wide range of materials, to appreciate the power of traditional, meshed-based methods. However, there is a vast range of material behaviour for which constitutive laws are almost impossible to obtain, or severely limited in applicability when they are obtained. Examples are the deformation and failure of granular assemblies and brittle solids subjected to complicated patterns of loading and unloading, or the flow of granular materials in general. It is in just these areas that one would turn to DEM.

In addition to standard DEM investigations aimed at solving particular industrial problems, discrete element simulations can be used to create a numerical laboratory, and thus be incorporated into powerful new research programmes utilizing experiment and numerical simulation. A discrete code can be primed with relatively simple contact laws, which qualitatively reproduce the interparticle behaviour of a given system. Through study of the evolution of the system, patterns of behaviour, including patterns leading to new constitutive relationships, can be isolated, observed and interpreted. This potential, to explore areas which are effectively inaccessible to experiment alone and beyond the bounds of current engineering knowledge, is one of the most exciting prospects for the future of DEM.

Despite what has been said, issues remain to be resolved and obstacles overcome before DEM matures into a full engineering tool. Firstly, DEM analysis is computationally expensive. A 3D simulation of a bench blast, which would simulate a large enough section of ground with enough detail to give meaningful results, would require, at a bare minimum, around 200 000 particles. Simulation time would be measured in weeks. A second issue is that of material parameterization, which is laborious and time consuming. The parameters used in DEM codes have no clear relation to the macroscopic variables traditionally used to characterize material. Determination of parameter values is an inverse problem.

Simulations of simple experiments, such as uniaxial or triaxial tests, are set up, and parameters varied until experimental results are reproduced. Ways will have to be found to automate the inverse process, or thorough investigations of the DEM parameter space will have to be conducted and the results documented.

A third issue concerns scale. A DEM 'particle' is invariably much larger than the particles in the granular assembly or the grains in the brittle solid being simulated. DEM simulations have been shown to qualitatively reproduce complex material behaviour and in some applications, such as the flow of coal or ore in chutes, have been used very successfully as a guide to chute design and in correcting poor design. In general, however, questions of the ability of DEM to give accurate numbers when the DEM particle size is appreciably larger than characteristic scale lengths of the material being simulated, remain to be answered.

Milling

Rajamani[7] was one of the first researchers to apply DEM to the modelling of the milling process. His Millsoft package has been widely used by the milling fraternity. It models a two-dimensional approximation featuring one layer of balls with their centres on a plane perpendicular to the mill axis. Eskom, our main funder in the DEM area, sponsored a visit by Rajamani to Wits in 1996. He assisted with the first experiments performed in our experimental '2D-Mill'.

The mill is 0.55 m in diameter and 0.023 m long—slightly larger than one ball diameter. It thus allows us to do experiments, which exactly correspond with the situation modelled in Millsoft. An example of the data obtained in this experimental programme is shown in Figure 8, which compares DEM predictions with experimentally measured power data over a wide range of mill speeds (10–180% of critical speed). Excellent prediction of mill power is obtained for speeds between 0 to 80 per cent of critical speed. Above this speed centrifugal forces begin to balance gravitational forces, so power predictions diverge somewhat; however, the overall pattern is well predicted. Figure 8 shows pictures of the load behaviour compared with DEM predictions at three different mill speeds.

At 100 per cent of critical speed a full layer of balls had centrifuged between the lifters, while at 160% of critical speed two layers of centrifuged balls are observed, explaining the substantial loss of power that was observed at this speed. Figure 8 showing the complex variation of power and load behaviour with mill speed, illustrates well the comments above on the 'emergent behaviour' of Nature.

An area of major application for DEM models of mills is the analysis of the effect of liner profile on the behaviour of the load in the mill, which in turn affects the kinetics of milling and the rate at which the pulverized fuel can be removed from the mill. All the power used for grinding passes through the liners, so this significance is not surprising. The effect of wear of the liner on the load behaviour is illustrated in Figure 9, which shows position density plots (PDPs, which represent the average behaviour of the load over several mill revolutions) for unworn and worn lifters. Note that the unworn lifters tend to project a certain proportion of the grinding media into the air (these media are said to be cascading) above the bulk of the media, which cataract down the surface of the load. Very little cataracting occurs with the worn lifters. This observation supports an hypothesis being currently investigated concerning the relationship between this aspect of load behaviour and the capability of the mill to produce fine product at an adequate rate. Minimal cataracting implies minimal projection of balls and interstitial coal above the load surface, leading to minimal opportunity for interaction between fine coal particles and the classifying air passing through the mill.

The DEM simulations can also be used to study the tendency towards mixing in the load. The behaviour of 10 balls in a simulation over twenty mill revolutions using worn lifters is shown in Figure 10. It is remarkable for 6 of these pictures (nos. 2, 3, 4, 5, 7 and 10 numbered row-wise) how repeatable these ball trajectories are, implying that the balls tend to follow the same path as time passes. This tendency is evident to a certain extent in the other pictures as well. Obviously a mechanism exists, which results in balls moving off a trajectory every now and then. This lack of mixing has implications for take-up of coal into the load and removal of PF from the load.

This implies that there is not much movement across these trajectories, so that balls or coal particles that are close to the centre of the charge will tend to stay there. This has significant implications for the effectiveness of the milling mechanism in these rotary mills: coarse coal will have difficulty entering the load, and fine particles will have a low tendency to be removed. Coal near the centre of rotation of the load will thus tend to be overground. It should be noted that other designs of mill (e.g. the vertical spindle mill) ensure minimal residence time of coal particles in the mill

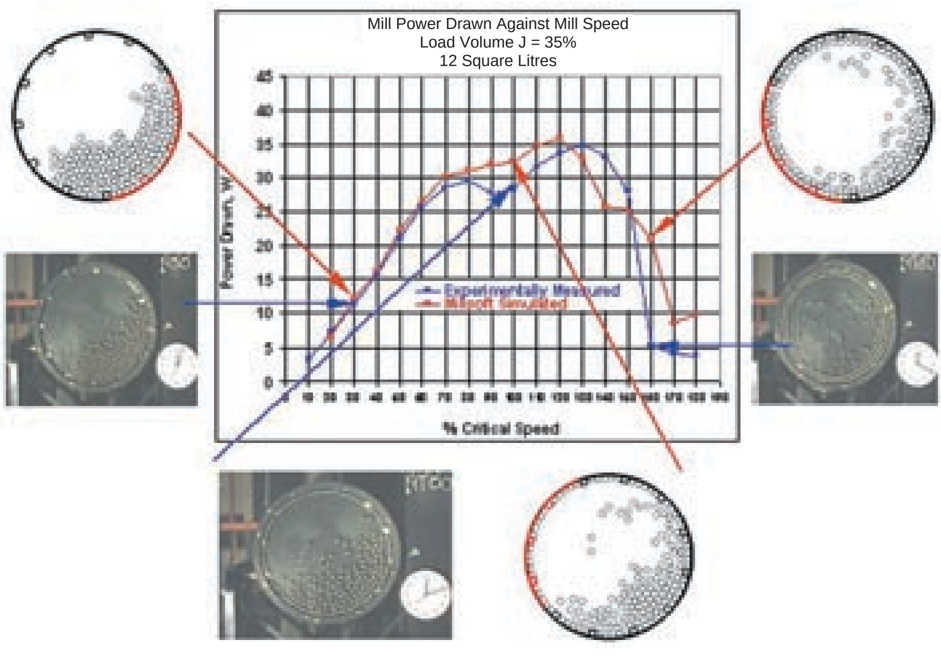

Figure 8—DEM prediction of power drawn by a 2D rotary grinding mill with 12 square lifters showing pictures of load behaviour at interesting speeds

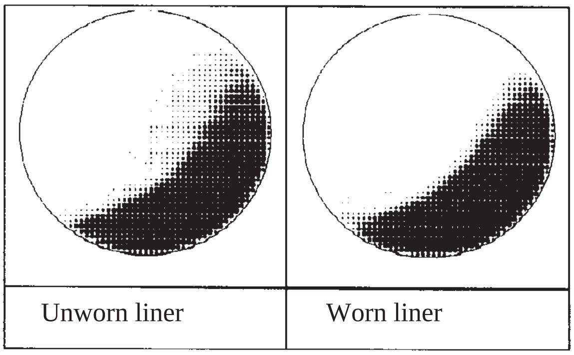

Figure 9—Position density plots (PDPs) showing the effect of liner wear on the behaviour of the load in a dry coal mill

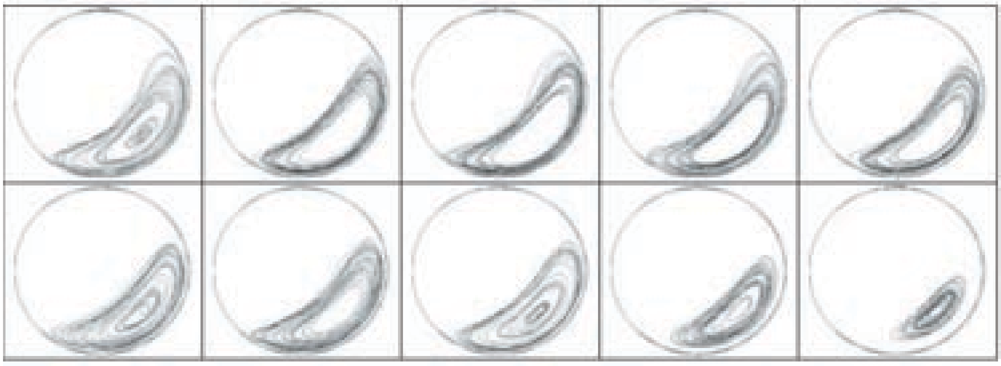

Figure 10—Single ball trajectories (for 10 balls) in a Lethabo mill with worn lifters indicates that balls generally tend to follow the same track in the mill load for a number of mill revolutions

before a classification process is applied; these mills are approximately 80% less expensive in terms of their energy utilization (kWh/t of ground product).

Fluidized Beds

Netshidongololwe, Moys and Horio[8] have described the results of Netshidongololwe's MSc. research project. It involved the use of an experimental 2D fluidized bed, illustrated in Figure 11, to obtain data for validating Horio's SAFIRE code, which combines the use of DEM and an elementary CFD model to provide remarkable simulations of fluidized bed behaviour. The DEM model is essentially as described above; the CFD model involved the continuity equation for gas behaviour (assumed incompressible) and published correlations (such as the Ergun correlation) for calculating the drag force exerted between the particles and the gas.

Results obtained are illustrated below. Figure 12 shows the correlation between experiment and the model for prediction of the pressure drop versus gas velocity for the bed for a wide range of gas velocities. This is important for the design of the bed and the sizing of the fan for forcing the air through the bed. The experimental data shows the hysteresis in pressure drop, which is typically observed when the gas rate is increased from zero for a well packed bed or decreased towards zero from the fluidized state (this arises because in the former case the bed will be well-settled and will therefore have a slightly lower voidage and will require extra pressure to mobilize particles before they enter the fluidized state). The simulation does not give rise to this behaviour (it could be persuaded to if a tighter initial configuration of the particles were 'forced'). The minimum fluidizing velocity is accurately simulated (this is recognized as being fortuitous, since the drag force correlation is subject to large errors).

The ability of the model to simulate the behaviour of a bubbling bed is illustrated in Figure 13. In this case the bed was set up with a single-hole orifice (a uniform distributor was used in most of the experimental work). The experimental bed exhibited a very interesting vortex behaviour just above the nozzle inlet, which was not simulated by the model; however, the gross behaviour of the bed is simulated reasonably accurately. The model should thus be useful for predicting aspects of fluidized bed behaviour such as residence time distribution of gas in the bed, mixing of solid particles, transition from uniform fluidization (typical at gas velocities just above the fluidizing velocity) to bubbling fluidization, etc. These features have a profound effect on reaction rates, conversion, etc. The model will be particularly useful for the simulation of processes that are difficult to observe, e.g. high pressure fluidized beds.

Chutes

DEM modelling of the flow of coarse, non-cohesive ore in chutes and through transfer points has had notable successes. Both Nordell[9] and Dewicki[10] have been able to use knowledge gained from DEM analysis of granular material flow at problem transfer points, to recommend retrofits which have significantly reduced belt wear and have eliminated the problems which were being faced.

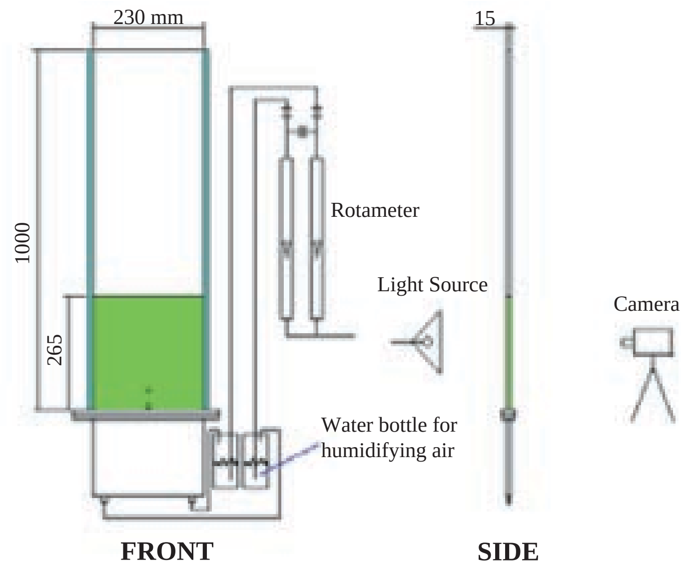

Figure 11—Front and side views of the experimental 2D fluidized bed rig

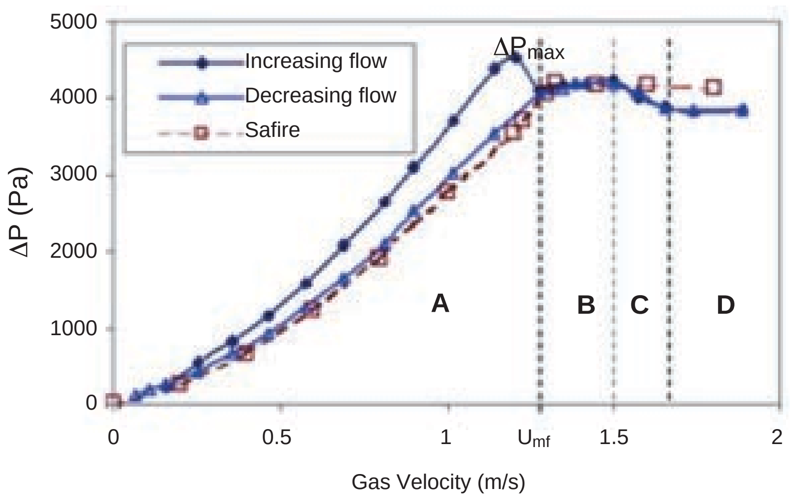

Figure 12—Experimental pressure-drop versus gas velocity diagram for 2 mm glass beads with a density of 2 600 kg/m3

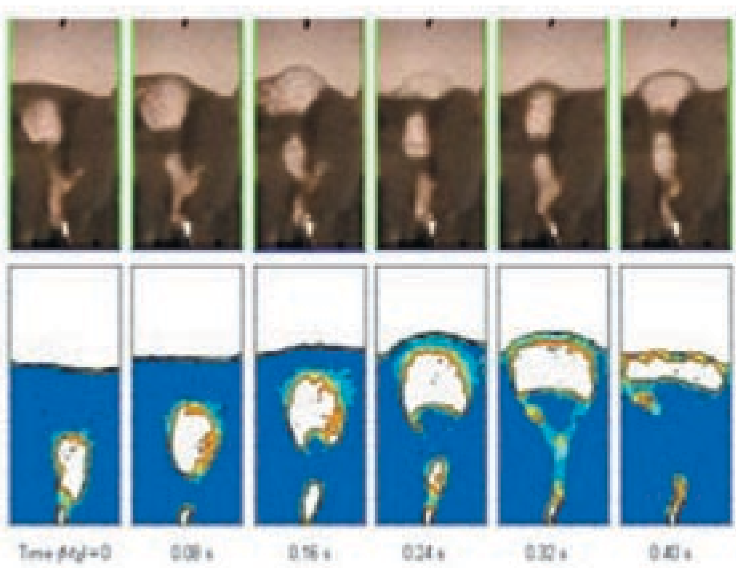

Figure 13—The bubbling bed for 2 mm glass beads at $U_{or}/U_{or,\,mf}$ = 1.3 with a single-hole inlet distributor. The top and bottom series are the experimental and simulation respectively

The COMPS group at Wits has begun a project to model the flow of ash in chutes and of coarse coal through 3D transfer points. The objective of the project is produce a tool for chute design, which will more accurately predict the geometry of coal flow through a three-dimensional chute so that the geometry of the chute that eliminates spillage can be found reliably. Figure 14 illustrates the effect of placing a guiding bonnet too close, and at too steep an angle, to the exit belt. On the left the particle stream has just begun to hit the bonnet. The right figure shows the flow some time later. A shock has moved back through the flow to the belt and is disrupting the material on the belt itself.

Figure 15 shows material moving through a relatively well-behaved 3D transfer system. The velocity vector of the stream has been smoothly rotated from the x-direction to the z-direction, but spillage of some particles is still evident. The DEM tool could be used to explore minor changes in the design of the chute to eliminate this spillage completely; it could also be used to select design parameters (such as the slope of the transfer chute), which will ensure that the particles are deposited on the lower conveyor at a velocity that is similar to the conveyor velocity (in order to minimize wear of the belt).

These and other similar phenomena can be simulated using DEM. Once the model is validated by comparison with measurements in existing chutes, it becomes available for designing new chutes; for example, we are currently investigating the method for simulating flow behaviour in spiral chutes, which have unique applications in certain situations.

Conclusions

Analysis of the behaviour of processes via measurements of temperature has been shown to provide valuable insights into process behaviour. Fault diagnosis (e.g. for the effectiveness of a wash water arrangement on a flotation column) and process control opportunities for both flotation columns and milling circuits have been illustrated.

The discrete element method has tremendous potential as an engineering tool for modelling particulate systems. It is currently the focus of very active research, along two general lines. One is development of the method itself. The time required to characterize material, and the time to complete simulations, must be reduced, and ways must be found to smoothly integrate DEM with more established numerical methods. The second area is exploration of its potential

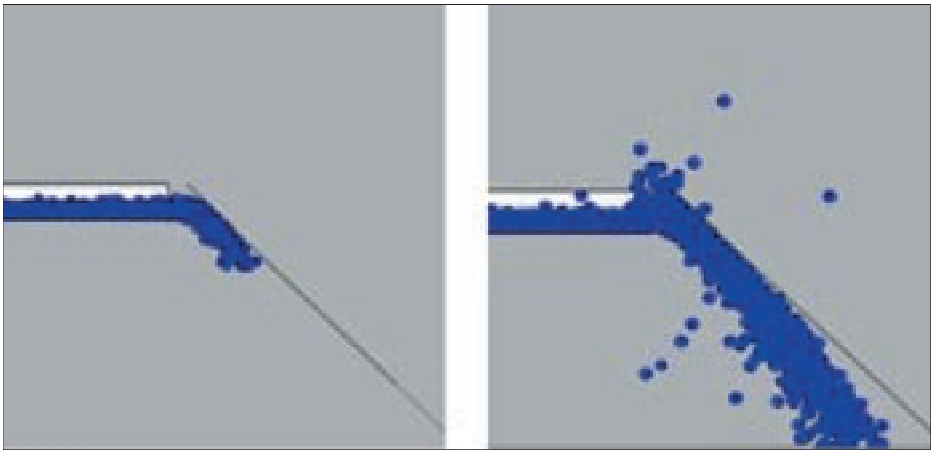

Figure 14—Simulation showing flow disruption resulting from back-up due to an improperly positioned bonnet

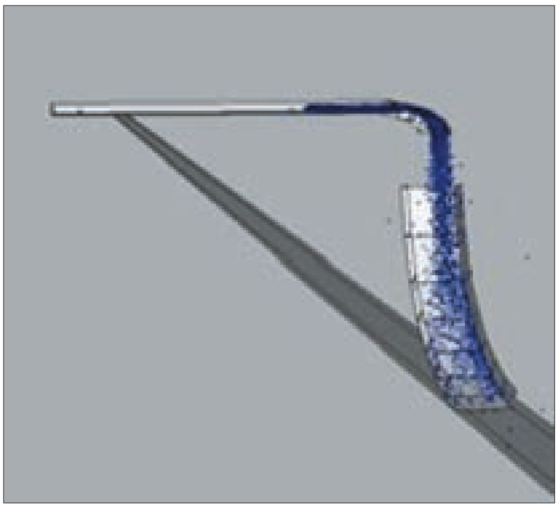

Figure 15—Simulation of the flow of coal through a 3D transfer point

through expanding the range of applications investigated through DEM, and the depth and detail of those investigations. The next decade will undoubtedly see a vast expansion in academic research into DEM and in the use of DEM in modelling industrial processes.

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