SIMULATION IN MINERAL PROCESSING
- THE PRESENT AND THE FUTURE

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Abstract

The simulation of mineral beneficiation processes commenced about 30 years ago at the time when electronic digital computers became available for general use. For many years progress was slow and spasmodic because it proved to be difficult to develop accurate process models and large computers were not accessible to plant engineers. Simulation was not driven by demand from the users and there was little emphasis by the modellers on developing simulation techniques which could be immediately available to plant engineers.

But there has been a change during recent years. Models are more accurate because they are now tested extensively in plants and modified where necessary, powerful desktop computers are making process simulation available to engineers wherever they may be and the software is being developed to make the models easy to use. Simulation is now well established as a design and optimisation tool in mineral beneficiation.

During the next ten years the increasing power of desktop computers will lead to the development of a new generation of models which will give much better descriptions of what is happening inside the processing units. These models will improve the accuracy of process design and will be used for the design of better equipment. Because they will be dynamic models they will be of particular

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value in simulators which are used for training and for testing plant control systems.

Introduction

The modelling of mineral treatment processes began several decades ago and the basis of many models in use today were proposed in the 1940's and 1950's. For example the concepts of breakage, selection and classification to describe comminution processes were discussed by Epstein (1) and, in more detail, by Broadbent and Callcott (2,3) while Schuhmann (4), Sutherland (5) and Morris (6) made important contributions to modelling flotation by considering it as a kinetic process. Classification as a unit operation, although apparently simple, proved to be very difficult to model. It was the idea of considering it as a process which was controlled by two almost independent mechanisms, entrainment and classification, (7, 8, 9, 10) which led ultimately to the development of a workable model.

These models set the scene for simulation as it is today but they were little more than mathematical curiosities because the extensive calculations involved in their use were beyond the capacity of calculators then available. This problem decreased with the development of minicomputers and has virtually disappeared over the last decade with the development of powerful personal computers. The first successful efforts in simulating comminution circuits were made about 30 years ago. These models used matrix equations to describe the behaviour of full sizing distributions in comminution and classification circuits (11, 12, 13, 14).

For many years progress in modelling and simulation was slow and intermittent and its application was site specific and very limited in scope. In fact, it gained a poor reputation because some of the advocates of modelling oversold the benefits which could be achieved, not realising that there were major barriers to be overcome before potential benefits could be turned into reality. The basic models could certainly be calibrated to specific processes but it was found that they could not be applied over a wide range of operating conditions or to changes in ore type. These capabilities would only be possible when the models included complete descriptions of the effects of all important variables on the process.
performance and of the ore type characteristics by standard techniques. It became
evident that comprehensive experimental data were required from many operating
circuits treating a variety of ores if these basic models were to be developed into
workable models which could be used with confidence on a day-to-day basis by
engineers for the design and operation of mineral processing plants. It was also
evident that advances were required in computer hardware and software to make
the models readily available to those engineers. Until those requirements were
fulfilled modelling mineral processing circuits would be an interesting, albeit
sterile, exercise.

During the past 25 years these requirements have been fulfilled, slowly and
painstakingly. The important factors have been powerful desktop computers,
software to make simulation an easy interactive process between the engineers and
the models, and refinement of many of the models to the point at which they
describe accurately the effects of changing ore-types or operating conditions.
Simulators are now used by many plant and design engineers and the long­
promised economic benefits are now being realised. However, it should be
emphasised that simulators are only an aid for engineers, they do not replace
engineering judgement.

The suites of models which are now available still have deficiencies, for
example, conventional flotation cells cannot yet be modelled with confidence
although good progress has been made with flotation columns. The problems with
flotation which now exist will diminish during the next few years because
measurement techniques are now available to obtain information about particles,
froths and pulps. These measurements will remove some of the present doubtful
assumptions.

During the last few years there has been major progress in the development
of user-friendly simulation structures. Without these simulators the models would
not have become available to a wide user base.

The purpose of this paper is to review the current status of modelling and
to discuss future trends. Many authors, for example Mular (15), Broussard et al
(16), and Napier-Munn and Lynch (17), have published reviews on this topic and
there is an extensive literature on the modelling of individual processes. This paper
will not be a comprehensive review, it will be more concerned with the present status of simulation, the problems which are still to be solved, and the impact of simulation on mineral processing in the future.

The Present Status of Simulation

Size Reduction

This is the process which has been investigated in most detail and which is well understood for most machines (18). The models which are now used contain parameters which describe the ores and the machines, and equations which describe the ore-machine interactions. Procedures are available for determining the abrasion and crushing breakage functions of ores at known input energies and how they change as the energy inputs change (19,20). There is a good understanding of the dependence of breakage rates and discharge rates on particle size for ball mills of different diameters (21), and linking these rates to the breakage functions has led to the development of reliable models. The same may be written about crushers (22,23).

It has been particularly difficult to develop reliable models for autogenous and semi-autogenous mills. In these cases, unlike ball mills and rod mills, the grinding environment changes as the ore type and feed rate change, and the key to the reliable model is to determine the complex relationships which exist between the ore type, mill load, energy available for breakage, and the breakage functions and breakage and discharge rates of the particles of different sizes. It has been a long and tedious task to accumulate data about the mass and size distribution of the mill loads in full size mills and their responses to changes in ore types. This is not surprising because of the physical difficulty in obtaining these data. However, a reasonable data base which includes actual mill loads has now been accumulated from production AG and SAG mills.

The accurate prediction of mill loads, which control the breakage rates and which in their turn are controlled by the breakage and discharge rates, is crucial to a useful model. An iterative procedure is now available to predict grinding loads which usually gives accurate results (24). The modelling of AG and SAG mills will be more accurate when the data base is larger and this will continue to expand
slowly. There is little doubt that models of these mills will have evolved to the point at which they will be generally accepted as accurate representation of mill behaviour, as ball mill models are now, within the next four years.

One of the limitations in modelling wet tumbling mills is a lack of understanding of the effect of pulp viscosity on mill performance, particularly on the rate at which particles are discharged from the mills. This limitation will be removed within the next few years because instruments are now available to measure pulp viscosity, as discussed by Kawatra et al (25), and Napier-Munn et al (26).

Size Separation

The modelling of size separation units progressed rapidly in the 1970's and models of hydrocyclones (27) and vibrating screens (28) were developed which have been extensively used in simulations. These models had limitations then and the limitations still exist although the accuracy of the models has certainly been improved. More information is needed to define accurately the effect of slurry viscosity on classifier performance and to separate the effects of solids content and slurry viscosity.

The behaviour of very fine particles in classifiers must be understood much better if we are to be able to improve the accuracy with which fine particles are classified. This understanding will develop rapidly because new techniques are now available to measure the characteristics of particles and pulps, and these will lead quickly to better understanding of process behaviour. At present it is important to resist the temptation to extrapolate classifier models into regions in which they are not yet proved to be accurate.

Another limitation of classifier models is that they do not necessarily apply to mixtures of coarse and very fine particles. This is particularly important with oxide ores which contain a high proportion of fines and must be deslimed before further processing.

With regard to vibrating screens more attention will be given to the behaviour of particles of different shapes and to separating these particles on the basis of shape. Shape is becoming an important factor in some processes,
particularly for aggregates. This is a problem of the future but a difficult problem at present is modelling screens and concerns the prediction of the effect of increasing the water content of an ore stream on screening efficiency and this problem has still to be solved.

**Concentration Processes (I) Flotation**

Models of concentration processes have lagged well behind models of comminution and classification. One reason is that in comminution and classification it is particle size, specific gravity and shape which are important but in concentration there are other properties of particles and pulps which are important but which are very difficult to measure. Flotation is a case in point.

In the flotation processes, particles enter the concentrate by adhering to bubbles and by entrainment within the froth. It is difficult to separate the contribution of the two mechanisms, particularly for composite particles.

Extensive plant data from circuits treating coarse grained, relatively well liberated particles, verifies that hydrophobic particles float in the concentrate at rates which are proportional to their concentration in the cell and that hydrophilic particles float at rates which are proportional to the flotation rate of water (29). These observations suggest a method to model the process and there is a copious literature on aspects of kinetic models of flotation and how problems with applying the models to real processes might be solved, for example, Woodburn and Wallin (30).

However, studies of circuits in which the slow floating composite particles dominate indicate that a comprehensive flotation model is particularly complex. One difficulty is that the basic measure of mineral behaviour in concentration is chemical analysis and this does not distinguish between the same mineral contained in composite and liberated particles. Furthermore, while the flotation process acts on the surface of each particle, almost all liberation data relate to sections of particles and not to particle surface. It is essential that flotation models should include information on particle types and not assays only if they are to describe accurately the behaviour of concentrated particles which necessarily contain many composites. But even taking this difficulty into account experience
now indicates that there is no general model which can utilise information specific to an ore - such as a single batch flotation test - to predict with confidence the grade recovery curve of a known circuit configuration.

One reason for this is that flotation is highly specific to each site, due to mineral liberation, water quality and reagent chemistry with the result that flotation rate parameters do not translate well from one part of the circuit to another. Another reason is that the process determining condition of the froth, which controls entrainment, is difficult to model and difficult to scale. The froth is an important part of the concentration process, it is shallow in a conventional cell and small changes in froth condition have significant effects on the concentrate quality.

Column flotation is relatively novel, but its modelling is further advanced than the modelling of conventional flotation cells because

- the froth is deep and stable and its behaviour can be regarded as a constant,
- the pulp zone can be modelled accurately in terms of residence time distribution, (31, 32)

Concentration Processes (2) Gravity Separation

In the case of gravity separation, jigs, dense medium drums and cyclones are now important for the processing of coal and iron ore and are becoming more important for preconcentrating base metal ores. Considerable progress has been made in modelling these processes during the past four years (33, 34).

Metallurgically these processes can be described by partition curves. The model objective is to predict the parameters of the partition curve function which can then be used to calculate the separation performance.

The model of dense medium drums is based on a hydrodynamic calculation of the terminal velocity of each particle size - density interval and correlates its terminal velocity with the observed partition number for a particular drum. The medium density and medium viscosity influence separation performance in different ways but the complication is that medium density also affects the medium viscosity. It has been difficult to distinguish between the effects but they can now be separated by measuring viscosity independently. This makes it
possible to predict the separate influence of medium density and medium viscosity on the metallurgical results.

The model of dense medium cyclones has been difficult to develop because the particles involved are finer and calculations to describe their behaviour are of doubtful value. The model which is now available is based on the observation that the partition curves for different sizes "pivot" about a point in exactly the same way as the reduced efficiency curves for hydrocyclones pivot around the 50% point. The co-ordinates of the pivot point for dense medium cyclones are characteristic of the operation and the equations in the model relate the position of the pivot point to the operating conditions.

Comprehensive plant data on dense medium cyclones so far available are limited because of the cost and physical difficulty in obtaining them but those data that are available indicate that this is a useful model for both low specific gravity and high specific gravity dense medium cyclones.

The concept of the pivot point is opening up a new approach to modelling dense medium cyclones because it provides guide-lines for theoretical developments.

The problem we now have in verifying models is that the size of samples which must be taken in plants to ensure statistical validity is very large, particularly for coarse particles, and the work in obtaining them is expensive. In order to solve this problem there has been a large program on the development of tracers which have a precise size and density, from 50 mm to 0.5 mm in size and from 3.2 to 1.1 in specific gravity units. This development has been successful and has aided modelling of heavy medium cyclones considerably. An important tracer application has been for coal spirals in which the spiral is loaded with tracers down to 63 μm but they have also been used extensively in drums, cyclones and jigs. Modelling of these units is now making rapid progress because of the availability of tracers.

Very good progress has been made in modelling electrostatic and magnetic separators for the processing of heavy mineral sands. This rapid progress has been due in part to the application of well established "laws of physics" for electrical and magnetic aspects. These are now being used in the industry with considerable
benefits for productivity.

**Simulators**

Simulation has reached the point at which mineral process simulators have been produced to make the models readily available to plant and design engineers. This development has been difficult and expensive. Early simulators were cumbersome and inflexible and could really only be used by the inventors but simulators now are much more flexible and easy to use.

The characteristics which they must have are well understood. The data in the simulator must contain full information about the streams and the machines and it must be possible to connect the units in a flow sheet exactly as an engineer would do on a drawing board. It must be possible to control the simulation process and present graphical outputs in a way which is suitable to the user and can accommodate particular preferences of the engineer.

The simulator package should use code which has been written to strict commercial standards and this is very expensive. It is pleasing to observe that many simulators have been developed at centres around the world, for example, Hess & Wiseman (35), Richardson et al (36) and Wiseman and Richardson (37). A few simulators have been successful in the market and these have had a big effect on transferring modelling technology to the mineral processing profession.

The powerful computers available today can be applied to simulation of the dynamics of mineral processing plants. This allows intermediate storage, materials handling equipment and even the process control system to be evaluated by simulation (38).

These dynamic simulators can also be configured as powerful training simulators (39) for operators or students.

**The Future of Simulation**

**Process Models**

In comminution the relationship between energy consumption and breakage is now understood well for particle sizes between 3 and 30 mm. With the increasing importance of fine grinding and the necessity to be able to break large...
particles precisely to minimise energy consumption there is no doubt that this range will be extended considerably during the next decade.

A major deficiency is the absence of generalised models for fine comminution (< 75μm) which incorporate a real breakage function for fine particles. A method for obtaining such a breakage function has not yet been developed.

Discrete element modelling will become a standard technique (e.g. tracking the behaviour of each individual ball and particle). This approach requires powerful computers (now at hand), and accurate single particle breakage functions (also available now). This was a topic for discussion at the SME Conference on Comminution held in Phoenix, Arizona, in February, 1992 and some progress is now being made (40, 41, 42). This work will lead to the design of comminution units to achieve precise size reduction objectives.

Similarly with crushers. It has been shown (22) that the energy consumed can be related accurately to particle breakage characteristics. A crusher model which also includes this relationship and information about the mantle and bowl will lead to improvements in crusher design.

Comminution models of the next decade will be so comprehensive that it will be possible to predict machine performance accurately with any ore when the breakage and viscosity parameters of the ore are known over a wide particle size range. These models will point the way to the design of better machines.

Computational fluid dynamics is being used in a new approach to the modelling of classifiers and this will lead to an accurate 3D description of the behaviour of particles and pockets of fluid within classifiers.

In concentration, the modelling of jigs by discrete element numerical methods, and of spirals by fundamental hydrodynamic modelling, is now well advanced. Tracers to 63μm have been used for spiral modelling, and image analysis is being used in a novel way to automatically count and characterise the fine tracers. With the increasing power of the new generation of desktop computers, these models will become standard tools without the need for simplification. The complexity will become invisible to the user if the simulator is sufficiently clever.
The final objective in the simulation of mineral processing plants is the effective integration of comminution and concentration models through liberation models. It is well known that in flotation there is a strong link between metallurgical results and grain size for specific ores, but the general nature of this link is not yet well understood.

The next step is to develop accurate liberation models and when this is done mineral processing will become established as a quantitative discipline. The main difficulty is that liberation is measured in two dimensions but particles are three dimensional and two dimensional data must be transformed to valid three dimensional information. It has not yet been possible to propose a complete solution to this problem.

The Use of Computers

The world is now well into the computer age and this is having an immense impact on every aspect of technology. The mineral processing industry was slow to make full use of computers because of the technical difficulties in modelling and controlling mineral treatment processes and the cultural difficulties in breaking with the long established traditions for the design and control of plants. But the industry is now eager to make best use of computers and the important questions are:

• what will be the big changes which will occur in the future?
• what preparations should be made to cope with these changes?

The principal forces which will drive the use of computers in mineral processing for simulation and control during the next 10 years are:

• small, low cost, high power computers which can be incorporated in machines of all types so that operations can be optimised and controlled remotely even from long distances
• better measurement techniques and sensors which will lead to smart automated instruments
• the necessity to reduce energy consumption, enforced perhaps by the imposition of a carbon tax
• the demands of the environment.
These forces will have an enormous impact. Advances in electronics will continue to provide greater abilities to measure and compute, and these will accelerate progress in modelling, control and equipment design. Communion in particular will be the target for research because it is such a huge energy consumer. The best way to reduce communion energy is to avoid or at least minimise the amount of breakage which is required. Present processing techniques involve unnecessary breakage of liberated particles because it is only in special circumstances that techniques are not available to recognise these particles and remove them from the process. In some plants magnetic separation has been effective and in a few others flash flotation and ore sorting has been used. However, progress is being made in this area and accurate liberation models will become available within a few years. This will then be used in conjunction with automated sorters with multi-element sensors to recognise and separate the particles which do not require further size reduction.

It will increasingly be recognised in the future that mineral processing is not confined to that group of operations which start with the crushers and end with the filters. Mineral processing is an integral part of the total system which is involved in producing a marketable product from an ore body and modelling will be extended to global optimisation of the entire mining and metallurgical operation, including the environmental effects of mining and processing.

Input for optimum usage of models will be required from many sources and technical disciplines. Linking the models together with a computer network is feasible today but persuading the technical and management disciplines to work together effectively is another problem altogether. Its importance is now being recognised but solving the problem still provides a great challenge for the future.

Comment

Perhaps the most valuable aspect of a good simple model is its worth as an aid to learning. The better a process is understood the more likely it is that the correct decision will be made about what to do next. However, modellers are frequently fascinated by computer power and tend to develop complex models which can be used in hypothetical simulations. These models and simulations have
value but a challenge for the future is to convert them into proven tools to ensure that they can be used on a day-to-day basis by plant engineers. A question to be asked of any model is how accurate is it? If hard evidence is not available the model is of uncertain worth.

What is really needed are models that are conceptually elegant and therefore easy to understand. Modern computers remove the previous requirement for computational simplicity.

The emergence of modelling as an important part of mineral processing technology has implications for the training of mineral process engineers. Tertiary level courses must continue to emphasise process understanding but they must become more computer- and model-based. Through this process understanding they must place strong emphasis on the use of models in real situations, not just on the hypothetical simulations. This is a problem because of the world shortage of engineers who are skilled and experienced in mineral process plant modelling and of the reluctance of the few engineers who are available, to work in universities. It is important that the mineral industry should make a concerted effort to augment the strengths of university departments so that engineers with the skills in modelling and computer usage are available for the industry in the future.

Conclusion

The models developed over the next decade will be more detailed and will require much more input information. This information - especially the detailed characterisation of properties such as breakage and liberation - will be collected by automated equipment.

These models will have a major impact on machine design variables - such as liner configurations, ball size distribution and magnetic and electric field configurations.

The major gains which will occur quickly will relate to the interactions between processes. The combined liberation/breakage model offers an integrated model which extends from the ore body to the separation process. Therefore it should be possible to assess pre-concentration ahead of separation and even to examine alternative operating philosophies.
The models will also have realistic dynamic capabilities. The major impacts of the dynamic models will be on plant and process control system design but they will also be extremely useful in training simulators.

References


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