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Macromolecular mass transfer: a new approach for mining process unit operations

A. P. Yovanovic
MODELO OPERACIONAL - Optimization and Control of Mineral Processing,Belo Horizonte-MG, Brazil

ABSTRACT: In the present work, a new theoretical interpretation for several minerals processing physical unit operations is presented. This interpretation is part of the *Modelo Operacional (Operational Model),* which was developed by the Author as an attempt to establish a new theoretical basis for mineral processing unit operations. The model considers an analogy between the mass transfer chemical processes and some of the ore beneficiation mechanical processes, configuring a new macrophenomenological interpretation for them. The model aims at establishing new theoretical bases for phenomena taking place in operations such as: Comminution (grinding, crushing) and Separation with Mass Concentration (gravity separation, magnetic separation, cyclones, froth flotation, etc.). In the chemical industry, the direct operations yield two phases from a solution of one phase alone for example by means of the application or extraction of heat (the fractionated distillation and the fractionated crystallization belong to this type). In the mineral area, the *comminution* of particles can be interpreted as a direct operation (irreversible, in this case) in analogy with the fractionated distillation operation. The rock is defined as a solution of particles of interest, in solid phase, inside of a gangue solution. The grain is considered as the macromolecular transport basic unit. This grain is initially inserted in the rock, "dissolved" in gangue and, together with the energy application, this grain follows the rock fragments that are being ground, with larger liberation degree.

The indirect operations involve the addition of another substance and consider, among others, the gaseous absorption and the desorption operations. *Concentration operations* are viewed as a phenomenon of macromolecular transport of mass (particles) between phases (froth and slurry phases, for example, in froth flotation). Mechanisms for mass transport and flow of particles between phases as a function of the hydrophobic potential in each phase are discussed. By establishing the so-called Equilibrium Distribution Curve between phases it is possible to calculate macroscopic balances that are related with metallurgical results, which in turn are a function of the Operational Line that is required by the process itself. The number of cleaning stages and their efficiencies can also be determined by simple laboratory scale experiments.

The concepts of the model can be summarized in some specifics principles and 3 mathematical laws that were derived by the author in 1987, and several industrial demonstrations in Brazil operations have been reported at this time, with reagents, energy and investments reductions. The model here proposed shall become a novel tool for researchers, mining engineering students, process engineers and operators who pursue evaluation, optimization and control of several minerals processing unit operations. The present paper illustrates the concepts of the *Modelo Operacional* and the new Macromolecular Mass Transfer approach introducing for mining process unit operations.

1 INTRODUCTION

1.1 *Necessity of a New Mineral Science*

Differently of that it happens in the field of Chemical Engineering unit operations, which are based on transport phenomena of *amount of movement, energy and mass*, the Mechanical Ore Processing units operations presents several difficulties that have not allowed the basic mechanisms description of these processes and, as consequence, they have limited the simulation models study and have made it difficult, also, the attainment of simple correlations between laboratory studies and industrial continuous operation.

The mass transfer operations observed in the chemical industry are molecular and allways tend to equilibrium, assuming steady state conditions based in transport gradient knowledge in any transversal point of the flow, or flows, generally in homogeneous phases. In this way, its modeling, based on transport gradient and kinetic behavior it approaches perfectly to the industrial reality, almost independent of scale relations.

In mineral operations the occurrence mechanisms are very complex; the ore is very changeable, exactly in those properties that affect directly the phenomenon, in the form of entrance disturbes (hardness, liberation, etc.), which normally happen in very low homogeneous phases (rock, pulp) and, in consequence, with difficulties to descrive in mathematical simulations. In grinding operations, for example, the basic comminution phenomenon is a result of three main components: impact, atrittion and abrasion.

Each component presents different efficiency on the ore energy aplication, whose action is executed by diverse types of grinding charge (iron, steel or porcelain balls, iron rods, "pebbles" of the proper ore, etc.) that also depends on the slurry viscosity and other variables.

For that reasons, the size reduction and separation with concentration operations need a new theoretical conception, as illustrated in the Figure 1.

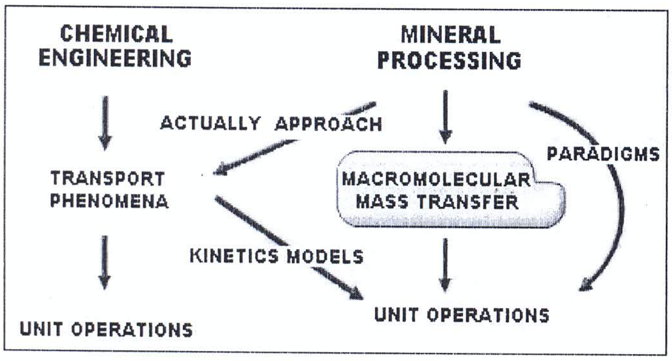

Figure 1. The New Approach of Mineral Science

1.2 *Mineral Processing Phenomena*

The Operational Model considers a new macrophenomenological conception on mineral processing operations study, with new theoretical bases. These operations are: Comminution (grinding, crushing) and Separation with Mass Concentration (flotation, centrifugal separation, magnetic separation, gravimetric separation and others). This approach still considers some auxiliary phenomena inherent to transport in viscous field.

Comminution operations, for example, are macromolecular mass transfer processes (grains), between rock and pulp phases (Yovanovic A.P., 2005).

The model considers an analogy with a chemical mass transfer operation: the fractionary destillation, where some interesting grains are extracted from solid solution (the rock) in fluidized field (slurry), by energy application. This comminution action, applied on rocks with heterogeneous components, as it normally happens, produces a certain separation degree and grain concentration (bigger liberation) that's mean a certain selectivity of milling process and more facilities to separate (concentration) mass through other sequentialy operations (as magnetic separation or flotation). Establishing the Liberation Curve (in function of energy application) it is possible to get macrocospic balances associates to metallurgical results, in accordance with the Operating Point required for the process or defined during the project of the plant. The Energy Application system can be optimized, using the phenomenon selectivity and good operation prctices to allows that material receives the maximum possible from total energy applied to equipment.

Mass Concentration by Froth Flotation, for example, also is interpreted as a macromolecular mass transfer process (particles), between pulp and froth phases (Yovanovic A.P., 2004). The model considers transport mechanisms in each phase and for the flow between them, in accordance with hydrophobic potential that promotes the transport.

Establishing the Distribution Equilibrium Curve between phases it is possible to get macrocospic balances associates to metallurgical results, in accordance with the Operating Line required for the process, or defined during the project of the plant. The Cleaner steps number and its efficiency also can be determined from very simple laboratory experiences.

Engineering students, using these displayed concepts, will be able to interpret the mineral operations of another form. The discipline "Operations with Macromolecular Mass Transfer", will be able to come to be a new support for chemical and mineral area professionals, particularly for these last ones, in this constant search of its particular space inside engineering sciences.

2 MACROMOLECULAR MASS TRANSFER

2.1 *Mass transfer*

In Chemical Engineering field, the mass transfer (molecular) it's understands as the modification of chemical compositions of solutions and mixtures by methods that not necessarily imply in chemical reactions. These operations are drived, habitually, to separation a substance in its components. The molecular mass transfer is the result of a concentration difference or gradient, in way that difunded substance goes from a high concentration place to another one of low concentration (Treybal R.E., 1970).

Some common ore dressing operations can be catalogued as being operations with molecular mass transfer, for example: Solvent Extration, Ionic Exchange using resins or activated coal (for Gold concentration) and Leaching. The great majority of the processes with mass transfer considers a system of two imiscíveis phases, with more than a component, where phases compositions are different, or either, the components are distributed differently between the phases.

In mineral particles such separations can be entirely mechanical, without concentration, as it occurs in some operations, for example: the filtering and the screen classification. But, the separation of particles on the base of its hardness, density or its magnetic properties and also the mass separation by froth flotation, among others, involves changes on chemical composition (grade) between products or separated phases and, as it was said, when including changes in the flows composition we will define these last ones as Operations with Macromolecular Mass Transfer, or Mineral Particles Transfer.

Normally, chemical engineering operations are described under three points of view: a) *kinetic* (Smith, J.M., 1971; Levenspiel, O., 1972), when the operations are involved with chemical reactions; b) by *physical models* introduced by the Transport Phenomena (Bird, R.B. et al, 1964), when are knowed the physical basics principles that regulates the transfer of amount of movement, energy or mass; c) or on the basis of *transfer gradients and equilibrium conditions,* as it happens with mass transfer operations (Treybal R.E., 1970).

Several mineral processing operations, due to lack of a particular phenomena conception, uses chemical engineering concepts to simulate processes and interpret its macrocospic mechanisms. The use of these approach, for mineral operations, has followed, with few exceptions, only the two first lines of work before described:

a) *Kinetics Models*: They needs a phenomenon velocity study and procedures for scale-up, to relate the time measured in batch laboratory test until continuous industrial operations;
b) *Physical Models:* They needs to know the basics physical principles of all the involved subprocesses, in continuity; or either, of the fed flow, the equipment, the energy application, the macromolecular transport in viscous way, entrance noises, etc.

Fatally, none of these boardings has resolved with confidence the basic mineral processes engineering aspects, as scale-up, the optimal equipment sizing, and simulation and optimization, that is widely recognized in the mineral scientific field. The Operational Model (Modelo Operacional) comes to present a new macrophenomenologycal interpretation for mineral processing operations, in general, based in the Macromolecular Mass Transfer, theme that we are suggesting to incorporate in academic curriculum for chemical and mine engineering students.

2.2 *Macromolecular Mass Transfer Operations*

To study this processes we will use the flowsheet presented in Figure 2.

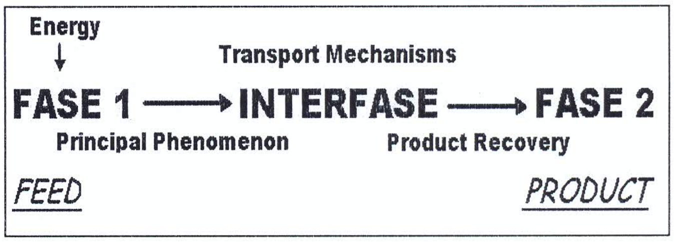

Figure 2. MMT Operations

Comminution operations transfers totality of Feeding mass to the Product phase (separation with concentration does not exist), with lower medium size (homogeneous operations) and also with bigger interest substance liberation (selective operations), depending on process Selectivity.

Separation with Concentration operations generates a main Product: the Concentrate, with a bigger interesting substance concentration, and Tail. A summary of the more important Macromolecular Mass Transfer mineral mechanical operations is presented in Table 1. In this Table are indicated the Part of the Book (Yovanovic A.P., in prep.) and the respective Chapter.

2.3 *Energy*

External energy, applied on original phase (Phase 1), promoving the fundanental phenomenon, with certainly selectivity and kinetic behavior. We call external energy, because particles don't move naturally, by concentration gradient like molecular operations, but in forced way.

Comminution operations used mechanics energy, transferred to the ore by means of atrition or impact plates (crushing), or by means of grinding bodies that transfer this energy (grinding mills) mixturing impact, atrition and abrasion.

In *Separation operations* the energy is used selectively, to activate some particles and force its migration, and can be applied in several forms, depending on the type of separation to be used, as illustrated in Figure 3. More than a type of energy can, occasionally, be used for the same operation, as happens with centrifugal and hydrophobic forces in some types of flotation cells.

Table 1. Organization of MMT Operations

COMMINUTION	SEPARATION
1. Macromolecular Mass Transfer	
Direct Operation Total Mass Transfer	Partial Mass Transfer Products Separation
2. Basic Phenonenon	
Breackeage and Desagregation	Forced Migration of Particles
3. Mass Transfer	
Gradient & Driving Forces Internal Classification	Gradient & Driving Forces Equilibrium Conditions
4. Product Recuperation	
Transport Function	Mass Concentration - Rcm
5. Energy Application	
Mechanical Energy: Energy transfer to impact plates or over grinding bodies	Selective activation energy: Hydrophobic force (Reagents); Centrifugal force; Magnetic Field; Gravity Force.
6. Kinetics of Mineral Processes	
• Fundamental Phenomenon rate • Batch / Continuos Operations • Residence Time and Scale-Up	
7. Selectivity	
• Fundamental Phenomenon Selectivity • Product Recovery Selectivity	
8. Macrophenomenological proprierty and Scale-Up	
• Macrophenomenological Proprierties • First law: Scale-Up	
9. Reactors – Contact Equipment	
• Batch / Continuous Contact • Design	
10. Circuits Rationality	
• 2nd Law: Continuity Equations • Closed Circuits and Extern Classification • Staged Circuits	
11. Mineral Processing Optimization	
• 3rd Law: Optimization Equations • Slurry Rheologycal Study • Operational Optimization • Control System	

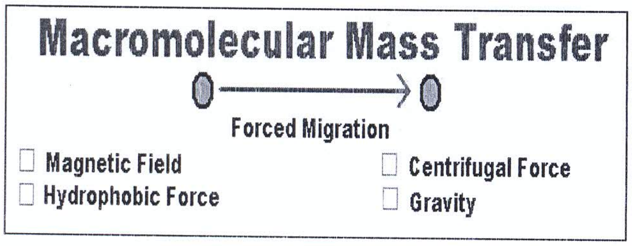

Figure 3. Forced Migration of Particles

Energy excess produces lower Selectivity on the process; the insufficient energy does not allow to reach the desired metallurgic performance. The basic phenomenon, activated by the applied energy, produces the mass transfer from the initial phase. In flotation operations, for example, the hydrophobic energy, propitiated by addition of determined reagent, is dosed in quantitatively form and not in permanent and intensive fiel like happens with the energy apllied in centrifugal, magnetic and gravity force.

2.4 Phases

The basic phases are: Rock, Slurry and Froth (Air), and the combination between them allow to summarize the most important operations. The differences between separation operations: slurry - solid or slurry - slurry, refleates the greater or minor fluidity of the product, for example, in hydrociclone operations, the exit and entrance flows follow the Hydraulical Laws. Thus exactly, exist dry magnetic separation operations, where the initial phase is not really the "slurry". Then, the name of the phase is only approximated, and each operation must defined its own one.

Interphase, in certain operations, corresponds to contact area between the involved phases, where it exists, generally, a movement among both directions of flow, creating a certain equilibrium between particles pushed by activation energy and the return of others of lesser susceptibility respect to used energy. This particle draining, in return to the original phase, is very common in froth flotation operations and in other operations with high intensity energy aplication, like hydrociclones. Some gravitics operations and the magnetic separation capture particles, selectively, from the initial phase, without interface between feeding and product, at least not in interest level for the presented boarding.

2.5 *Basic Phenomenon*

Corresponds to the mechanism of occurrence derived directly from the application of external energy. There are others auxiliaries phenomenons that participate into the process, inherent in the transport of mass in viscous media and in the mechanism of withdrawal of the product, and that influence significantly, as much in quality (Selectivity and Metallurgic Recovery) as in amount (SPLIT of concentrated mass).

In the operations of Separation with Concentration, in general, the *Rcm* (Fed Mass/concentrated Mass) is introduced by the Operational Model as an element of mass recovery of the concentrated product, and corresponds to an operational decision, or of "administration" of the basic phenomenon. In the case of hydrocyclons, we can observe that other mechanisms derived from the hydraulics laws have priority over the attainment of the grain sized cut, that is the main metallurgic objective.

The Selectivity is relates to the form that this operation is executed, as much in the basic phenomenon as in product recovery. In comminution operations, the Selectivity shows the preferential form that the interest substance is set free. In Separation with Concentration operations, a selective operation allows to separate the particles of interest with bigger clearness, allowing high metallurgic recoveries with little amount of concentrated mass.

The external classification corresponds to the closing of the comminution circuits, whose joint performance with the basic phenomenon must be studied in the rationalization of the circuits.

2.6 *Mass Transfer*

In this item, we relate to the equations of description of mass transport, proposed by the Operational Model, based in the fundamental equation illustrated in Figure 2.

Example:

From the metallurgic point of view, for example, for the comminution of homogeneous materials, or when the interest of comminution operation is merely size reduction, the mechanism is summarized in the change of average size between the feeding F until a product P, by means of energy application.

Homogeneus Comminution

$$\underset{FEED}{F} + \text{energy} \rightarrow \underset{PRODUCT}{P}$$

All the operations with TMMM can be expressed in this way, also adding quantitative details that reflect intended metallurgic results, as for example, for the case of the griding of heterogeneous materials, we can express the disaggregation reaction taking into account the selectivity derived from the A substance of interest concentration (x, grade %) in determined grain sized bands, in the operation of selective griding, where the product can later be separated to produce the pre-concentration of the interest ore.

$$R\,x\,x + energy \rightarrow G\,x\,x_g + M\,x\,x_m + F\,x\,x_f$$

Where,

R = *Rock; [R]* = $R \; x \; x$ = concentration of the interesting substance in the Rock

G = *Lumps, with x_g grade;*

M = *Pre-concentrated ore, with x_m grade;*

F = *Fines, with x_f grade.*

From the physical point of view, the speed which the particles abandon the phase rock, that is, when they reach a certain combination, size/liberation/wheight, to be carried out as a product, can be represented such as:

$$N_x = \textit{Transference Coefficient x Area x Gradient}$$

Where N_x is the mass flow (mass/time)

In the case of the comminution, the magnitude of the applied energy, with relation to the break tension or hardness of the material, either for impact, attriction or abrasion, is the Gradient that provides the impelling force (diameter of the mill, size of the ball, for example). The transference coefficient relates to the speed of occurrence of breaking events (speed of rotation of the mill, for example) and to the available time for this application (length of the mill, for example). The contact area has relation with the meeting surface between the particles and the grinding bodies (size of the ball, relation ore/ball, load level of the mill, etc.). In this way, the comminution capacity could be expressed in the following way:

$$N_x\,,\; t/h \;=\; K\;x\;A\;x\;\Delta E$$

2.7 *Product Recovery*

The product recovery is the main form "to manage" the occurrence basic phenomenon, and is a space that belongs, to a greater extent, to the plant operator. This is an important concept introduced by the Operational Model, that has motivated the proper name of the model. Returning to the presented basic scheme in Figure 2, we can observe that the basic phenomenon transfers naturally the activated mass for the applied energy until the interface, that in many cases is only one theoretical figure, but, the mechanism of Product Recovery, commanded by the operator, manages this transference, carrying the product in various forms in quality terms (selectivity) and amount (Mass Concentration Rate - *Rcm).*

The recovery of product possesses an hydraulical component and other only massic component; in many cases a mixture of both mechanisms occurs. For example, in the operation with hydrociclons, the transportation function is hydraulical, and separates the flows according to the hydraulics laws, in way that the mass separation is a consequence of the previous one, motivated by the forced sedimentation in the concentrate flow. Given one determined centrifugal force, as a function of the flow rate and pressure of the fed flow, a change in the size of the APEX, for example, it allows to change the ratio of recovery mass (SPLIT). Also we can increase the ratio of mass for underflow adding more new water in the fed flow.

In the operation of Flotation, the mass recovery possess two components:

1) The simple manipulation of the existing foam layer thickness allows to change the amount of concentrated mass;
2) The water addition to the fed pulp, aiming at to increase the volumetric SPLIT of concentrated flow by the lip of the cell. This situation happens when the manipulation resources of the

discharge floodgate are insufficient, many times because of insufficient number of flotation cells in the bank.

Accommodating the floodgates or valves of discharge of a cell or bank of flotation cells and the air feeding, it is possible "to operate" the circuit and, within certain limitations, to concentrate the mass that ones judges it is convenient. It can be obtained high concentrate grades (with low metallurgic recovery) removing of the cell the superior foam layer - "soft" operation. On the other hand, the circuit can be hurried and a bigger amount of mass can be removed (lesser Rcm), with bigger recovery, even with lesser final concentrate grades - "fast" operation.

In grinding operations, as separation with concentration of the produced mass does not exist, the Transport Function relates to the volumetric withdrawal of all the mass as product, from inside the equipment, by means of water or air flow, depending on the type of used milling. In these cases, the transportation function is fundamental to get determined characteristics in the milling product; a high flow of transport "drags" bigger particles, within certain limits; that is to say, the opportune withdrawal of the product is so important as the proper comminution that happens in the zone of milling inside the mill.

In many operations, the cleaning circuits are also a way to manage the result offered by the basic phenomenon, improving the amount and the final product quality, as for example, the froth cleaning, generated by the basic phenomenon of Flotation. In this last case, the joint applications of the basic phenomenon and the recovery of the product, make this operation to be better defined as Mass Concentration by Froth Flotation, that is, generically: recovery of the product by means of application of one determined basic phenomenon.

3 CONCLUSIONS

The New approach offers a new perspective for the mechanical unit operations of ore processing:

- facilitating its phenomenologic understanding;
- creating a new and trustworthy procedures for the research of mechanisms;
- improving the interpretation of the metallurgic results; e
- allowing a solid advance of engineering in the stages of project, at the way that operations of chemical engineering are normally studied.

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