Magnetic-gravity separation in the simulation modeling paradigm

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Abstract. An interdisciplinary approach to the simulation of magnetic gravity separation is proposed. The approach is based on revealing the laws of motion of mineral particles taking into account their magnetic properties in a computational experiment and establishing the form of an empirical multidimensional function for calculating the deposition rate of aggregated ferromagnetic particles in a multiphase multi-speed process medium. Based on the results, a comparative assessment of the convergence of the obtained deposition kinetics parameters with respect to the practice of applying the classical Stokes formula is given. The possibility of interpreting the fractional separation characteristics of the magnetic-gravity separator using the error function is shown. A method for integrating the simulation model of magnetic-gravity separation into an analytical prototype of the technological enrichment scheme is considered, for which the basic principles of constructing technological schemes for mineral processing are presented and the principles of constructing their simulation models are formulated.

1. Introduction

With the development of methods and practices of mathematical modeling, the need and the possibility of involving modern information technologies in solving problems in the field of mineral processing became obvious. These include: accumulation in specialized databases of information accumulated during many years of research on the geological and mineralogical composition of ore raw materials, physical, chemical and physico-chemical properties of the minerals included in its composition; creation of specialized knowledge bases on methods for processing mineral raw materials with known physical, chemical and physico-chemical properties; improvement of existing technological equipment and the development of new separation apparatus using specialized CAD-CAM-CAE complexes; development of models and creation of automated control systems for technological devices and technological schemes of enrichment enterprises; simulation of technological schemes for determining more efficient modes of production processes [1].

One of the methods for obtaining and using knowledge about physical and technological processes is modeling. The type of mathematical model depends both on the nature of the real object and the tasks of researching the object, the required reliability and accuracy of solving this problem. A special type of mathematical models are simulation models – computer programs that describe the structure and reproduce the behavior of a real system over time, allowing you to obtain detailed statistics on the functioning of the system depending on the input data. These include: empirical (a set of algebraic
equations obtained on the basis of the dependences of internal statistics and the input and output data of the system); phenomenological (a set of algebraic or differential equations obtained from engineering, physical and (or) chemical positions and requiring calibration (material balance model)); fundamental (a set of algebraic or differential equations based on the fundamental laws of physics and chemistry and requiring minimal calibration) [2].

2. Computational Experiment
The essence of magnetic-gravity separation is the separation of ferromagnetic particles by size and magnetic susceptibility in an upward swirling liquid flow with the application of a vertical weakly inhomogeneous constant magnetic field. In the upward flow of water, a fluidized layer of particles of the initial suspension is formed, which differ in size, shape and content of the useful component magnetite, which leads to their distribution in density and magnetic susceptibility. In fluidized beds, solid particles move randomly and at the same time intensively mix, which impairs their segregation and reduces the separation selectivity. When a vertically oriented constant magnetic field is applied, ferromagnetic particles of the fluidized bed form vertically oriented chains—ferromagnetic aggregates that freeze the chaotic motion of the particles of the layer. The composition of ferromagnetic aggregates includes particles for which the interaction force of the magnetic moments of the particles exceeds the strength of their hydrodynamic resistance [3, 4].

The height of the magnetically stabilized fluidized bed of suspension particles depends on the difference in the mass flow of the feed of the initial suspension, wash water, drain and separator concentrate. Particles that are part of the ferromagnetic aggregates are discharged into the concentrator of the separator, the rest go into the drain.

Technological suspensions of enrichment plants are a mixture of finely ground mineral particles of various size fractions with water. Such a substance cannot be assigned to the class of liquids, gases, or solid deformable bodies and is defined as a heterogeneous medium. The separation of components of technological suspensions in enrichment (including magneto-gravitational) devices can be described using the mathematical apparatus of a multiphase multi-speed continuum (MMC), where the medium is considered as a superposition of interpenetrating continua, each of which belongs to its phase. Moreover, at each point in the medium, one can determine $N$ densities, $N$ velocities, etc., as well as the parameters characterizing the medium as a whole. Since the parameters of the phases and the whole medium vary in space and time, the substantial derivatives associated with the movement of the $i$-th phase and with the movement of the medium as a whole:

$$\frac{d_i}{dt} = \frac{\partial}{\partial t} + v_i \nabla; \quad \frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v} \nabla.$$

With this in mind, the MMC theory is implemented with the balance relations of mass, momentum, and energy for each of the phases. The mass conservation equation for the $i$-th phase:

$$\frac{\partial \rho_i}{\partial t} + \rho_i v_i \nabla = \sum_{j=1}^{N} J_{ji},$$

where $J_{ji}$ characterizes the mass transfer intensity from the $j$-th to the $i$-th phase. The mass conservation equation for the whole medium:

$$\frac{\partial \rho}{\partial t} + \rho \mathbf{v} \nabla = 0.$$

Momentum conservation equation for the $i$-th phase:

$$\rho_i \frac{dv_i}{dt} = \nabla^{k} \sigma^{k} + \rho_i g_i + \sum_{j=1}^{N} (P_{ji} - J_{ji} v_i),$$

where $P_{ji}$ is the intensity of momentum exchange between the $j$-th and $i$-th phases, $k$ is the upper index indicating the number of the Cartesian coordinate, $\sigma$ is the surface force tensor, $g$ is the mass force vector relating to the medium as a whole.
The momentum conservation equation for the entire medium:

\[ \sigma = \sum_{i=1}^{N} \sigma_i, \quad \rho g = \sum_{i=1}^{N} \rho_i g_i. \]

The momentum conservation equation for the entire medium:

\[ \rho \frac{d\mathbf{v}}{dt} = \nabla^k \sigma^k + \rho \mathbf{g} - \sum_{i=1}^{N} \nabla^k (\rho_i \omega_i^k \mathbf{w}), \quad (4) \]

where \( \omega_i \) is the radial velocity of the \( i \)-the phase at the interface and \( \mathbf{w} \) is the velocity of relative motion of phases. The energy conservation equation for the \( i \)-th phase:

\[ \rho_i \frac{d}{dt} \left( u_i + \frac{v_i^2}{2} \right) = \nabla (c_i - q_i) + \rho_i g_i v_i + \]
\[ + \sum_{j=1}^{N} \left[ E_{ji} - \frac{1}{2} \left( u_i + \frac{v_i^2}{2} \right) \right], \quad (5) \]

where \( u_i \) is the internal energy of the \( i \)-the phase, \( v_i^2/2 \) is the kinetic energy of the \( i \)-th phase, \( c_i \) is the work of external forces, \( q_i \) is heat flux, \( E_{ji} \) is the energy exchange intensity between the \( j \)-th and \( i \)-the phases. The energy conservation equation for the whole environment:

\[ \rho \frac{dE}{dt} + \sum_{i=1}^{N} \nabla^k (\rho_i \omega_i^k E_i) = \nabla^k (c_i^k - q_i^k) + \rho g^k v^k + \sum_{i=1}^{N} \rho_i g_i^k \omega_i^k. \quad (6) \]

Balance relations (1)–(6) show that the fundamental laws of conservation of mass, momentum, and energy, expressed analytically in the theory of molecular magnetic complexes, correspond to the equations of motion of the phases of a heterogeneous medium in the Euler approach. Moreover, since the phases of a heterogeneous medium, filling its entire volume, infinitely penetrate each other and retain their instantaneous volume, the necessary refinement and addition of the balance ratios is the introduction of the volume fraction of the phase. This value is a function of space and time, the algebraic sum of all volume fractions of the medium is equal to unity.

Thus, the mathematical apparatus of the MMC is ideally suited for simulating the motion of multiphase heterogeneous media in which the separation of mineral components during magnetic-gravity separation takes place and describes: representing a single technological mineral suspension in the form of a set of separate discrete fractions, each of which occupies its own volume fraction; fractions of particles with different densities, fineness and magnetic susceptibility within a single apparatus volume; change in velocities and concentrations of different fractions under forces of different physical nature, concentration, condensation and removal from the apparatus separating the products [5, 6].

The computer model that allows obtaining the values of the parameters of the magnetic-gravity separator was developed in the ANSYS Fluent software package. Figure 1 shows the geometry of the model.

The design includes a cylinder-conical housing with a drain device and a concentrate outlet pipe. A device combining the functions of supplying the initial suspension, supplying washing water and swirling it is placed in the apparatus body. Outside, the housing is surrounded by an electromagnetic solenoid, which creates a vertically directed weakly inhomogeneous magnetic field.

For the computer model, a source feeding model was developed (Table 1), which was based on a rough magnetite concentrate containing 67.84 % of total iron. In addition to magnetite particles, the initial feed included intergrowths of magnetite with weakly magnetic minerals of various density and size. In addition, slimy particles of magnetite and a non-magnetic mineral with a particle size of 0.15e-4 m were included in the initial feed. In total, 16 different particle fractions were formed. The feed rate was 0.5 kg/s or 1800 kg/h.
Figure 1. The geometry of the model of the magnetic gravity separator.

Computational experiments with the model made it possible to study the hydrodynamics of separation processes occurring in the apparatus. Figure 2 shows the distribution of volume concentrations of the liquid and solid phases of the suspension on a vertical section of the apparatus. It can be seen that solid particles form a magnetically stabilized layer with a pronounced boundary, which makes gravitational vibrations.

The analysis of the simulation results of the separation process of the components of the initial suspension enabled obtaining the technological characteristics of the magnetic-gravity separator. The total mass of solid particles of the fluidized bed amounted to 3623.6 kg. Table 2 shows the mass and mass content of individual fractions in the volume of the apparatus. The separator concentrate contains 70.6% of total iron.

Table 1. Initial feed parameters

| Particle fraction size [m] | 1.2e-4 | 0.85e-4 | 0.6e-4 | 0.4e-4 | 0.15e-4 |
|---------------------------|--------|---------|--------|--------|--------|
| Magnetite mass content [%] | 100    | 90      | 80     | 70     | 30     | 20     | 10     | 100    | 20     | 10     | 100    | 10     | 100    | 10     | 100    | 10     | 100    | 0      |
| Fraction particles density [kg/m³] | 5100   | 4855    | 4610   | 4365   | 3385   | 3140   | 2895   | 5100   | 3140   | 2895   | 5100   | 2895   | 5100   | 2895   | 5100   | 2650   |
| Fraction mass fraction in feed | 0.157  | 0.018   | 0.014  | 0.01   | 0.002  | 0.004  | 0.006  | 0.158  | 0.004  | 0.014  | 0.195  | 0.01   | 0.19  | 0.0198 | 0.006  |

Table 2. Parameters of fractions in the concentrate

| Particle fraction size [m] | 1.2e-4 | 0.85e-4 | 0.6e-4 | 0.4e-4 | 0.15e-4 |
|---------------------------|--------|---------|--------|--------|--------|
| Magnetite mass content [%] | 100    | 90      | 80     | 70     | 30     | 20     | 10     | 100    | 20     | 10     | 100    | 10     | 100    | 10     | 100    | 10     | 100    | 0      |
| Fraction mass in separator magnetic fraction [kg] | 663.62 | 298.53  | 164.14 | 50.55  | 0.005  | 0.008  | 0.104  | 947.79 | 0.007  | 0.024  | 796.19 | 0.015  | 442.41 | 0.016  | 259.98 | 0.01   |
| Magnetic fraction mass content in separator volume | 0.183  | 0.182   | 0.045  | 0.014  | ~0    | ~0     | ~0    | ~0     | ~0    | ~0     | 0.262  | ~0     | 0.122 | ~0     | 0.072  | ~0    |

Magnetic-gravity separation is a promising separation process that allows selectively separating the components of ferromagnetic suspensions with similar magnetic and hydrodynamic properties, which ensures its use to control the quality of the concentrate, to enrich the crude magnetite concentrate and to obtain products suitable for nonblast-furnace steel production.
3. Analytical aspect of transition to simulation model

Analysis of the simulation results showed that in the model of the apparatus there are three zones differing in their hydrodynamic characteristics: a downward flow zone, starting from the feed device of the initial suspension and ending in the cone of the device for swirling the upward flow of water; a zone of upward fluid flow, starting in the cone of the swirling device and extending in the wall region to the device for draining non-magnetic fractions; a turbulence zone located in a volume from a concentrate discharge device to a fluid swirling device. The turbulence zone is characterized by a sharp change in the direction of fluid movement, which contributes to a better washing of the magnetic fractions of the suspension moving in the direction of the concentrate discharge device.

In the axial zone of the downward flow, the rotational speeds are close to zero. Hydrodynamic zoning affects the distribution of concentrations of magnetic and non-magnetic fractions of the suspension in the volume of the apparatus model. In the axial region, from the initial slurry feeding device to the washing water swirling device, there is a downward flow of the initial suspension that enters the separation zone, which coincides geographically with the zone of existence of the magnetically stabilized fluidized bed. In the separation zone, non-magnetic fractions are carried upstream into the discharge of the apparatus, while fractions with high magnetic susceptibility structurize the magnetically stabilized layer and are deposited in the turbulent zone, where they undergo additional washing from non-magnetic fractions. The magnitude of the interparticle force in the dipole–dipole interaction depends on the angle of inclination of the ferromagnetic aggregate in the shear flow. In the turbulence zone, complete destruction of the ferromagnetic aggregates and the removal of thin non-magnetic fractions into the near-wall zone of the upward flow are observed.

Figure 3 shows the distribution of the downward velocity of the magnetic fraction flow.
The increased viscosity of the ferromagnetic suspension in the region of existence of the magnetically stabilized layer leads to a decrease in the rotation speed of the washing liquid. Thus, a decrease in the fluid rotation rates leads to an increase in the magnetic force of the interparticle interaction with an increase in the height of the separation space. In the area of the drain device, the angle of deviation of the ferromagnetic unit from the vertical is close to zero. The strength of interparticle interaction in this area is maximum. At the same time, the upper section of the solenoid is at the level of the feed device of the initial product. In the center of the solenoid is a region of a uniform field. In the area of the drainage device, the magnetic field has a significant negative gradient, which, along with the interparticle magnetic force, creates an additional mass magnetic force that is aligned with the gravitational acceleration vector. The maximum values of interparticle and gradient magnetic forces prevent the removal of fine fractions of ferromagnetic particles, thereby increasing the separation selectivity in the apparatus.

Thus, as a result of a computational experiment, not only hydrodynamic, but also technological characteristics of the process were obtained, which made it possible to establish the form of the empirical function of the fractional separation characteristic:

\[ \varepsilon(\rho) = \frac{1 + \text{th} \left( \frac{\rho \cdot (1000 + \frac{v}{1800} \cdot d^2)}{5.6 \cdot 10^{-6} \cdot H^2 - 0.133 \cdot H + 900} \right)}{2} \] (7)

where \( \text{th} \) is the function of hyperbolic tangent, \( \rho \) is the mineral density, \( v \) is the velocity of upward liquid flow, \( d \) is the particle diameter, \( H \) is the magnetic field strength.

The applicability of function (7) is limited by the absence of taking into account the deposition rate of aggregated ferromagnetic particles. The classical Stokes formula, in turn, does not allow establishing the dependence of the particle deposition rate on the intensity of an external magnetic field. Therefore, before using the mathematical editor Mathcad and then during the computational experiment, necessary clarifying analytical regularity needed to be identified. As a result, the following equation was derived:

\[ V(d) = d^2 + (A + BC + SC^{3/2}H^2), \] (8)

where \( V \) is deposition rate of a ferromagnetic particle in an upward fluid flow in a weakly inhomogeneous magnetic field, \( m/s; d \) is the particle diameter, \( m; C \) is the magnetite concentration in a particle, fractions of unit; \( H \) is the magnetic field strength, \( A/m; A, B, S \) are empirical coefficients depending on the magnetic susceptibility of the mineral, the degree of magnetization of ferromagnetic particles, the gradients of the magnetic field in the apparatus, the solid content in the original pulp, the geometric dimensions of the apparatus.

Comparative testing of the obtained formula for estimating the deposition rate of particles of binary ore of ferruginous quartzites was carried out for materials with pure quartz densities \( \rho_1 = 2650 \text{ kg/m}^3 \) and a magnetite content of \( 10^{-5} \) and for materials with magnetite densities \( \rho_2 = 5100 \text{ kg/m}^3 \) in the absence and presence of magnetic fields. As a result of testing, the data presented in the form of graphs in Figure 4 were obtained.

The deposition rate of aggregated ferromagnetic particles in a weak inhomogeneous magnetic field and an upward flow of water determines the entering of particles into the concentrate or into the separator discharge without taking into account the probabilistic characteristics of the separation process.

When the separator is working, elongated magnetite aggregates are formed. In this case, their drag coefficient changes when moving in water, the magnitude of which depends on the applied field. Magnetite aggregates are precipitated, the particles of suspension are condensed and discharged into the separator concentrate.

At a given feed rate of the wash water, the particles of the initial suspension differ in velocities relative to the apparatus body. Particles of small diameter and with a low concentration of magnetite
and, therefore, having a lower deposition rate are discharged into the separator drain. Obviously, the relative particle deposition rate can be defined as

\[ V_R = V(d) - V_{H_2O}. \]

At the same time, it is also obvious that there is a certain fraction of particles of magnetite suspension, which has a zero deposition rate and, therefore, is equally likely to be extracted both in the concentrate and in the discharge of the separator. To determine its size, one can use the following equation:

\[ d_{50} = \sqrt[3]{\frac{V_{H_2O}}{A + BC + SC^{3/2}H^2}}. \]

*Figure 4.* a) Dependence of deposition rates of particles with a density \( \rho_1 \) in water on their size, calculated by eq. (8), \( V \) (d), and according to the Stokes formula \( V_S \); b) Dependence of the deposition rates of particles with a density \( \rho_2 \) in water on their size; c) Dependence of the deposition rates of particles with a density \( \rho_2 \) in water when applying a uniform magnetic field \( H = 4000 \, \text{A/m} \) on their size.

This can be the basis for the principle of forming the separation characteristics of the separator, taking into account the deposition rates of aggregated ferromagnetic particles. The separation characteristic function gives the probability of extracting particles of a fraction of a certain diameter and with a certain concentration of magnetite into the separator concentrate. It is possible to determine the probability of removing the fraction of particles in the concentrate, while using the normal distribution function with a known mathematical expectation and a given variance—the function of the “probability integral”

\[ E(d, c, H, V_{H_2O}) = \frac{\text{erf}(Q(d - d_{50})) + 1}{2}, \]

where \( \text{erf}(d) \) is the function of the probability integral; \( d_{50} \) is the diameter of the suspension particle fraction that is equally likely to be extracted into the discharge or the separator concentrate; \( c \) is magnetite concentration in a particle; \( H \) is the magnetic field strength; \( V_{H_2O} \) is the washing water feeding rate.
For example, in Figure 5, we give the separation characteristic of one of the narrow fraction of particles

![Figure 5](image.png)

**Figure 5.** Separation characteristic of a magnetic-gravity separator for a fraction of suspension particles with a magnetite concentration of $C = 0.5$ with controlling parameters of $H = 4000$ A/m, $V_{H2O} = 0.012$ m/s

4. **Conclusion**

The decisive influence on the efficiency of technological schemes for mineral enrichment is provided by their structure. Existing empirical methods for developing and monitoring the structure of technological schemes, especially in cases where a large number of types and units of technological equipment are used, do not allow reaching the expected result in terms of achieving the specified values of the criteria for optimizing separation processes. The relevance of this problem is exacerbated by the development of objectively manifest tendencies of involvement in the processing of depleted ores and the intensification of competition in the world markets of mineral resources [7, 8].

When developing models of structurally complex technological schemes for mineral processing, the principle of block structure is applied [9–11]. The allocation of blocks is made taking into account the separation of the model into stages and modes of operation. The division of the model into blocks, decomposition, can be carried out on the basis of the required degree of detail of the description of the structure, the visibility of the display of the features of functioning in it. In this regard, we can distinguish two basic principles for constructing technological schemes for mineral processing: cyclical and staged. They allow for functional (by function), component (by type of elements) and structural (by type of relations between elements) decomposition of the technological scheme, the minimum component (DMC) of which is the complex of the stage of size reduction and separation, which has, as a rule, one entrance and three outputs (Figure 6).

![Figure 6](image.png)

**Figure 6.** Minimum component of the technological scheme decomposition. a) direct-flow component; b) with reverse flow at the stage of particle size reduction
The inputs and outputs of the DMC in the technological scheme are connected by material flows. Such a construction of a technological scheme in the form of series and parallel connected complexes allows establishing uniform input and output qualitative and quantitative technical and technological parameters based on the revealed patterns of their functioning.

The structure of any technological scheme of mineral processing is based on the possibility of using one or another separation process in it, based on the contrast of the physical properties ($\xi$) of solid particles. Therefore, it is the separation property, and not the content of the valuable component ($\beta$), that is responsible for the particle getting into the concentrate stream or, conversely, into the tail stream of the technological operation. Given the mass and variety of intergrowth forms of particles involved in the operation of mineral processing, direct and indirect, internal and external force factors, the separation result, expressed in numerical values of technological indicators, is probabilistic. Due to the fact that the intensity of the manifestation of the separation property varies in the aggregate of solid particles in a wide range $[\xi_{\text{min}}, \xi_{\text{max}}]$, it can be divided into smaller ranges $[\xi_{i}, \xi_{i+1}]$, while in the limit $[\xi_{i}, \xi_{i+1} + d\xi]$, referred to as fractions or, accordingly, elementary fractions. Then, it is obvious that if the $\xi$ property, which varies in the range $[\xi_{\text{min}}, \xi_{\text{max}}]$, is inherent in the entire set of solid particles, then the range $[\xi_{i}, \xi_{i+1} + d\xi]$ will be inherent for every elementary fraction.

In this regard, the integration of the simulation model into an analytical prototype of the technological scheme is carried out by filling in the information structure of their direct and feedback links in a single, for each specific chain of technological ore-concentrate processing, system for monitoring the current material composition of mineral raw materials and products of its processing [12]. Therefore, as in the case with the construction of the technological scheme, the concept of constructing simulation models of mineral processing processes assumes the existence of principles that include the principle of universality of the model infrastructure, which consists in the fact that when building a digital model of the technological scheme of mineral processing, only coupled simulation models of processing processes can be used. In this context, the processing processes include preparatory, separation and auxiliary processes. Thus, simulation models should have a certain universality of the infrastructure; their coupling should be done by ensuring that the content and capacity of the information in the communication channels between each previous simulation model and the subsequent one are consistent. The correspondence between the type of mineral raw materials and the equipment used is determined by the target useful component of the mineral raw material and the method for enriching the useful product (concentrate). One should also implement the principle of unification of the modeling object, which, in turn, consists in the fact that the simulation model of the processing process is the result of a statistical interpretation of the logical and mathematical description of a series of physical and (or) computational experiments reproduced in predetermined conditions, one of which is the inverse of the forecast and refinement of the model.

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