

MAGNETIC SEPARATION OF THE SECOND KIND: MAGNETOGRAVIMETRIC, MAGNETOHYDROSTATIC, AND MAGNETOHYDRODYNAMIC SEPARATIONS

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ABSTRACT

Magnetogravimetric, magnetohydrostatic, and magnetohydrodynamic separation techniques can be classified as magnetic separations of the second kind. Magnetic separation of the first kind (ordinary magnetic separation) relies on the inherent magnetic susceptibility of the material to be separated. When the medium of separation rather than the separated particles is made magnetizable, a new system of gravity separations can result (magnetic separation of the second kind). In magnetogravimetry, a colloidal solution of a ferro- or ferrimagnetic substance (magnetic fluid) acts as the separation medium. Magnetohydrostatic separations are conducted in an aqueous solution (or melt) of a strongly paramagnetic salt. Magnetohydrodynamics applies the Faraday effect (mutual orthogonality of the force thrust, electric, and magnetic fields) on suspended conducting minerals in an electrolytic solution placed in crossed electric and magnetic fields. The first technique was pioneered mainly in the United States, while the last two techniques were pioneered by Bunin and Andres in the Soviet Union and introduced to the West by Andres. The principles underlying the three separation techniques will be discussed.

INTRODUCTION

Mining and metallurgical sorting practice has so far adopted classification, flotation, and magnetic separation as its principal tools. Because it is far easier to mix than to unmix, separation is necessarily an energy-consuming step. This follows from the second law of thermodynamics and the principal of Boltzmann ($S = k \ln W$), which relates probability, W (or disorder in the mixed state) to entropy, S , and conversely relates information (or the ordered state) to negentropy¹ or "negative entropy." Because the entropy of the system (separator + separated materials) must remain on the rise, a positive change in entropy would occur in other parts of the system to offset the negative entropy change of unmixing. Mineral and material separations must, therefore, adapt to new technologies to increase separation efficiencies, lower their costs, and broaden their scopes.

Only a few minerals are commonly separated magnetically. Ordinary magnetic separation depends on the inherent magnetic susceptibility of the material to be separated. The distinction between magnetic and nonmagnetic minerals is quite arbitrary and depends on the types of magnets, field strength, and field gradients employed. In the iron ore industry, a magnetic fraction refers to iron oxides that are recoverable by a drum-type magnetic separator having a field intensity of 3 kOe at its surface. This would attract magnetite (Fe_3O_4), which is technically ferrimagnetic, but not hematite ($\alpha\text{-Fe}_2\text{O}_3$), although the latter compound is technically a weak ferromagnet with canted spins² and can be attracted to higher field gradients as encountered in high intensity magnetic separations. The magnetic ordering of spins and the resulting cooperative phenomena² that lead to the ferro-, ferri-, and antiferromagnetic states are illustrated in Fig. 1. In this figure, metallic iron would be represented by case (b), hematite by case (g), magnetite and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) by case (d), and wustite (FeO) by case (c). In this paper, the term "magnetic separation of the first kind" will be used to describe those separations in air or in water that rely on the magnetic susceptibility of the separated products.

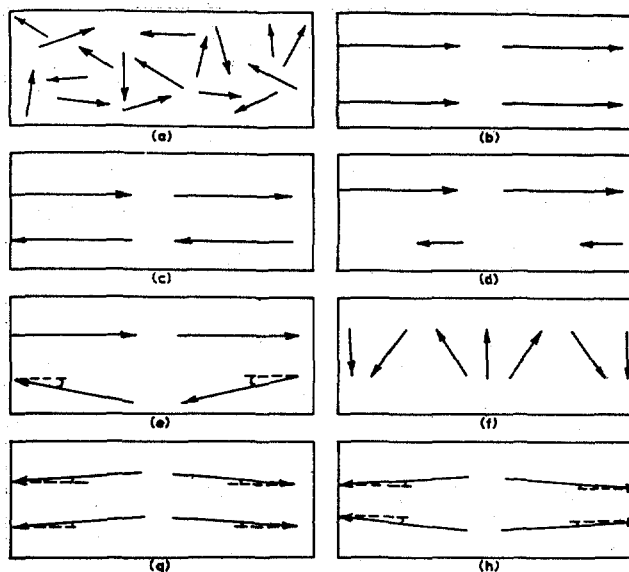


Fig. 1. Schematic representation of spin arrangements:

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|---|---|
| (a) disordered paramagnetic state | (b) parallel spins: ferromagnetism |
| (c) antiparallel spins: Néel type antiferromagnetism | (d) uncompensated antiparallel spins: Néel type ferrimagnetism |
| (e) triangular antiparallel spins: Yafet-Kittel type ferrimagnetism | (f) helical spiral structures: compensated antiferromagnetic or uncompensated ferrimagnetic |
| (g) canted spin Dzyaloshinskii type weak ferromagnets | (h) canted spins compensated antiferromagnets: hidden canting. |

Fig. 1. Order-disorder phenomena in magnetic substances (Reference 2).

Magnetic Separation of the Second Kind

Rather than depend on the inherent magnetism of the particles to be separated, a new approach that magnetizes the medium itself will separate nonmagnetic particles of a broad density spectrum. To distinguish it from ordinary magnetic separation, this type of separation will be labeled as "magnetic separation of the second kind." This new type of separation involves a sink-float segregation of inherently nonmagnetic particles in a medium which is magnetizable and remains fluid in a magnetic field, and the apparent density of which can be adjusted by applying a magnetic field gradient. In this manner, the effective buoyancy force acting on suspended particles can be varied over a wide range. Separations depending on this principle have been conducted in both the Soviet Union and the United States since the mid-sixties. At the Bureau of Mines of the U.S. Department of the Interior, a colloidal solution of a ferro- or ferrimagnetic substance (henceforth called magnetic fluid) acts as the separation medium. This has led to the development of magnetogravimetric (MGM) separations because the object is at equilibrium from both a magnetic force and the gravity force. Magnetohydrostatic (MHS) separations are conducted in an aqueous solution (or melt) of a strongly paramagnetic salt (henceforth called magnetic liquid). For purposes of this discussion, a magnetic liquid represents a true solution, while a magnetic fluid represents a colloidal solution, both being magnetizable by

a magnetic field. Researchers at the Bureau of Mines were aware through the Chemical Abstracts of the American Chemical Society of the use of solutions of manganese chloride or sulfate in MHS separations by the Soviet school of G. Bunin, U. Andres and others^{3,4,5,6}. In 1975, articles by Andres on MHS separations began to appear in Western journals. The same authors have also conducted MHD separations by utilizing the thrust force created in an electrolyte placed in crossed electric and magnetic fields. Akopov⁷ et al used MHD separations to obtain superpure coal concentrates of very low ash content.

Both MGM and MHS separations operate on the same principle, namely that of creating a magnetic levitation force within a pool of a magnetic fluid in the former case, or a magnetic liquid in the latter case. In this review, the process names given by the respective authors will be preserved, although some may prefer to lump the two techniques under one suitable title.

The objective of the present paper is to review the three techniques of MGM, MHS, and MHD which constitute magnetic separations of the second kind. A brief discussion of magnetic levitation will be first presented before proceeding to the techniques and procedures adopted.

The Magnetic Levitation Force

A mathematical expression for the magnetically induced buoyant levitation force created in a pool of magnetic colloid placed in an inhomogeneous magnetic field can be derived from simple magnetostatic theories. The potential energy, U , of a magnetic dipole of volume V and moment $\vec{\gamma} = \mu V$, in a magnetic field, $\vec{H}$, is given⁸ by the negative of the dot product of the two vectors; thus

$$U = - \vec{\gamma} \cdot \vec{H} = - \gamma H \cos \theta = - \mu HV \cos \theta \quad (1)$$

where θ is the angle between the two vectors $\vec{\gamma}$ and $\vec{H}$, γ and H are their magnitudes, respectively, and μ is the volume averaged magnetic moment. If a small volume of magnetic fluid is placed in an inhomogeneous magnetic field such that the lowest value of the ambient field saturates the fluid magnetization, then equation 1 becomes applicable since μ is a constant independent of H . Because the fluid magnetizes along the local field direction, $\theta = 0$, and

$$U = - \mu HV. \quad (2)$$

Also, force is defined as the negative space rate of change of the potential function. Hence the magnetic force per unit fluid volume, $\vec{f}_m$, will be given by the negative gradient of the scalar function U/V :

$$\vec{f}_m = - \frac{1}{V} \text{grad } U = \mu \text{grad } H. \quad (3)$$

The assumption made is that the magnetic moment, μ , per unit volume of the fluid is independent of the spatial coordinates within the magnetic field, and that it is relatively constant independent of H . The force $\vec{f}_m$ is in the same direction of the vector quantity "grad H " and tends to move the fluid towards the magnet.

In a two-phase system of large magnetic particles in a nonmagnetic fluid, the particles alone will move in the direction of maximum field (separation of the first kind). By contrast, a magnetic colloid is a one-phase system and will be attracted as one unit to the magnet. The particles essentially impart their magnetic character to the continuous phase, both phases becoming magnetically indistinguishable in a true colloid. Because the fluid is constrained in its position by being confined in an immovable vessel, a reactionary force of equal and opposite sign will be created within the fluid and will manifest itself on immersed objects. This follows from Newton's third law of motion, "to

every action there is always opposed an equal reaction." A magnetic levitation force $\vec{f}_l$ will therefore be exerted per unit volume of an immersed body in a magnetic fluid placed in an inhomogeneous magnetic field. This force will be equal - and opposite in direction - to $\vec{f}_m$, and per unit volume of the immersed body, will be given by

$$\vec{f}_l = - \mu \text{grad } H = - \frac{M}{4\pi} \text{grad } H \quad (4)$$

where M is the fluid magnetization.

In this work, the fluid magnetization is represented by M , while the symbol μ represents the magnetic moment per unit volume, sometimes called the intensity of magnetization. The two symbols are interrelated⁹ by $M = 4\pi \mu$. The emu unit of both quantities is the same; namely, erg per Oe·cc, or gauss.

The other hydrodynamic force exerted per unit volume of an immersed object of density, ρ' , is the Archimedes buoyancy force, which is equal to the weight of the fluid displaced by unit volume of the solid, ρg , where ρ is the fluid density. Because the true body weight is $\rho'g$ per unit volume, the magnitude of the gravitational force, f_g , on the immersed object is $(\rho' - \rho)g$, and the gravitational force vector is

$$\vec{f}_g = (\rho' - \rho)g\vec{h} \quad (5)$$

where $\vec{h}$ is the unit vector in the vertical direction. The net force per unit volume, $\vec{f}$, exerted on the immersed body is the vectorial sum of the magnetic levitation force and the gravitational force and is given by

$$\vec{f} = \vec{f}_g + \vec{f}_l = (\rho' - \rho)g\vec{h} - \mu \text{grad } H. \quad (6)$$

Since "grad H " can be impressed upon the system in any desired direction, it is possible to overcome gravity by orienting the field gradient in a direction opposite to $\vec{h}$. This means that a nonuniform magnetic field whose magnitude decreases in an upward direction, and hence whose gradient vector is directed downward, will tend to lift an immersed body upward. Similar relationships were rigorously derived by Epstein¹⁰ for an electrostatic field and by Rosensweig¹¹ for a magnetic field. Upon integrating the surface and volume forces experienced by an immersed body, and differentiating a modified Bernoulli equation to evaluate the pressure gradient, Rosensweig¹¹ derived a mathematical expression for the buoyant levitation force of the first kind.

The magnetization curves of magnetic colloids did not exhibit the hysteresis loop expected for ferrimagnetics or ferromagnetics, but produced instead a symmetrical sigmoid curve¹² about the origin (Fig. 2). Methods of preparation of ferrofluids, their unusual properties, and their vast applications were summarized in a recent article.¹³

The photograph in Fig. 3 depicts a magnetic fluid sample of about 0.8 gram per ml density containing water and some alumina beads with a density of 3.8 g/cm³. Naturally, these constituents will sink in the magnetic fluid. Figure 4 illustrates the creation of a magnetic levitation force, sometimes called an anti-gravity force, in a magnetic fluid/magnetic field combination. In this figure, the same container shown in Fig. 3 is placed on a laboratory horseshoe magnet whereby both the water and alumina are floated on top of the fluid. Thus, in a magnetic field the fluid appears to have a density greater than 3.8 g/ml. With fairly concentrated fluids and higher magnetic field gradients, platinum wires were levitated to the surface of a kerosene-base magnetic fluid, and the fluid thereby exhibited an apparent density of at least 21.5 g/ml. The apparent increase in density of these fluids with increasing magnetic field gradient suggests their utilization as substitutes for heavy liquids in mineral

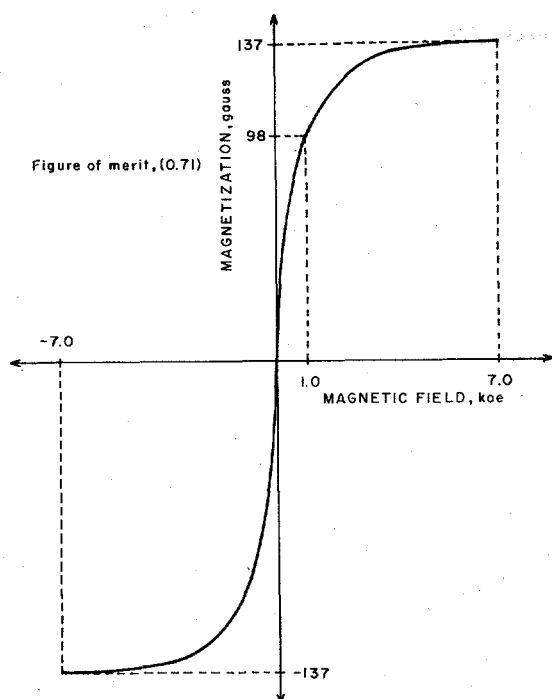


Fig. 2. Hysteresisless magnetization curve typical of superparamagnetic colloids.



Fig. 3. Alumina beads and water submerged in magnetic fluid.

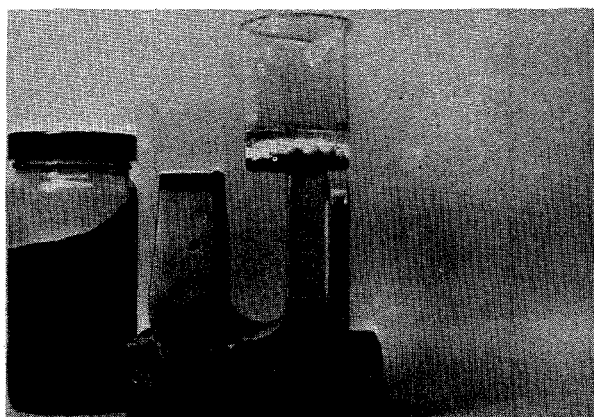


Fig. 4. Magnetic field gradient floats alumina beads and water on a magnetic fluid of lower density.

separation. Because the fluid's apparent density can be varied as desired by varying the magnetic field, one should be able to selectively separate particles according to their density spectrum in a manner similar to the Cartesian diver.

MAGNETOGRVIMETRIC SEPARATIONS

Theory¹¹ predicts that the magnetic levitation force per unit volume of an immersed object is equal to the product of the fluid magnetization by the magnitude of the magnetic field gradient. One can, therefore, increase the levitating force either by increasing the fluid magnetization (stronger magnetic fluid) or by increasing the field gradient, or both.

Modern magnetic fluids can easily provide transient zero-gravity conditions when placed in inhomogeneous magnetic fields. Kaiser¹⁴ used an on-off magnetic field for the separation of particles (positioned at different elevations in the fluid) according to density, while Rosensweig¹⁵ employed the fluid as a horizontal sieve. Both methods utilized the magnetic levitation force created within the fluid in an inhomogeneous magnetic field as an antigravity force, i.e., the former force was always oriented in the vertical direction as illustrated in Figs. 3 and 4.

Figure 5 shows the principles of a continuous magnetogravimetric separation technique that orients the magnetic reactionary force in a nonvertical direction.¹⁶ This approach allows continuous separation of materials by means of a single magnetic fluid-magnetic field combination. The mixture is fed from a chute, and the components are received at different receptacles in the exit section. In this separation the fluid acts as a density spectrograph, diverting particles in different trajectories according to their density. A major advantage of this technique is that magnetic particles would be deflected to the back side of the separation cell and hence can be mechanically separated from the various nonmagnetic fractions.

In Fig. 5, a mixture of alumina balls (white) and lead shot (black) was poured into the magnetic fluid contained in a cell that was obliquely sandwiched between two steel blocks on the poles of a laboratory magnet. The mixture instantly separated, with the components falling separately into the two beakers shown on the left side of the picture. The white alumina was partially covered with the dark fluid in the front beaker. Because of its lower density, the adhering fluid can be recovered by washing the separated products with water. To achieve the same separation with heavy liquids, a medium with specific gravity greater than four would be needed, in which alumina would float and lead would sink. This liquid would be effective only for this separation; in contrast, the magnetic fluid can separate components over the entire density spectrum.

It should be noted that the horseshoe magnet in Fig. 5 was tilted so that the magnetic field gradient was tilted from the vertical axis. The total force acting on a body immersed in the magnetic fluid is the vector sum of the gravitational and magnetic levitational forces. A diagram of the orientation of these forces is shown in Fig. 6. The concept in this continuous method is quite different from that of previous separation procedures which utilized the magnetic levitation force in a vertical direction. In the latter procedures, either the magnetic field gradient was changed by use of an intermittent variable electromagnet¹⁴, or a bottomless vessel containing the magnetic fluid was placed between the inclined poles of a magnet with the magnetomotive force holding the fluid in place¹⁵.

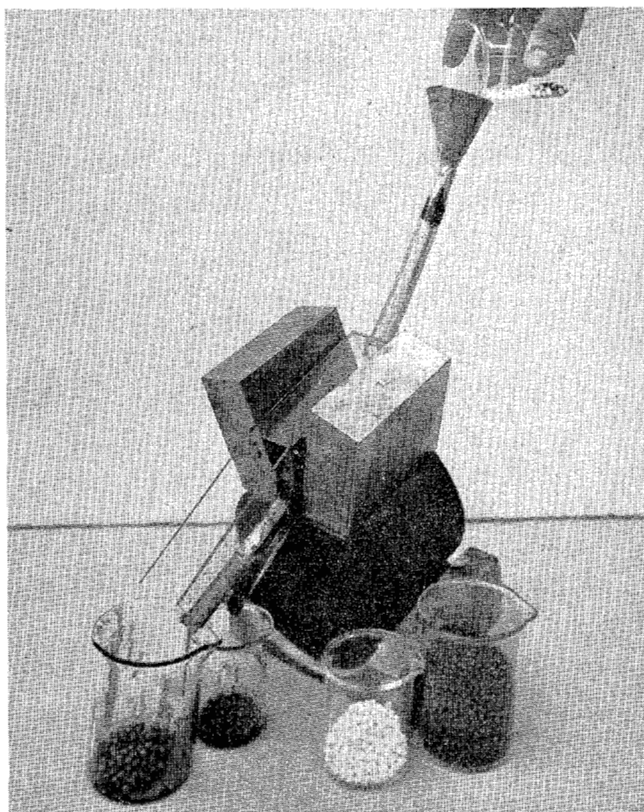


Fig. 5. Magnetogravimetric particle separator.

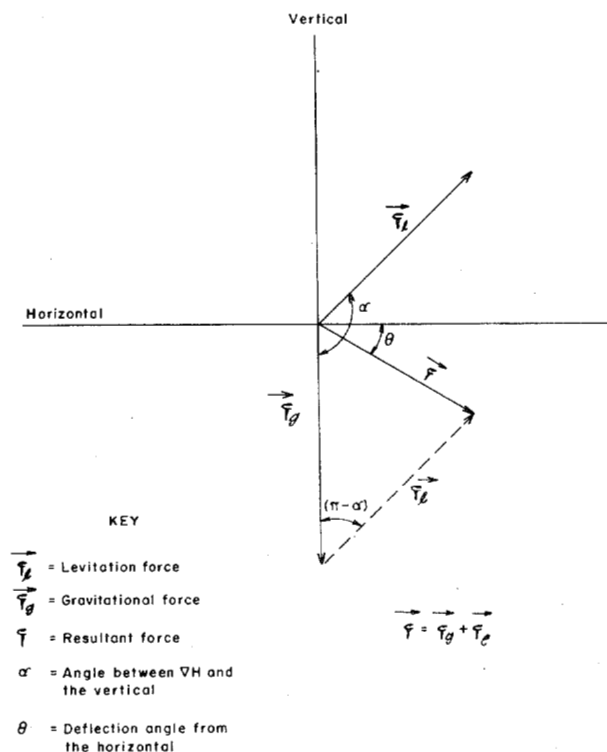


Fig. 6. Diagrammatic sketch of force orientations in material separation.

The theory and principles underlying the procedure for continuous particle separation have been developed at the Bureau of Mines.¹⁶ This method was also successfully applied to fractionate nonferrous metals from the residue of an experimental solid waste incinerator.¹⁷ Screening the incinerator residue to -4, +14 mesh removed the bulk of silica (glass), reduced the sample size by about 52 percent, and gave a residue rich in aluminum, copper, and zinc with less than 3 percent silica. Separation of this residue into its components was accomplished using a permanent magnet and a magnetic fluid with a saturation magnetization of 80 gauss. The light fraction collector contained 58 percent of the sample and was rich in aluminum (84.7%). The heavy residue was further fractionated using an electromagnet with the field adjusted to 2.4 kilo-Oersted and a magnetic fluid with a saturation magnetization of 215 gauss. Materials with mass density less than 7.2 g/cm³ were received in the light fraction receptacle and were rich in zinc, while the heavy fraction receiver contained material rich in copper. The bulk of the magnetic fluid that adhered to the separated particles was recovered by floating it on water and skimming it off with the aid of moving magnets. Figure 7 is a photograph of the separator used in these bench-scale experiments and illustrates a method for returning the skimmed fluid to the separation cell.

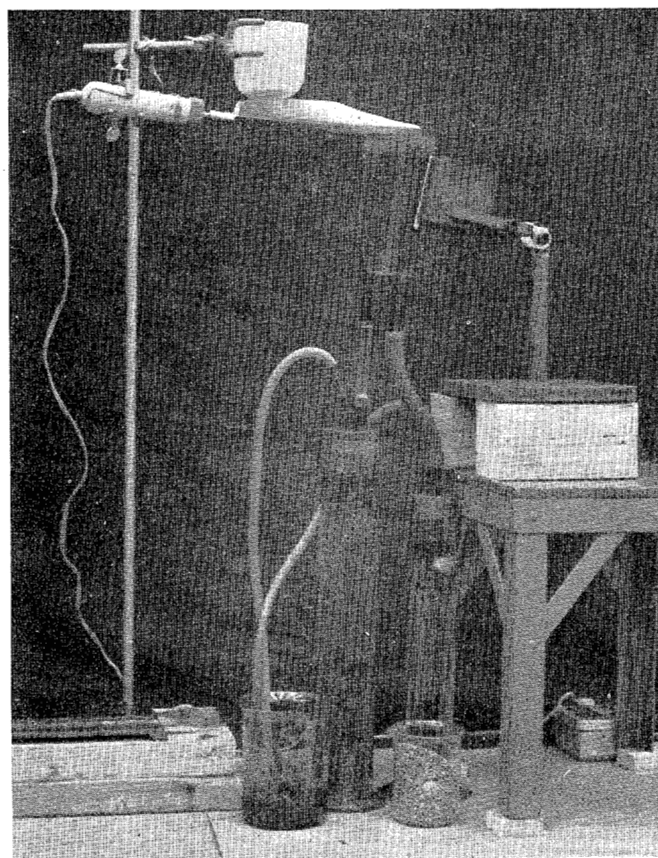


Fig. 7. Bench-scale equipment for separation of Al from Cu and Zn in incinerator residue.

At this time, separation processes based on magnetic fluid technology can be envisaged in reclaiming nonferrous metals from concentrated unburned urban refuse, recovering titanium and lead and unalloyed copper and zinc from wasted nonferrous scrap, recovering lead-free zinc die-cast alloys (trade name, Zamac) from the nonferrous segments of automobile scrap, separating the gangues from native copper ores to upgrade their copper content, and recycling military wastes and scrap and processing their electronic scrap for precious metals.

Figure 8 shows a large MGM separator powered by a 4,000-kilogram magnet. The pole caps are designed to produce a nearly constant magnetic field gradient within the air gap region. A motor-driven variable output transformer allows current adjustment from 45 to 125 amperes with a regulation of better than 1 percent of full current. The electromagnet assembly is mounted on a support trunnion such that the direction of the magnetic field gradient and hence the magnetic force can be oriented vertically, horizontally, or anywhere in between. At full power, the lower region of the separation zone has a magnetic field of about 10 kOe, and a field gradient of about 230 Oe cm^{-1} in the separation zone. This separator is being used by Reimers¹⁸ et al at the Twin Cities Metallurgy Research Center to separate nonferrous metals from shredded automobile scrap at a throughput of 1,000 to 1,500 pounds (450 to 680 kilograms) per hour.

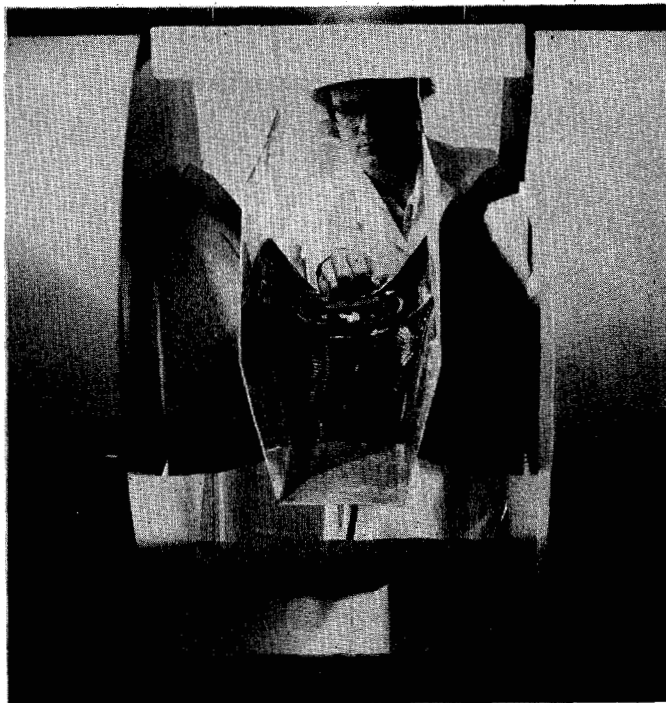


Fig. 8. Pool of ferrofluid in the constant gradient gap of a large electromagnet to separate zinc from copper.

MAGNETOHYDROSTATIC SEPARATIONS

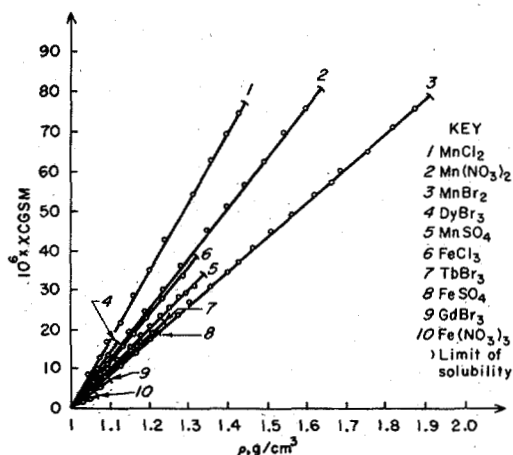
In this system of separation a paramagnetic liquid (or melt) replaces the magnetic fluid in MGM separations. It was pioneered as early as 1962 at the Soviet school.¹⁹ The magnetic moment of a paramagnetic salt solution is much smaller (about three orders of magnitude less) than that of a magnetic fluid, and it never reaches saturation. Thus, the quantity μ in the defining equation 3 of MGM separations is linearly dependent

on the applied magnetic field, and must be replaced by χH , where χ is the magnetic susceptibility of the paramagnetic salt solution. Also, the magnetic susceptibility of these salt solutions is much smaller (three to four orders of magnitude less) than that of typical magnetic colloids, and is indeed only somewhat larger than the susceptibility, χ' , of most of the so-called "nonmagnetic objects". In MHS separations, χ' cannot therefore be ignored when compared to the susceptibility of the medium of separation, and the effective susceptibility χ_e will be given by the difference between χ and χ' . The defining equation for MHS separations can therefore be derived from equation 3 with the foregoing substitutions; thus

$$\vec{f}_m = \mu \text{ grad } H = \chi_e H \text{ grad } H = (\chi - \chi') H \text{ grad } H. \quad (7)$$

Hence the contours of constant magnetic force, $\vec{f}_m$, are determined by the constancy of the product " $H \text{ grad } H$ " in MHS separators. By contrast, it is sufficient to use only the constant gradient caps of the commonly used Faraday balance to achieve constant magnetic forces within a pool of magnetic fluid in the MGM separators.

Andres²⁰ determined the bulk susceptibility and density of a series of paramagnetic salt solutions. Figure 9 shows the dependence of magnetic susceptibility on density for these salt solutions up to the limit of saturation. He concluded that bulk susceptibilities of the order of 10^{-4} emu can be achieved by aqueous solutions of the nitrate, chloride, or bromide of either manganese or iron. In an effort to further increase the volume susceptibility of magnetic liquids, Andres²⁰ et al suggested raising the temperature to increase the solubility, or even using the melt of the paramagnetic salt. Although the reported²¹ melting point of $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ is only 58°C , this melting probably represents dissolution of the manganous salt in its own water of crystallization. This is attested by the loss of the first water molecule at 106°C and the last three water molecules at 198°C . On the other hand, the melting point of anhydrous MnCl_2 (scacchite) is reported²¹ as 650°C . It should be remembered that the increase in solubility with temperature may be more than offset by the decrease in magnetic susceptibility with rise in temperature in accordance with the Curie-Weiss law, $\chi = C/(T + \Delta)$, where C and Δ are constants. Under these conditions, raising the temperature, or melting the salt, may be counterproductive.



Source: U. Andres, Mineral Science Engineering, volume 7, No.2, April 1975

Fig. 9. Magnetic susceptibility as a function of density for aqueous solutions of paramagnetic salts.

A schematic diagram of a batchwise MHS separator in a wedge-shaped gap is shown in Fig. 10. Lin and Finkelstein²² discussed the promising features together with the drawbacks of MHS separations. They concluded that this technique will never become a widely used general processing technique. Commercial applications may therefore be envisaged in special cases such as the production of precious metals from low volumes of relatively coarse concentrates, perhaps the product of a preceding beneficiation step, or the making of a very pure product by elimination of the last traces of an impurity from which the product is completely liberated.

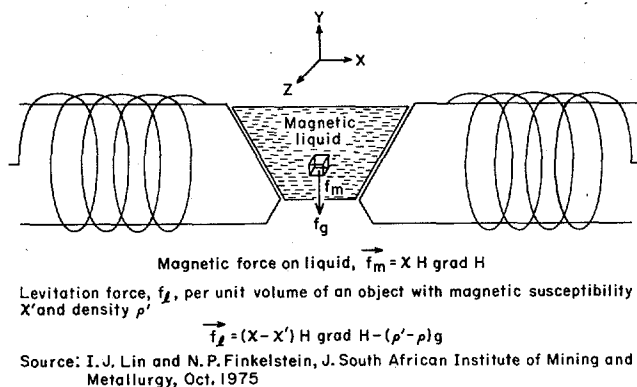


Fig. 10. Magneto-hydrostatic separator.

Figure 11 shows a three-product MHS separator that can produce monomineral fractions¹⁹ under laboratory conditions. The separating cell, about 60 cm long, is made of plexiglass filled with saturated manganous chloride solution. The material to be separated is fed by a vibrator with a sloping grid chute suspended on a long arm. The arm passes through the hollow shaft of a mixer that slowly stirs the material fed from the bunker. The poles shown in the lateral cross section part of Fig. 11 provide an isodynamic magnetic field. The horizontal drift of the particles is caused by the horizontal gradient of the magnetic force. The vertical component of the magnetic force (levitation force) is responsible for the vertical distribution of particles at points of equilibrium with the force of gravity (or buoyancy) and determines their exit port to the respective receptor. The lateral (or transverse) component of the magnetic force is balanced by the reaction of the duct wall. The mean speed of horizontal drift depends on particle size and reportedly¹⁹ varies within the range of 5 to 15 cm sec⁻¹.

It must be realized, however, that the magnetic fields and field gradients involved in MHS separators are of very large magnitudes. Bunin³ reported fields such that

$$H \text{ grad } H \approx 10^7 \text{ Oe}^2 \text{ cm}^{-1}. \quad (8)$$

The magnetization of paramagnetic salt solutions was measured by a vibrating sample magnetometer¹² and found to range from 0.1 to 0.5 gauss at fields between 1 and 2 kOe. The magnetization of the superparamagnetic ferrofluids ranges from 100 to 500 gauss and reaches saturation at fields in the neighborhood of 1 kOe. Hence, to effect the same separation, the quantity " $H \text{ grad } H$ " in the MGM separators need be only about $10^4 \text{ Oe}^2 \text{ cm}^{-1}$ instead of the $10^7 \text{ Oe}^2 \text{ cm}^{-1}$ required in MHS separators. For an average gap width of 50 cm, MGM separators require magnetic fields of about $(5 \times 10^5)^{1/2} = 707 \text{ Oe}$, whereas the MHS separators require fields of the order of 22,500 Oe. Ferrofluids can therefore perform bench-scale separations with ordinary permanent magnets and large-scale separations (large magnet gap widths)

with normal electromagnets. By contrast, paramagnetic salts in the MHS separators need strong electromagnets for bench-scale separations and probably cannot be enlarged in throughput without the introduction of newer concepts of magnetic field generators, such as the widely acclaimed but not yet adopted superconducting magnets.

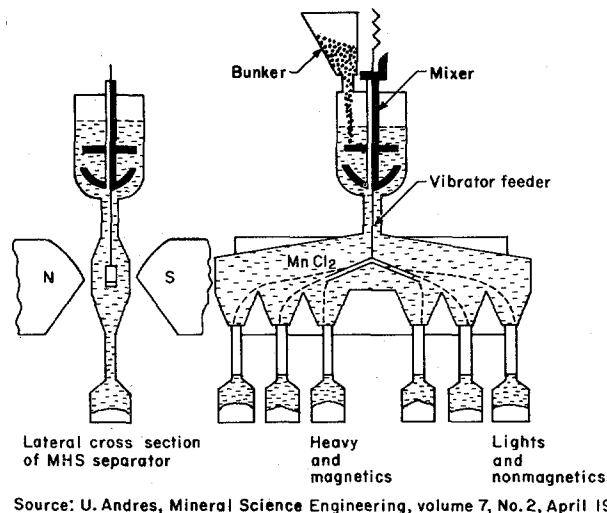


Fig. 11. Three-way split magnetohydrostatic separator.

Andres¹⁹ defined the separation parameter, β , in MHS separators as the ratio of the buoyancy force to the magnetic levitation force; thus

$$\beta = \frac{(\rho' - \rho) g}{(X - X') H \text{ grad } H}. \quad (9)$$

The technique of MHS jiggling was patented in the USSR by Andres and Bunin²³. It makes use of the natural tendency of a fluidized layer of mineral particles to stratify into layers in accordance with the value of the parameter β . Similar to hydraulic jiggling, MHS jiggling can be carried out either mechanically in a constant magnetic field, or by a pulsating magnetic field that vibrates the mineral particles. The frequency of the jiggling cycle can be optimized with respect to the dimensions of the particle to be separated and the value of the parameter β . MHS jiggling would ostensibly permit the separation of fine and ultrafine particles by compensating the viscous and drag forces that normally hinder their separation.

MAGNETOHYDRODYNAMIC SEPARATIONS

This is the oldest approach in the class magnetic separations of the second kind. It was used by Gates²⁴ as early as 1900 to separate precious metals from non-conducting minerals. Some 60 years later, Micheletti²⁵ separated dielectric and semiconducting minerals according to their specific gravity with an MHD separator.

Although MHD is now a celebrated device for generating power by direct conversion to electricity of the kinetic energy of a conducting material (plasma of hot ionized gas in modern MHD generators) flowing in a magnetic field, the inverse effect of creating a thrust on an electrolyte by the flow of electricity in a crossed magnetic field has long been used as a separating device. Both devices are based on the Faraday effect discovered by Michael Faraday in 1831 when he made mercury flow through the field of a magnet. An electric field was produced in a direction perpendicular to both

the magnetic field and the direction of mercury flow. Five years later, Faraday demonstrated MHD when he showed that a current was registered in a galvanometer connected to two electrodes placed on the banks of the Thames river²⁸. Because that river is mixed with salt water, its water has a high conductivity. This conducting fluid interacted with the earth's magnetic field to produce a small current.

MHD separation is based on the excitation of an electromagnetic thrust force, $\vec{f}_{em}$, in an electrolyte by a crossed electric and magnetic field. A diagrammatic sketch of an MHD separator in a wedge-shaped magnet is shown in Fig. 12. In a typical MHD separator, KOH may be used in the electrolyte solution, the magnetic field may range from 10 to 12 kOe, and an optimum current density of 0.75 amp/cm² was reported⁵ for bottom feeding of iron ore that was ground to 0.1 to 1 mm size.

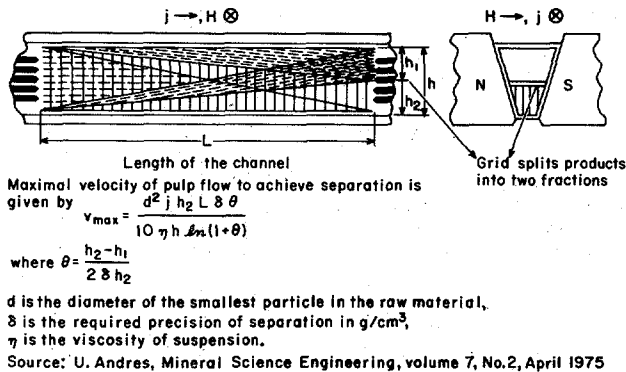


Fig. 12. Magnetohydrodynamic separator.

According to Andres¹⁹, the electromagnetic force acting on unit volume of a nonmagnetic sphere of conductivity, σ' , immersed in a liquid of conductivity, σ , in crossed electric field of current density, j , and magnetic field of magnitude, H , is given by

$$\vec{f}_{em} = \frac{3}{2} jH \frac{(\sigma' - \sigma)}{(\sigma' + 2\sigma)} \quad (10)$$

For conducting particles $\sigma' \gg \sigma$, the force is about $3/2 jH$. When $\sigma' \ll \sigma$, the force would be about $3/4 jH$, and when $\sigma' \approx \sigma$, the force would be approximately $\Delta \sigma jH/2\sigma$. When the electromagnetic force on a particle exactly balances the gravitational force, then

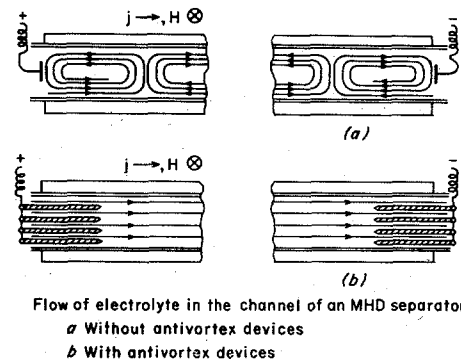
$$(\rho' - \rho)g = \frac{3}{2} \frac{(\sigma' - \sigma)}{(\sigma' + 2\sigma)} jH \quad (11)$$

and the parameter, α , determining separation is given¹⁹ by

$$\alpha = \frac{3}{2} \frac{g(\rho' - \rho)(\sigma' + 2\sigma)}{jH(\sigma' - \sigma)} \quad (12)$$

Distortions of the current flow as well as the magnetic field lines were observed at the boundaries of MHD separation cells when flat plate electrodes were used to introduce the electric current. The variable electromagnetic force produced therefrom tends to produce vortexes within the electrolyte as shown in Fig. 13. Evidently, the Lorentz force, which manifests itself as the Hall voltage (a transverse electric potential), distorts the field lines in the electrode vicinity. The resulting vortexes caused great difficulties¹⁹ in attempting to apply MHD separations on a continuous industrial scale. The vortex effect was alleviated by dividing the entrance and exit of the channel with horizontal grids. When some of these grids are used to introduce the current, then several small

vortexes were formed instead of one large one. These small vortexes tend to flow in opposite directions and under optimum conditions would cancel each other. The lower section of Fig. 13 shows a continuous MHD separator with antivortex devices that was developed by Andres¹⁹. The output of MHD separators is essentially determined by the flow rate of the electrolyte that transports the mineral particles. A linear variation of the electromagnetic force along the vertical direction of an MHD channel separator can be achieved¹⁹ by a wedge-shaped magnetic field, by a wedge-shaped electric field, or by both as illustrated in Fig. 12. MHD separators with capacities of 50 t/h and 5 t/h were reportedly¹⁹ tested in coal preparation and tin ore industries, respectively. In MHD jigging, either the magnetic field or the electric voltage is oscillated. This permits the production of clearly defined boundaries for the separated products.



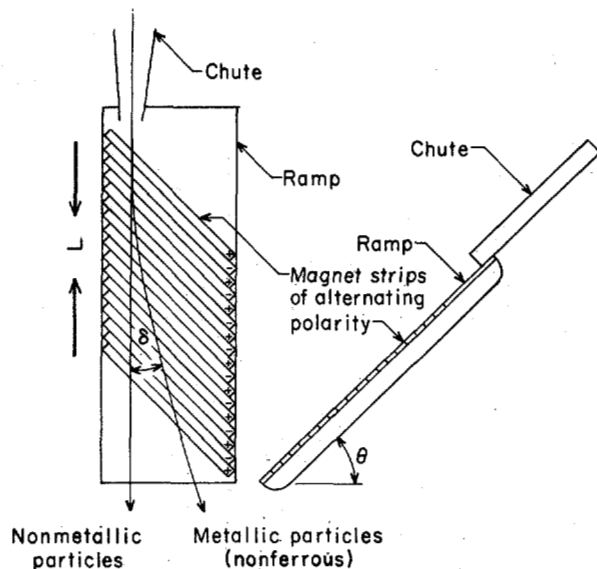
Source: U. Andres, Mineral Science Engineering, volume 7, No.2, April 1975

Fig. 13. Vortex formation and elimination in MHD separators.

Eddy Current Separators

Faraday's induction laws predict that solid conductors moving across a magnetic field suffer conspicuous damping forces which are caused by side thrusts due to currents induced within the conductors. These currents are called eddy or Foucault currents. They circulate within conductors and may be very intense if the resistance is small. Despite the absence of fluid motion, separators making use of these eddy currents could be considered as a special case of MHD separators since they make use of the Faraday effect.

Schloemann²⁷ has recently described a new dry method to separate nonmagnetic metals from solid waste. The method depends on the much higher electrical conductivity of aluminum, copper, tin and zinc as compared to that of glass, ceramics, and wood. Hence particles made of the former materials and not the latter will experience eddy currents when traveling through a time varying magnetic field. Separation is achieved by means of a ramp (Fig. 14) which has permanent magnets embedded in its surface. The magnets are arranged in strips of alternating polarity at 45° to the ramp axis. Nonconducting particles will slide undeflected straight down the ramp, whereas conducting particles will be deflected laterally. Schloemann calculated the angular deflection, δ , as a function of particle conductivity, σ ; density, ρ ; size; initial velocity; length, L ; and inclination, θ , of the ramp; period and strength of the ramp magnets; and coefficient of sliding friction with the ramp surface. He found that the deflection is proportional to the ratio, σ/ρ , and varies with the $3/2$ power of the ramp length, L . Deflection also increases with the square of the particle diameter up to diameters that are comparable with the period of the magnet strips when it becomes independent of the particle size.



Schematic design of metal separator in frontal view (left) and side view (right)

Source: E. Schlöman, *J. Applied Physics*, volume 46, November 1975

Fig. 14. The Eddy current separator.

The eddy current deflection method was found to be best suited for aluminum. Schloemann reported that a laboratory model was able to separate 85 percent of the aluminum²⁸ in solid wastes with one pass down the ramp. He also reported that the technique can be used to separate metals such as aluminum and zinc from one another to some extent.

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