MAGNETOHYDROSTATIC SEPARATION

U. Ts. Andres, G. M. Bunin, and B. B. Gil

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When a liquid is placed in crossed electric and magnetic fields, there is developed a force of electromagnetic origin, supplementary to the normal Archimedean force, with density

$$\mathbf{f} = k_1 \operatorname{grad} H^2 + k_2 \operatorname{grad} E^2 + k_3 [\mathbf{E} \times \mathbf{H}]. \qquad (1)$$

Here H is the magnetic field, E the electric field, and k_1, k_2 and k_3 are constants representing the liquid's physical properties (magnetic and dielectric susceptibility and conductivity). A medium of this type can be used to separate mechanical mixtures according to various characteristics (density, conductivity, etc.). The first topic examined in the present paper is the stratification of the particles to be separated. This situation is somewhat similar to that of a heavy liquid which changes in density according to depth. Hence it is immediately clear that separators of the type examined will be at their most efficient when required to separate several end-products simultaneously, e.g., they are ideal for fractional analysis.

Figure 1 shows the stratification produced in a four-component mixture by a laboratory device (the medium used was a paramagnetic liquid in a nonuniform magnetic field: the figure shows the position before and after the field was switched on). A magnetic field of the order of $1.5 \cdot 10^4$ gauss is required to produce supplementary weighting of the order of 1 gm/cm^3 due to magnetic field nonuniformity in a region with a characteristic size of the order of 10 cm in a paramagnetic liquid (manganese chloride solution of magnetic susceptibility $k_m \approx 8 \cdot 10^5$). On the other hand, a potential difference of the order of $1.5 \cdot 10^5$ V is required to achieve the same effect by electric field nonuniformity in a dielectric liquid (water with a dielectric constant $\varepsilon \approx 80$). These assessments show that the role of electric field nonuniformity in separators of the type examined is infinitesimal, with the magnetic and electric fields which can be achieved in practice. Nevertheless, a dielectric liquid in a nonuniform electric field could be used in deflector-type separators operating at substantially lower effective densities. In the usual case of separation in crossed fields (magnetohydrodynamic separation) the particles to be separated enter the separation zone and distort the force pattern which initially existed in it [1].

Now follows an examination of magnetohydrostatic separation, i.e., separation of nonferromagnetic particles in paramagnetic liquids in the absence of an electric field (where E = 0). The term "magnetohydrostatic separation" reflects the fact that the initial potential distribution of magnetic force in the liquid is never disturbed, and the local eddy currents characteristic of crossed fields do not arise in the vicinity of a submerged foreign particle.

From the condition of hydrostatic equilibrium of a particle on the x axis (vertically downward) we have

$$\Delta\rho_g - \Delta k_m \, HdH / dx = 0, \qquad (2)$$

where $\Delta\rho_g$ and Δk_m are the differences in the densities and magnetic susceptibilities of particle and liquid, respectively: it follows that stratification in a nonuniform magnetic field will follow the parameter

$$\alpha = \Delta\rho_g / \Delta k_m = HdH / dx. \qquad (3)$$

The basic problem in magnetohydrostatic separation is to create those magnetic fields which give a satisfactory supplementary weighting curve.

The HdH/dx curve must meet the following requirements: a) it must be stable, i.e., the effective density must not decrease from above downward ($d\alpha/dx > 0$); b) it must correspond to the range of physical properties of the mixture to be separated ($\alpha_{min} \le HdH/dx \le \alpha_{max}$); c) it must ensure that the "resolving power" of the separator $d\alpha/dx$ conforms to the volumetric concentration distribution of the mixture components.

The physical properties of the liquid substantially affect separator output and accuracy, so the second problem in magnetohydrostatic separation is to select a liquid. Aqueous solutions of iron, manganese, nickel, cobalt, etc. salts with fairly pronounced paramagnetic properties can be used. Figures 2 and 3 show the relationship of magnetic susceptibility k_m and viscosity η of $MnCl_2$ and $FeCl_3$ solutions to concentration at 18° C. To increase effective density, finely dispersed suspensions of the above paramagnetic salts in high-density organic liquids or suspensions of ferromagnetic substances (iron, magnetite, cobalt, nickel) in water can be used [2, 3].

Some simple magnetic field configurations, which are of interest in magnetohydrostatic separation, will now be examined. Since the magnetic field is irrotational and its potential is a harmonic function in regions where there are no electric currents, we find the following in the gap between the poles:

$$\mathbf{H} = \operatorname{grad} V, \qquad \Delta V = 0. \qquad (4)$$

It is desirable to use the known solutions for the Laplace equation (4) and study their corresponding supplementary weighting fields. The pole piece shape can then be found without difficulty; any two equipotential surfaces can be adopted as outlines. Restricting ourselves to a two-dimensional situation, we can now examine a system of partial solutions for equation (4), which take the form $V = X(r)Y(\theta)$ in polar coordinates (r, θ). Analysis of these solutions shows that only the following are of practical interest:

$$V_0 = A_0\theta, \qquad V_k = A_k r^k \sin k\theta. \qquad (5)$$

Here $k > 1$ is a constant, and A_k are arbitrary constants. Solutions of (3) determine the choice of magnetic field configurations to ensure a central supplementary weighting field,

$$\mathbf{f}_0 = -k_m A_0^2 e_r / r^3, \qquad \mathbf{f}_k = k_m A_k^2 k^2 (k-1) r^{2k-3} \mathbf{e}_r. \qquad (6)$$

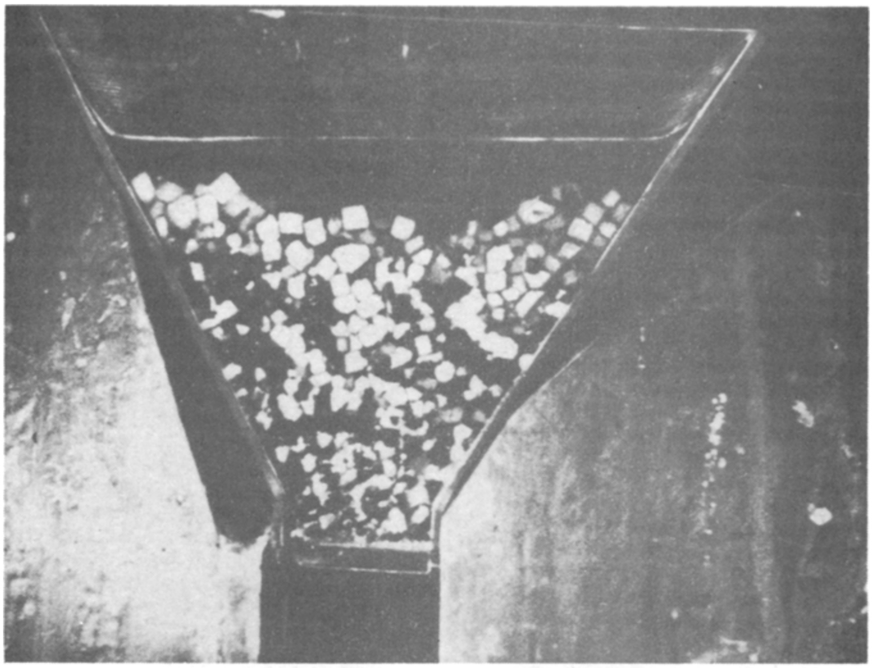
This force field will cause the following supplementary pressure in the liquid:

$$p_0 = {}^1/_2\, k_m A_0^2 / r^2, \qquad p_k = {}^1/_2\, k_m A_k^2 k^2 r^{2(k-1)}. \qquad (7)$$

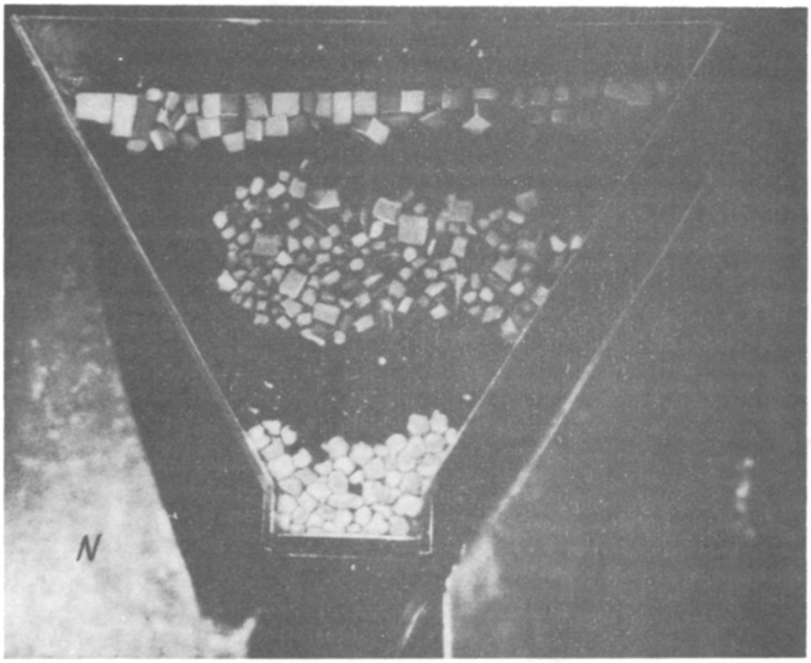
Relations (6) and (7) show that appropriate selection of constant k will give essentially different weighting fields. The effect of k on pole gap geometry is illustrated by Fig. 4. When k = 0 (Fig. 4a) there is a wedge-shaped gap in which weighting diminishes with distance from center as r^{-2}. When k = 5/4 (Fig. 4b), weighting diminishes as $r^{-1/2}$, and a wedge-shaped neutral pole (iron insert) appears. When k = 3/2 (Fig. 4c) there is an isoforce field, and when k = 2 (Fig. 4d) weighting increases linearly with distance. The insert aperture angle increases as k increases.

We will now compare the results of calculating the expulsive force acting on a spherical particle in a wedge-shaped gap with the results obtained by experiment.

An infinite wedge-shaped pole gap filled with paramagnetic fluid of magnetic susceptibility k_m (Fig. 4a) will be examined. A nonmagnetic



a



b

Fig. 1. Stratification of a four-component mixture: a) mixture not exposed to magnetic force; b) mixture stratified by action of magnetic force.

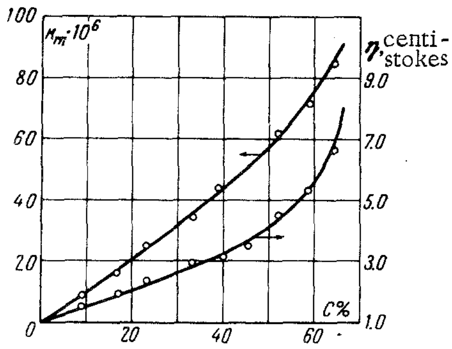


Fig. 2. Relationship of magnetic susceptibility and viscosity of aqueous $MnCl_2$ solution to $MnCl_2$ concentration.

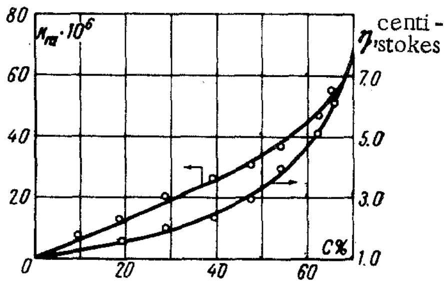


Fig. 3. Relationship of magnetic susceptibility and viscosity of aqueous $FeCl_3$ solution to $FeCl_3$ concentration.

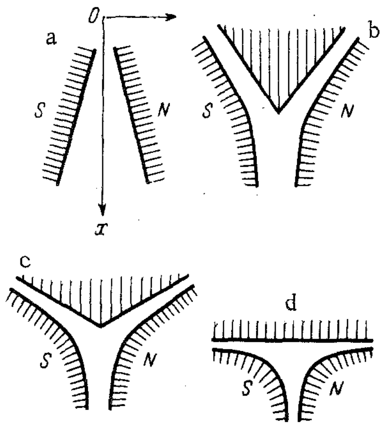


Fig. 4. a) Wedge-shaped pole gap; b) pole gap with k = 5/4; c) pole gap with k = 3/2; d) pole gap with k = 2.

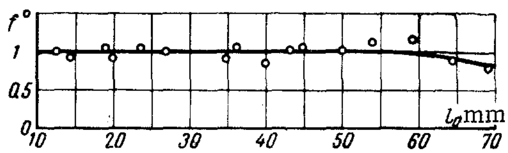


Fig. 5. Relationship between calculated and observed magnetic expulsive forces acting from a magnetic liquid on a 0.5 cm radius glass sphere in a wedge-shaped pole gap.

sphere of radius r_0 is placed at a distance l_0 from the wedge apex. The hydrostatics formula

$$F_x = -\oint p\,(\mathbf{e}_x\mathbf{n})ds$$

is used.

Here n is the vector of the normal to the surface of the sphere, ds the component of area and e_x the single vector in the direction of the x axis. After introducing the spherical system of coordinates r', θ', φ' and substituting p_0 from (7) we obtain

$$F_x = \frac{k_m r_0^2 A_0^2}{2}\int_0^{2\pi} d\varphi' \int_0^{\pi} \frac{\sin\theta' \cos\theta'\, d\theta'}{l_0^2 + r_0^2(1-\sin^2\theta'\cos^2\varphi') + 2r_0 l_0 \cos\theta'}. \quad (8)$$

After integration we obtain

$$F_x = 2\pi k_m A_0^2 \left[\frac{1}{\sqrt{1-(r_0/l_0)^2}} \arcsin\frac{r_0}{l_0} - \frac{r_0}{l_0}\right]. \quad (9)$$

With $r_0/l_0 \ll 1$ formula (9) takes the form

$$F_x \approx {}^4/_3\pi k_m A_0^2 (r_0/l_0)^3. \quad (10)$$

In experiments, the magnitude of r_0/l_0 was of the order of 0.1. Figure 5 gives a comparison of calculations by formula (10) and the experimental data. It is apparent from Fig. 5 that the theoretical and experimental results coincide satisfactorily at almost all heights in the gap. This makes it possible to determine the susceptibility of a nonferromagnetic liquid simply by weighing a nonmagnetic sphere in a wedge-shaped gap.

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