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# THE APPLICATION OF HETEROGENEOUS POLARISABLE FLUIDS IN MINERAL PROCESSING

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Abstract: The paper deals with the application of ferrofluids in mineral processing. The efficiency of primary and secondary raw material separation by the magnetohydrostatic method is dependent on convenient distribution and on the stabilisation of density of the ferrofluid. To determine this density, the effective dynamometric method based on measurement of the buoyant force was constructed. A density controller has been developed for stabilisation and control of the density. Influence of some factors on the separation process, as well as the results of magnetohydrostatic separation are described.

## INTRODUCTION

Ferromagnetic fluids are defined as stable colloidal systems of mono–domain particles in a liquid carrier. Ferrofluids can be utilised in treatment of primary and secondary raw materials as follows:

As wetting agents which are selectively adsorbed on the surface of the grains and in this way enhance the magnetic susceptibility of certain components, for improvement of parameters of magnetic separation.

A medium for separation of non–ferromagnetic materials characterised by various densities and particle size.

Ferrofluids were, for the first time, successfully applied in coal preparation and in separation of a tungsten ore [1]. They are employed mainly as a separation medium in mineral processing. In this case all separation techniques utilise the primary lateral magnetic buoyant force acting on non–magnetic particles. This force is caused by the pressure difference in the magnetic polarisable medium of separation. This pressure difference is a function of the configuration the magnetic field.

The utilisation of the magnetohydrostatic (MHS) technique for fine–grained particles is limited by the gravitational force. This limitation can be removed by the application of the centrifugal force acting on particles to be separated and placed in a magnetic field of suitable configuration. Rotation of the separation space can be realised by means of spirals, cyclones, the channel rotation and their variations. The best results of separation mineral mixtures by the application of the centrifugal force were achieved by the Magstream separator [2]. The ferrofluid cyclone with the continuous off–take of the floating product was successfully applied by Lin, Fujita and Mamiya [3] to separation of SiC and $LiTaO_3$.

The most important results achieved at the Institute of Geotechnics will be summarised in this contribution. These results were obtained when solving theoretical and practical problems of separation of various materials in ferrofluids.

## THE INFLUENCE OF VARIOUS FACTORS ON THE EFFICIENCY OF MHS

Successful installation of the production of ferrofluids opened a possibility of the application of the magnetohydrostatic technique in mineral processing. Our research was directed towards the separation devices designed to use ferrofluid as a separating medium. To this end, a magnetohydrostatic separator equipped with interchangeable pole–pieces was designed.

Configuration of the magnetic field has a principal influence on the magnitude and distribution of the effective density of the ferrofluid [4]. Desirable distribution of the magnetic field was determined by means of the methods of the electromagnetic theory. Shape of the pole–pieces was calculated according to equations shown below.

If $y_c$ is the width of the discharge slot and $\ell$ is the height of the pole–piece, an equation for the surface curves of the pole–pieces, in cylindrical coordinates, is given [5] by:

$$r = \left[(y_c^2 + \ell^2)^{\frac{1}{2}} \sin\left(\frac{3}{2} \arctan \frac{y_c}{\ell}\right)\right]^{2/3} / \sin \frac{3}{2}\, \theta \tag{1}$$

where $r$ is the polar coordinate [m] and $\theta$ is the polar angle.

This type of poles is suitable for separation of materials characterised by densities up to 6000 kg/m$^3$. Differences in densities of individual components can be small.

Pole–pieces required to achieve high effective densities in the separation zone in non–homogeneous magnetic field were made. Their shape is described by the following equation:

$$z^2 = \frac{0.36}{1 - 0.18y} \tag{2}$$

High values of the effective density were obtained by using suitable geometric cross–sections. This type of pole–pieces for suitable for separation of fine–grained materials.

In order to achieve high density of separation, under non–homogeneous magnetic field in a separating channel, hyperbolic pole–pieces were manufactures. Their shape is given by:

$$z = \frac{15.6\times10^{-4}}{y} \tag{3}$$

Shape of the pole–pieces for separation of two components was computed according to a method introduced in [6]. High homogeneity of the magnetic field was guaranteed by using the above mentioned poles. Shape of these poles can be described by the following equations:

For coal $$z = 1.8 \ln \frac{3.4\times10^{-2}}{y} \tag{4}$$

For magnesite $$z = 2.5 \ln \frac{3.2\times10^{-2}}{y} \qquad (5)$$

Types of pole–pieces introduced above (eqs. 4 and 5) are suitable for separation of substances characterised by low densities. Wedge–shaped pole–pieces characterised by an angle of 22° with vertical and horizontal orientations were manufactured for separation of polymineral mixtures in a continuous regime.

Precision of determination of the effective density, the difference in densities of the separated particles, particle size, particle shape, physical properties of the ferrofluid and of the minerals to be separated, the construction parameters of the separator, mode of the feed, mode of the material removal and the throughput of the separator are the factors that affect the efficiency of the MHS process.

The influence of several of these factors on the efficiency of separation is discussed in [7]. A complete study of correlation among these factors has not been described as yet in available literature.

The results of separation, and particularly the selectivity of the process depend on accurate adjustment of the density cut point. The effective density of ferrofluid is given by:

$$\rho_{\mathrm{eff}} = \rho_{\mathrm{f}} + \frac{\mathrm{I\ grad\ H}}{\mathrm{g}} \qquad (6)$$

where $\rho_{\mathrm{eff}}$ is the effective density of ferrofluid [kg/m$^3$], $\rho_{\mathrm{f}}$ is the density of ferrofluid at $\mathrm{H} = 0$ [kg/m$^3$], $I$ is the magnetic polarisation of ferrofluid [T], $H$ is the intensity of the magnetic field [A/m] and $g$ is the acceleration of gravity [m/s$^2$].

Configuration of the magnetic field has the decisive effect on the distribution of the effective density in the separating zone of the magnetohydrostatic separator since the magnetic polarisation of the ferrofluid depends on the magnetic field intensity. Experimental results show that the magnetic field intensity greater than 80 kA/m $I = I_{\mathrm{s}} = \mathrm{const}$. Therefore, the required distribution of the effective density in the separating zone depends on the shape of the pole tips generating the gradient of the magnetic field in the air gap of the electromagnet. Continuous determination of the density of the ferrofluid by conventional techniques is impractical because magnetic field is non–homogeneous.

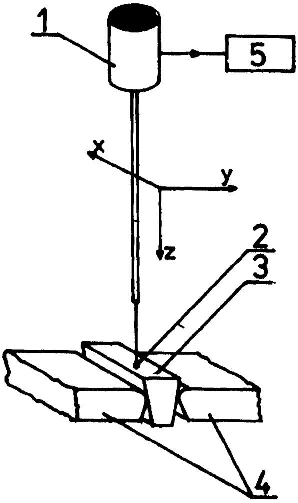

Fig. 1 Principle of the measurement of the buoyancy force.
1–dynamometer, 2–non–magnetic ball, 3–ferrofluid, 4–pole–tips, 5–millivoltmeter.

In order to measure density, a point pressure gauge based on comparison of buoyancy force was developed (Figure 1). The force of buoyancy acting on a non–magnetic ball hanging on an arm of a dynamometer is scanned. The determination of the density iso–lines in the entire zone of separation determines the accuracy of the system, as is shown in Figure 2. The accuracy of measurement is $10^{-5}$ N.

The effective density can be determined from the relation:

$$\rho_{\mathrm{eff}} = \frac{\rho_1 f}{f_1} \qquad (7)$$

where $f$ is the buoyancy force acting on the ball, in the ferrofluid of density $\rho_{\mathrm{eff}}$, $f_1$ is the force acting on the ball in the fluid of the known density $\rho_1$, $y$ is the length of the separation zone (in mm), and $z$ is the height of the separation zone (in mm).

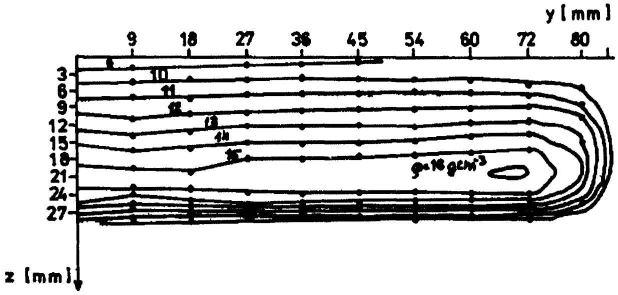

Fig. 2 A map of iso–lines of the ferrofluid density in the separation zone of a magnetohydrostatic separator when pole–tips described by eq. (2) are used. The values of the ferrofluid density are given in g/cm$^3$.

Figure 2 shows the map of iso–lines of the ferrofluid density determined by the dynamometr under a high gradient of the magnetic field. Configuration of the magnetic field, as well as the distribution of the effective density depends on shape of the pole–tips. In this case the distribution of the gradient is oriented vertically.

Knowledge of the magnetic properties of ferrofluid is important for the design of magnetohydrostatic separators. Because of instability of the magnetising current and of the changes of physical properties of the ferrofluid, the effective density also changes. In a continuous process of separation, stability of density is the fundamental condition which is assured by the controller of a ferrofluid density, and by a controller of the magnetising current.

The controller of the ferrofluid density shown in Figure 3 is designed on the basis of a bridge connection of tensometers with electronic processing and compensation of the resultant signal for temperature and drift. The controller of the ferrofluid density with an option of the proportional band is designed on the basis of the MHB–8035 chip processor. Its output is a voltage proportional to the difference between the required density and the actual one.

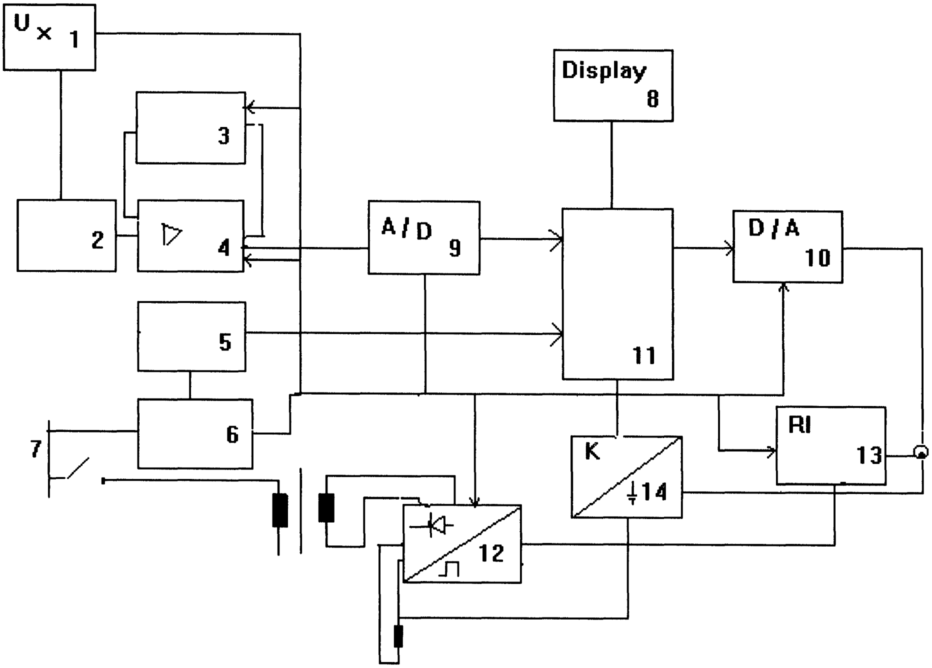

Fig. 3 A controller of the density of the ferrofluid.
1–measured voltage, 2–tensometer bridge, 3–correction circuits, 4 and 6–amplifiers, 5–pilot selector, 7–power supply, 220V, 8–display, 9–analog–to–digital converter, 10–digital–to–analog converter, 11–digital density controller, 12–triode thyristor circuit and pulse generator, 13–pulse reader, 14–resistive and capacitive units.

Circuits of the processor, the density indicator and the current controller communicate through the 8–bite converters. The current controller consists of PID control circuits, pulse generator circuits, current feedback circuits and a power output thyristor bridge of current capacity up to 15 A [8, 9].

## OPTIMISATION OF THE MHS SEPARATION TECHNIQUE

The optimum regime of the MHS separator equipped with various pole–pieces was determined by means of a method of full factor planing of experiment type $2^K$. When pole pieces described by eq. (4) were applied, the following factors were observed:

1. Factor [$x_1$] – particle size
   –lower level 1 to 4 mm
   –upper level 15 to 18 mm

2. Factor [$x_2$] – height of the feed with respect to the level of ferrofluid
   –lower level 10 mm
   –upper level 70 mm

3. Factor [$x_3$] – output of the separator
   –lower level 100 g per minute
   –upper level 1500 g per minute.

The optimisation factor $y_n$ expresses the number of the s–called "defective" particles (in per cent). The best results can be obtained at the value $y_n = 0$. The efficiency of separation decreases with an increase of the value of $y_n$.

The function can be expressed in the form:

$$y_n = 3{,}375 - 2.125x_1 - 0.975x_3 + 0.825x_1x_2 \tag{8}$$

Selectivity of separation improves with an increase in the particle size, and decreases with an increase in the output of the separator.

Analysis of specific gravity of coal, as well as separation of magnesite were carried out under optimum regime of the separator. Results that were thus obtained were compared with the results determined from separation in heavy medium. The Kolmogorov–Smirnov test was used for this comparison. Differences in the results from magnetohydrostatic separation and heavy medium separation are statistically negligible. The MHS technique can thus be applied to the separation of of coal and magnesite.

The optimisation experiments can be also carried out using pole–pieces described by eq. (2) which is suitable for separation of fine–grained materials under continuous regime. The influence of the following factors on the separation process was observed:

1. $x_1$ – grain size lower limit 0.071 to 0.125 mm
   upper limit 2.5 to 7 mm
2. $x_2$ – height of the feed
   lower limit 10 mm
   upper limit 100 mm
3. $x_3$ – angle of inclination of the separating channel
   lower limit $1^0$
   upper limit $10^0$.

A mixture of grains characterised by the difference in density of about 1000 $kg/m^3$ was subjected to separation. The recovery of heavy grains into the floating product was observed. The resulting formula is given by equation:

$$y = 91.225 + 4.05x_1 - 2.1x_3 - 2.575x_1x_2 \tag{9}$$

These pole–pieces are suitable for separation of minerals and of non–ferrous metal wastes, in a wide interval of densities [13]. A decrease in the purity of the concentrate of fine–grained material is a function of viscosity and surface tension.

## THE APPLICATION OF THE CENTRIFUGAL FIELD IN MHS

The fine–grained weakly magnetic particles dispersed in a ferrofluid under a magnetic field behave as holes characterised by a mutual interaction of their dipole magnetic moments. Creation of chains in the direction of the magnetic field intensity as a result of mutual interaction of the particles was observed.

The intensity and orientation of the magnetic field, magnetic properties of ferrofluid, as well as the geometric shape and magnetic properties of grains affect the structure of particle formed in a volume of the ferrofluid under the influence of the magnetic field. The mutual interaction forces between non–magnetic balls was measured by Fujita and Mamiya [10].

The dependence of the intensity and orientation of the forces of mutual interaction on magnetic properties and shape of the grains, as well as comparison of the experimental results with a theoretical dipole model have been described in [11, 12]. The formation and stabilisation of the structures has undesirable effect on the separation process of fine particles. In the case of a wide range of particle size, viscosity of the separating medium increases.

Laboratory investigation of separation under a centrifugal field was carried out by applying a laboratory hydrocyclone. A suspension of $SiO_2$ and $CuFeS_2$ particles, with particle size –0.051 + 0.040 mm, in a ferrofluid, was fed, by a volume–controlled pump, to the hydrocyclone, under pressure of 0.1 to 0.5 MPa. The sink and float products were collected under a continuous regime.

After the first step of separation the purity of products thus obtained was about 75%. The grade of the sink and float products can be increased by using cleaning and scavenging separation stages. When compared with magnetohydrostatic microseparation, the application of the centrifugal force is characterised by a higher efficiency.

## CONCLUSIONS

The laboratory tests have shown that a ferrofluid can be used as a separating medium for physical treatment of primary and secondary raw materials. High efficiency of of separation can be achieved by the application of this technique in practice.

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## REFERENCES

[1] V.N. Gubarevich: Development of a new magnetic separator for mineral processing and separation of non–magnetic materials ion ferrofluids. *In: Proc. of Conf. "Theoretical and technological problems of magnetic separation of raw materials"*. Košice (1981) (in Russian)

[2] *Magstream News* **1**/1 (1988)

[3] J.I. Lin, T. Fujita and M. Mamiya: Separation of particles in hydrocyclone using magnetic fluids. *In: Proc. XVI IMPC*, Elsevier Science Publishers, Amsterdam (1988), p. 915

[4] U. Andres: *Magnetohydrodynamic and magnetohydrostatic methods of mineral separation.* John Wiley and Sons, New York, Toronto, Jerusalem (1976)

[5] M. Lovas: Theoretical and practical evaluation of isodynamic channel of MHS separator. *Seminar of Young Scientists*, Kosice (1987), (in Slovak)

[6] S. Jakabsky, M. Lovas, V.N. Gubarevich and V.S.Vidsota: Magnetohydrostatic separation of primary and secondary raw materials. *In: Proc. XIXth Sci. Colloq.* (Prague), 1991 (in German)

[7] A.B. Galjuchin et al.: *Separation of raw materials in quasiheavy medium.* Novosibirsk (1984), (in Russian)

[8] S. Jakabsky, T. Ratajczak and J. Topolnicki: Measurement of upthrust density in magnetic fluids. *Arch. Gorn.* **4** (1989), 707

[9] S. Jakabsky, I. Zahatnansky, M. Lovas and D. Bachleda: Automatic regulation of ferrofluid density in a magnetohydrostatic separator. *In: Proc. Conf. "Automation and computer control in mineral processing"*, Herlany (1991), (in Slovak)

[10] T. Fujita and J. Mamiya: Interaction forces between non–magnetic particles in the magnetised magnetic fluid. *J. Magn. Magn. Mater.* **65** (1987), 207

[11] M. Lovas and S. Jakabsky: Interaction among solid bodies in a homogeneous magnetic field. *In: Proc. 8th Czech. Conf. Magnetism*, Kosice (1988), (in Slovak)

[12] M. Lovas: Interaction among solid particles in homogeneous magnetic field. *Seminar of Young Scientists*, Kosice (1988), (in Slovak)

[13] S. Jakabsky and M. Lovas: Magnetohydrostatic separation of secondary raw materials. *In: Proc. Conf. "Materials and Ecology"*, Tanger Ltd., Ostrava (1992)

**Michal Lovás**: for biography see *Magn. Electr. Sep.* **7** (1995)

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*Keywords*: ferrofluids, magnetohydrostatic separation, density, controller, optimisation

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