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HIGH GRADIENT MAGNETIC SEPARATION ORDERED MATRICES

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INTRODUCTION: Magnetic separation is a complex physical process based on the magnetic phenomena and the magnetic properties of the substances. Several separation procedures are known: separation according to magnetic susceptibility, magnetohydrostatic separation, magnetohydrodynamic separation, separation using eddy currents. The principle of separation by magnetic susceptibility consists in the different action of the magnetic force upon the components of a mixture in competition with other forces, such as drag force, gravity or friction force. Within the separation by magnetic susceptibility procedures, the high gradient magnetic separation (HGMS) technique has a special place because of the practical necessity of capturing very small particles with low magnetic properties from the fluids. The HGMS direct and indirect (also called magnetic seeding) techniques were applied to purify kaolin clay, desulphurize coal, process rare metals ores, treat water polluted with heavy metal ions, organic substances or microorganisms, treat water from conventional and nuclear power plants, treat urban waste water, purify industrial gas etc.

The magnetic separation of some biological entities that have intrinsic magnetic properties (red blood cells, "magnetic" bacteria) can be described as *a direct separation method*, because the magnetic force is directly applied on the entity that has to be separated. For this reason we are considering that the magnetic carrier technique (by which there are manipulated non-magnetic entities bound to magnetic particles) is *an indirect separation method.*

DISCUSSION: The main factor in the magnetic separation is the magnetic force, F_m. The general expression of F_m acting on a paramagnetic particle, which has the magnetization linearly proportional to the applied magnetic field is

$$F_m = \mu_0 V_p (\chi_P - \chi_L) H \nabla H \qquad (1)$$

where V_p is the particle volume, χ_P - the particle susceptibility, χ_L - the fluid susceptibility and ∇H is the magnetic field gradient. As one can see, F_m depends on ∇H, so in order to obtain a high value of magnetic force it is necessary to create a high

gradient magnetic field. There are two different means to obtain a high gradient magnetic field. One possibility is a special design of the polar pieces (edges, peaks etc.) that limit the separation volume. In this case, ∇H value is often strong enough to capture or to deviate the small sized paramagnetic particles that are placed at a relatively long distance from the polar pieces. The other possibility is by adding some small and easily magnetizable ferromagnetic elements (wires, balls etc.) within the separation volume. The role of these elements is to create high local gradients of the magnetic field (of the order $\sim 10^5$ kOe/m); these gradients allow the appearance of very intense magnetic forces with short-range action. This setup of ferromagnetic elements that disturb the background magnetic field forms a HGMS matrix that is the characteristic component of a HGMS separator [1]. The most used matrices are made from thin wires obtained from soft magnetic alloys (i.e. Fe-Ni alloy). The wires can be disorderly packed or can be arranged in an ordered net. The ordered matrices have some advantages compared to the random ones: they have a constant packing factor throughout the entire volume, the local fluid velocity variations are small and the removal of the captured particles is easier.

A HGMS ordered matrix could be made in three flow - capture variants: transversal configuration (T) for which the fluid flow, the magnetic field and the wires are reciprocally perpendicular; longitudinal configuration (L) for which the fluid flow and the magnetic field are parallel with each other and perpendicular to the wires; axial configuration (A) for which the flow and the collecting wires are parallel and the magnetic field is transversal (Figure 1).

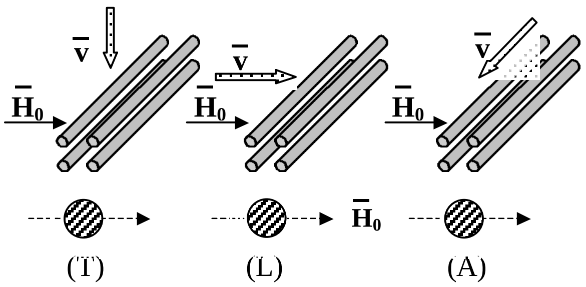

Fig. 1: Flow – capture configurations for HGMS ordered matrices: transversal (T), longitudinal (L) and axial (A).

In essence, a magnetized ferromagnetic wire can capture a paramagnetic particle if F_m is at least equal to the drag force (one could neglect the gravity force). As can be seen in Figure 1, the particles are captured in two regions of attraction situated around the axis parallel to the direction of the applied field H_0 and form deposits that have an approximately fan shaped section.

Usually, one could vary the force F_m by increasing or decreasing the applied field H_0 and the drag force by changing the average fluid flow velocity.

For a ferromagnetic wire – paramagnetic particle system there is another possibility to modify the force F_m. It consists in the different alignments of the wire to the direction of the applied magnetic field H_0. In this case, the force F_m on a particle is:

$$F_m = (4/3)\,(\pi\mu_0 b^3 a^2 \chi_p M_S H_0 / r_S^3)\,\sin^2\alpha \qquad (2)$$

where b is the particle radius, a the wire radius, χ_p the particle susceptibility, r_s the distance between the wire axis and the particle and á the angle between the wire and the H_0 direction [2].

The relation (2) shows clearly that F_m depends on á; consequently, in order to modify the magnetic force between the wire and the particle, it is enough to modify the angle between the wire and the applied field H_o direction (Figure 2).

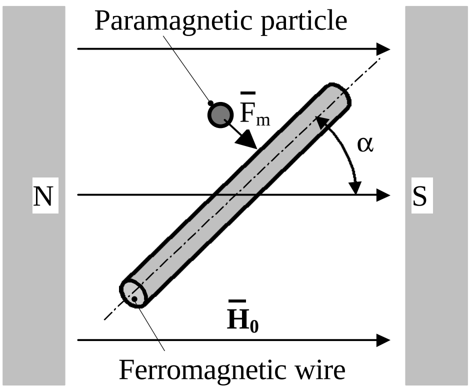

Fig. 2: System of a ferromagnetic wire and a paramagnetic particle: F_m depends on the α angle.

APPLICATIONS: Figure 3 shows a possible practical application of the relation (2). A HGMS ordered matrix (configuration T) made from parallel wires is placed in a background magnetic field H_0. The matrix must have the wires perpendicular to the field H_0 direction (á = 90^0) in order to capture the particles from the fluid. It is not necessary to cancel the applied magnetic field H_0 to remove the captured particles. A simple rotation of the matrix so the wires become parallel to the H_0 direction (á = 0^0) will lead to the cancellation of F_m and, as a consequence, to the detachment of the particles from the wires. Another advantage is that one could use permanent magnets as magnetic field source [3].

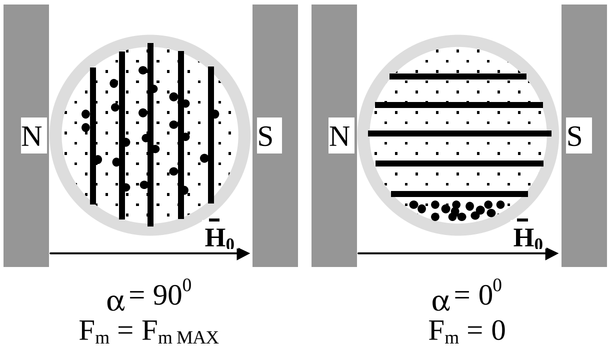

Fig. 3: The capture and the removal of the paramagnetic particles in a HGMS ordered matrix.

Such an ordered HGMS matrix, manufactured from thin ferromagnetic wires (25-60 ìm diameter) covered (or not) with a biocompatible coat (glass) and placed in the gap of a magnetic circuit excited by NdFeB magnets, could be a magnetic separator for sorting magnetic beads (1-3 ìm) in biological assays.

One could also obtain the concentration of the magnetic entities with or without intrinsic magnetism by magnetic deviation under F_m action in which case the laminar flow is an essential condition for the separation.

Adequate ferromagnetic elements situated within the separation volume can disturb on a short distance the flow trajectory stronger compared to the disturbance obtained on the same distance when the magnetic field gradient is generated by external polar pieces. In this case, the laminar flow is not an essential condition.

A magnetic separator that can be used to concentrate the paramagnetic microparticles is schematically shown in Figure 4. The HGMS ordered matrix consists of some parallel plans of wires (see in section in Figure 4b) situated also parallel to the magnetic poles. The wires from the same plan make two identical nets that form an angle (10^o-30^o) with the central vertical axis. Under the dominant action of the magnetic forces determined by the wires, the magnetic particles are deviated laterally and down and finally evacuated through two lateral collector tubes [4].

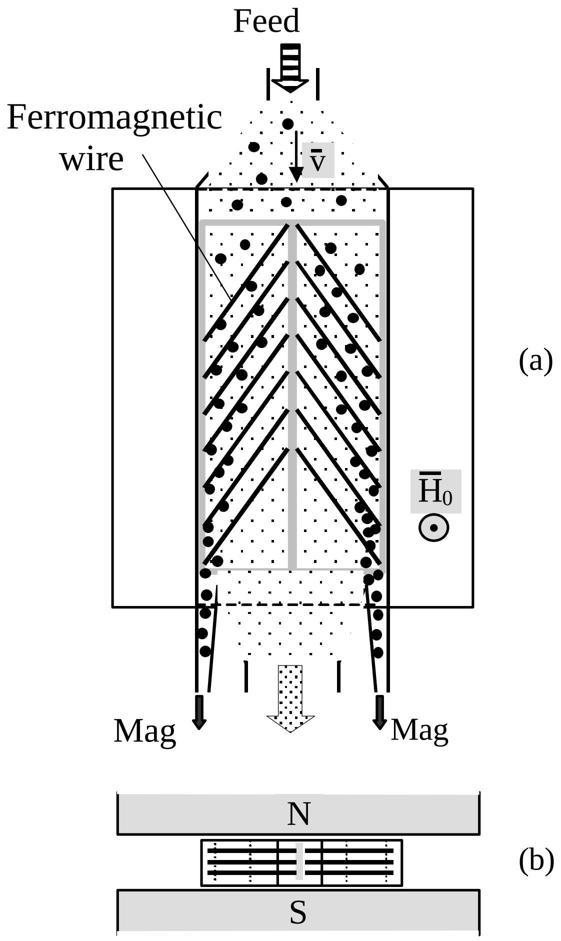

Fig. 4: Magnetic sorter with HGMS matrix used to concentrate paramagnetic particles: (a) longitudinal section, (b) transversal section.

We realized an experimental set-up of a magnetic separator as shown in Figure 5. This separator is made from a magnetic circuit excited by a pair of NdFeB magnets; a HGMS matrix is placed in the gap in axial configuration (A).

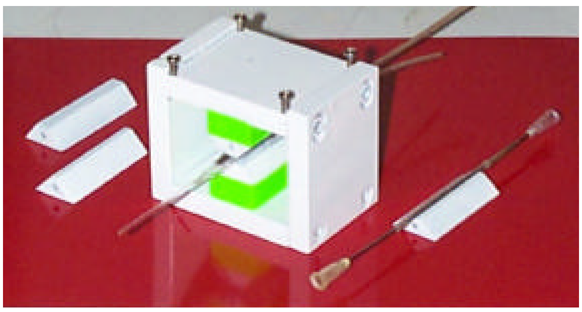

Fig. 5: Experimental set-up of a magnetic separator with axial HGMS matrix.

The matrix has an active length of 40 mm and consists of amorphous magnetic metallic wires covered by a glass coat (total diameter of 36 ìm). The magnetic field background can vary by moving the upper polar piece or by using polar pieces of different shapes (up to H_{max} = 12.6 kOe). The magnetic separator was manufactured for experiments of capturing with high efficiency low paramagnetic microparticles from flowing fluids.

CONCLUSIONS: In some cases, the magnetic separation process can be improved by using HGMS ordered matrices, because they promote the appearance of short-range intense magnetic forces that are able to capture or to deviate more efficiently low paramagnetic microparticles or biological entities with induced paramagnetism.

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