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SEPARATION EFFICIENCY DETERMINING PARAMETERS IN HIGH GRADIENT MAGNETIC CENTRIFUGATION

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ABSTRACT

Biotechnological processes are established as a standard method in industrial production processes. As a result of intensive and expensive purification of the fermentation broth, product yield is dropping heavily in each processing step and price even skyrockets for some products. Therefore classical downstream processing is considered to be a bottleneck. By means of magnetic carrier particles with specific surface functionalization, a selective separation of the target product out of the gross bio broth is possible. High Gradient Magnetic Separation (HGMS) allows highly efficient product recovery at a minimum of process steps. Apart from industrial reservation in the utilization of this novel technology the lack of large scale magnetic separation equipment inhibits the transfer into industrial application. A novel magnetic separator utilizing a rotating magnetic matrix within an external magnetic field was developed at the MVM. The combination of the highly efficient HGMS principle with continuous centrifugation allows for large scale selective separation. The capacity limitation of classical HGMS filters is avoided by continuous cleaning of the magnetic matrix due to centrifugal forces. This paper presents the basics of selective magnetic separation strongly focused on the novel separator design as well as experimental results. The work is complemented by theoretical considerations.

KEYWORDS

Magnetic Separation, Magnetic Enhanced Centrifugation, HGMS, Selective Separation, Bioseparation, Debottlenecking, Down Stream Processing, Finite Element Method

1. Introduction

The great impact of biotechnological products demands new downstream technologies for smarter product recovery and process intensification. An approach which fulfils the requirements for higher quality and production yields is the application of a hybrid separation process like High Gradient Magnetic Separation (HGMS). Bottom line of this new concept is to recover the biological target molecules selectively in a magnetic field using surface functionalized magnetic carrier particles. The method allows a continuous separation of the target product from a raw fermentation broth. With this technique it is possible to separate sophisticated products with less process steps. This leads to lower product loses along the downstream process line.

Using batchwise HGMF (High Gradient Magnetic Filtration) assures high separation efficiencies of the loaded magnetic carrier particles at lab scale, but suffers from cleaning insufficiencies and capacity limits at large scale. Consequently magnetic

separation technology has not been transferred into industrial application for biotechnological processes yet, even though it is well established in micro scale for analytic applications.[3]
At the Institute of Mechanical Process Engineering (MVM) a magnetic enhanced centrifuge has been developed as a test facility (Fig. 1, left). The apparatus is composed of a centrifuge which is installed in the centre of an electromagnetic coil. The external electromagnetic field is enhanced by a magnetisable matrix which is positioned inside the apparatus. Magnetic particles are collected at the matrix surface like in classical HGMF, but centrifugal forces are used for continues removal of the collected particle from the matrix. This way the magnetic enhanced centrifuge can be actuated continuously.

To sum up, the new Magnetic Enhanced Centrifuge (MEC) combines the conventional HGMF with its high magnetic gradient with the continuous operating centrifugation; enabling therefore a highly efficient and continuous operating separation process.

2. **Theory**

The HGMS technology takes advantage of a high magnetic field gradient $\nabla \mathrm{H}$ which excites a powerful magnetic force $\mathrm{F_M}$ [1].

$$\mathrm{F_M} = \mathrm{V_P} \cdot \mu_0 \cdot \mathrm{M_P} \cdot \nabla \mathrm{H} \qquad \text{Eq. 1}$$

with
$\mathrm{V_P}$: particle volume $[\mathrm{m}^3]$
μ_0: vacuum magnetic permittivity $[\mathrm{Vs/Am}]$
$\mathrm{M_P}$: particle magnetization $[\mathrm{Am^2/kg}]$

A high gradient is induced by a magnetisable wire matrix which strongly distorts the external magnetic field strength H .

$$H = (B - B_r) / \mu_0 \mu_r \qquad \text{Eq. 2}$$

with
μ_r: relative magnetic permittivity $[\mathrm{Vs/Am}]$
B: magnetic field density $[\mathrm{T}]$

The strength, scope and extension of the distortion of H depend on the geometry of the matrix.

Besides the magnetic force, two other major forces influence the collection, transport and detachment of particles at the rotor: the centrifugal forces F_z and friction force F_F.

$$F_z = m\omega^2 r \qquad \text{Eq. 3}$$

$$F_F = \mu_F \cdot F_M \qquad \text{Eq. 4}$$

Due to rigid body motion of the liquid inside the rotating bowl hydrodynamic forces in rotation direction can be neglected while axial flow condition is crucial for the separation. On one hand it determines the residence time of the non-magnetic particles and on the other hand it influences the capture radius of the wire through. Particles approaching the wire in the area spanned by a capture radius R_{Ca} (Eq. 5) can be considered as collected on the wire.[2] The capture radius only depends on the axial superficial velocity v_0 and the magnetic velocity v_m which can be calculated according to Eq. 6.

$$Rc_a \cong \frac{3}{4}\sqrt{3}\left(\left|\frac{v_m}{v_0}\right|\right)^{\frac{1}{3}}\left[1-\frac{2}{3}\left(\frac{v_m}{v_0}\right)^{-\frac{2}{3}}\right] \qquad \text{Eq. 5}$$

$$v_m = \frac{2}{9}\mu_0 \Delta\kappa M_D H_0 \frac{b^2}{a\eta} \qquad \text{Eq. 6}$$

Due to the magnetic force, the product-carrying magnetic beads are attracted to the matrix, where the centrifugal force transports them along the wires in direction to the wall and collection container where they are flushed out of the apparatus (Fig. 1). Non-magnetic particles and the fermentation media are discharged with the main stream at the bottom of the centrifuge.

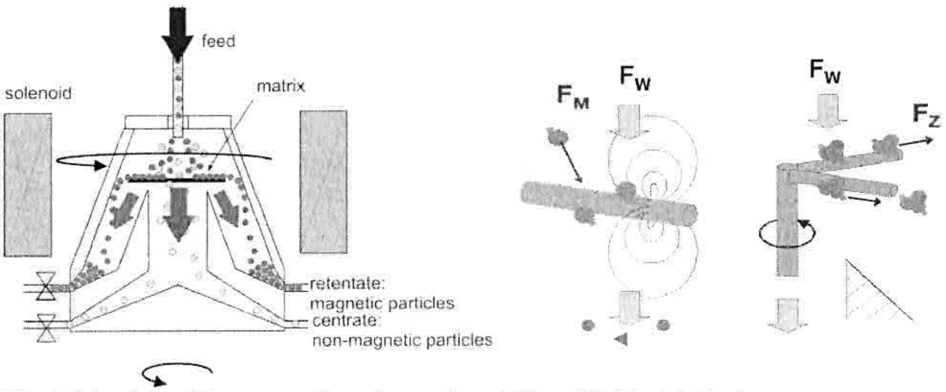


Fig. 1 Principle of the magnetic enhanced centrifuge (DuPont Patent EP000001715956A1)

The combination of the centrifugal force and the superimposed force of the electromagnetic field provide not only a selective segregation of the magnetic particles from the fermentation media but also a continuous cleaning of the matrix and discharge.

3. Methods and Material

As experimental product for the separation trials a watery 2g/l PVAc particle suspension has been prepared and fed into the magnetic field enhanced centrifuge. The magnetic carrier M-PVAc particle from Chemagen which were used for testing are shown in Fig. 2. The particles are super-paramagnetic due to their very low magnetic remanence M_R of 0.65 Am²/kg. Their saturation magnetization M_S is about 45 Am²/kg. The mean particle size is 1.7µm (Fig. 3).

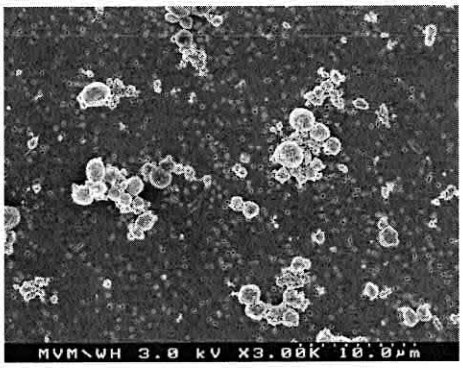


Fig. 2: SEM of M-PVA Magnetic Beads

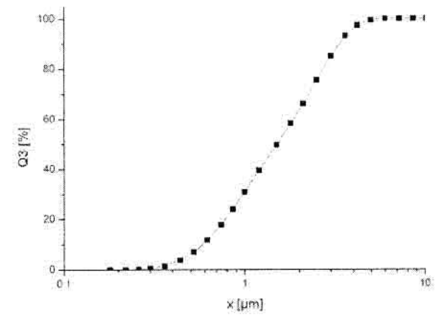


Fig. 3: Particle size distribution of magnetic beads (Sympatec HELOS (H9236) SUCELL)

During the experiments the centrate is continuously floating out of the centrifuge and several samples are taken at stationary condition, which has been determined to be after about 3min depending on concentration and rpm.

For the investigation of the separation capabilities of the centrifuge water suspended non-functionalized particles are used. The bio product adsorption has been omitted therefore. The separation efficiency E_i is calculated as the ratio of centrate and feed concentration.

$$E_i = 1 - \frac{c_{i,centrate}}{c_{i,feed}} \qquad \text{Eq. 7}$$

The separation efficiency has values between 1 (perfect separation) and 0 (no separation). The concentration analytics are performed gravimetrically.

The separation efficiency is influenced by the operation method, the apparatus design, especially the matrix stages and geometry, the magnetic carrier particles and the fluid system. The most important parameters are shown in Fig. 4.

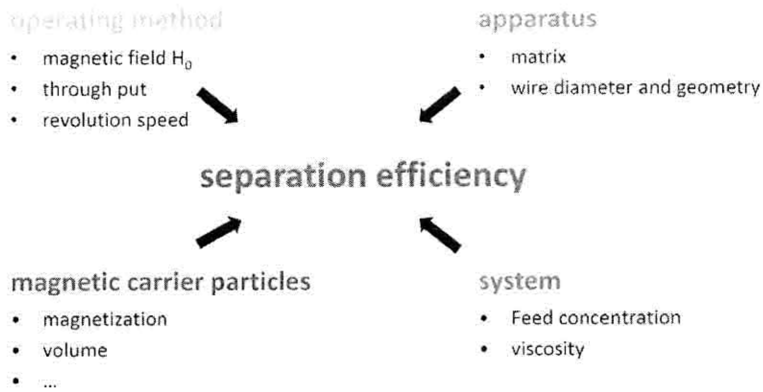
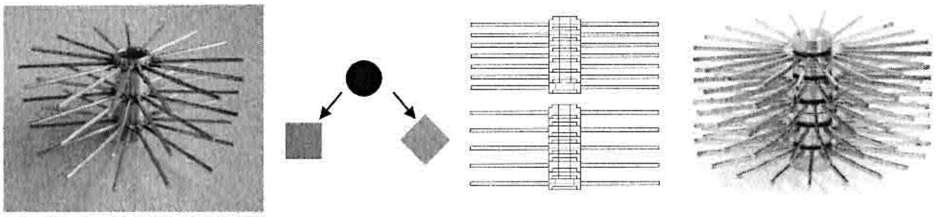


Fig. 4 Parameter which influence the separation efficiency

4. Results

In the course of the development of the new MEC, different parameters which influence the separation efficiency are investigated. The results in this work focus on the optimization of the HGMS matrix. Experiments showed that the raise of the matrix stages from 1 to 3 improves the separation efficiency from 75 % to 97 % [2]. This shows that the matrix geometry and fabrication still have optimisation potential to improve the performance of the separation apparatus for high throughput.

The more wire surface is offered the higher is the expected separation efficiency. Therefore a new matrix type is developed (Fig.5). Each element consists of 20 cuboids wires and it is fabricated by laser cutting and welding to a cylindrical holder. The individual matrix elements can be assembled in different distances to each other. The number of matrix steps can be raised to maximum 6 stages, due to the available space inside the centrifuge.



a) b) c) d)

Fig. 5: a) cylindrical 3-ary matrix with 15 wires at each stage b) cylindrical, rectangular and rectangular (rotated by 45°) wire intersection c) variation of the assembly of rectangular matrix elements d) rectangular 6-ary matrix with 20 wires at each stage

As a first step the matrix geometry was simulated by the finite element method analysis software, COMSOL Multiphysics. In order to determine the distribution of magnetic flux density around the different wire geometries, a 3D simulation model was built in AC/DC Module Magnetostatics. The model includes a magnetic wire, 10mm in length and 1mm in edge length or diameter, with the relative permeability μ_r = 4000. The wire is centred between two permanent magnets which are positioned face to face to each other generating a nearly homogeneous field in between.

The magnetic flux density of the simulated wire is shown in Fig. 6. Comparing the gradient of the magnetic flux density of the cylinder with that of the cuboid along the y-direction (parallel to H_0 and v_0) in Fig. 7 is about 0.2 T/mm higher than that of the cuboid. However, the strong rise of the flux density towards the edges of the rectangular geometry shows a superelevation of the gradient of B in 45° angle direction: The gradient B in the mentioned direction is about 0.6 T/mm higher than that of the cylindrical geometry. Besides, the gradient B of both geometries is alike.

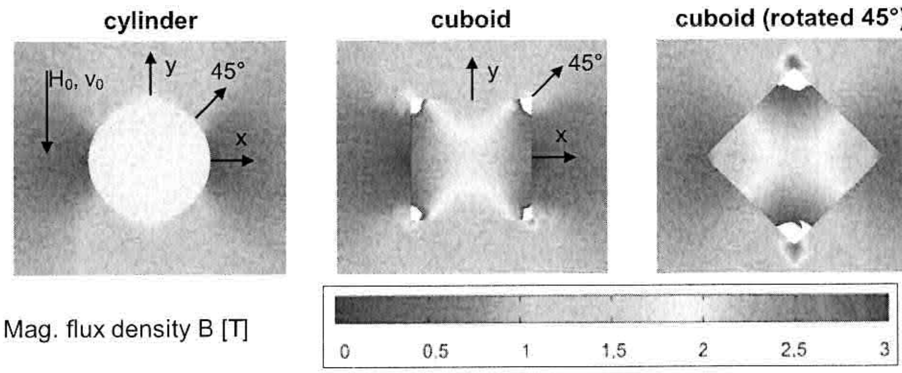


Fig. 6: Magnetic flux density of the three comparative geometries

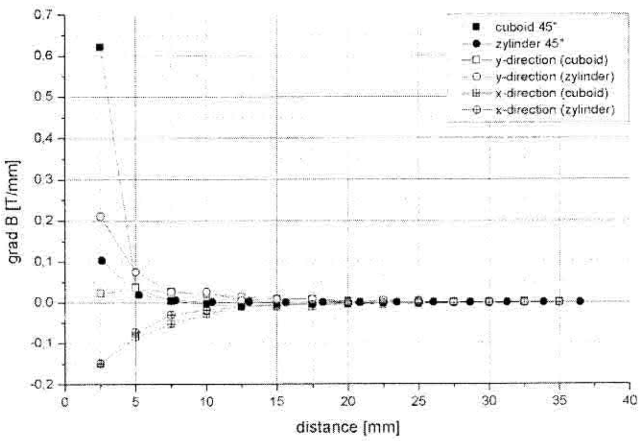


Fig. 7: Gradient of the magnetic flux density along three directions: y-direction, x-direction and in 45° angle to the flow velocity v_0 and the background field H_0

The isosurface lines of the magnetic field strength in Fig. 8 specify the attachment area of paramagnetic particles. Due to Eq. 1 particles experience a positive magnetic force if the gradient of the magnetic field strength ∇H is positive. In other words particles which flow into an increasing magnetic strength field are attracted to the wire; decreasing strength provides an repulsion of the magnetic beads. Comparing the dimension of the attachment area, it seems that the one of the cuboid geometry is slightly larger than that of the cylinder. The cuboid which is rotated by the angle of 45° shows an attraction area that is similar to that of the cylinder. Regarding the simulation results it is expected that the separation efficiency of the newly developed cuboid matrix is at least as good as that of the cylinder matrix. Due to the fact that the rectangular matrix step has a major number of 20 wires comparing to 15 wires of the cylindrical matrix step, it is assumed that the separation efficiency will be even higher.

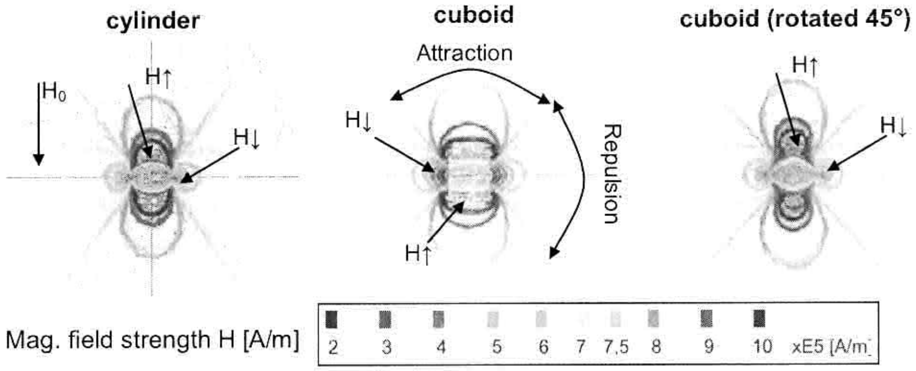


Fig. 8: Magnetic field strength of the three comparative geometries

Separation experiments with a three-ary rectangular and cylindrical wire matrix were performed. Due to the increase of the matrix wires from 15 to 20, the capture area is enlarged by the factor ¾. The distance between the matrix steps is kept equal.

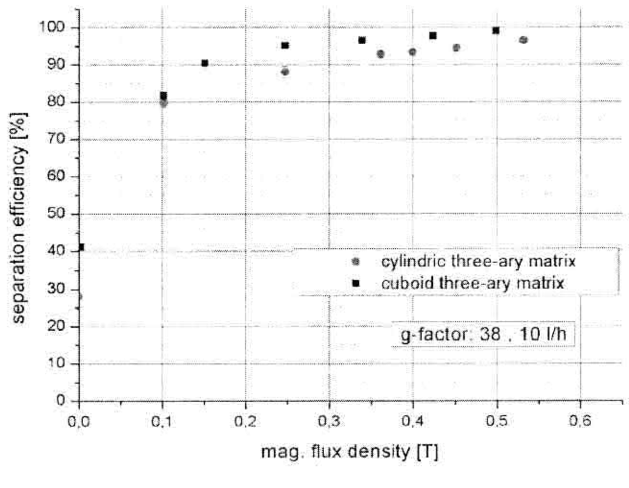


Fig. 9 Separation efficiencies of the cylindrical and rectangular three-ary matrix at 10l/h feed stream and a max. g-factor of 38 (1000rpm)

Experiments with the newly developed rectangular wire matrix show a significant increase of the separation efficiency compared to the cylindrical wire matrix (Fig. 9). While the maximum separation result of the cylindrical 3-ary wire matrix at 0.53T is (96.5±0.5)% a maximum separation efficiency at 0.5 T of (99±1)% is reached with the rectangular 3-ary matrix. The experimental results confirm the prediction which was made with the simulation of the wire: The matrix performance is enhanced by the new development and the fabrication process is simplified.

5. Conclusion

The new hybrid separation device has proven to be a very efficient and flexible tool for the separation of magnetic particles out of feed stocks. By utilising High Gradient Magnetic Wire Matrices it is capable of processing magnetic material and/or small particle sizes. Due to its design a continuous separation is possible. The presented results show the high potential in the area of bio separation using surface functionalized magnetic particles and HGMS separation equipment for bio affinity driven selective separation.

6. Acknowledgements

The authors owe special thanks to all organisations and companies supporting magnetic separation at the Institute of Mechanical Process Engineering and Mechanics (MVM). Among those are the European Union – FP6, the German Ministry of Economy (BMWI), the NanoBioMag Consortia, DuPont USA, Bokela GmbH, LUM GmbH, BiLaMal GmbH, Wolftechnik GmbH, Steinert GmbH and the Research Center Karlsruhe (FZK).

REFERENCES

[1] Franzreb, Mathias. Magnettechnologie in der Verfahrenstechnik wässriger Medien. Habilitation FZKA 6916, Forschungszentrum Karlsruhe, 2003.

[2] Gerber R. and Birss R.R. *High Gradient Magnetic Separation*. Research Studies Press, 1983.

[3] Stolarski, Mathias; Keller, Karsten; Eichholz, Christian; Nirschl, Hermann. Continous Selective High Gradient Magnetic Bio Separation Using Novel Rotating Matrix Centrifugation. *American Fitration & Separations Society Annual Conference*, 2008.