A new approach of magnetic separation

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Abstract

Magnetic separation is a very old separation technology, which is mainly used, in the mineral industry. In these applications, the magnetic force is applied to separate magnetic from non-magnetic materials. The separation efficiency strongly depends on the magnetic properties of the materials as well as the particle sizes. This paper introduces a totally new magnetic separation process, which combines aspects of magnetic separation with aspects of cake filtration. It describes the phenomenology of this new hybrid separation process and points out various fields of applications.

The experimental results presented in this work show the significant influence of a superposed homogeneous or inhomogeneous magnetic field on the filtration performance of inorganic iron oxide pigments. The reason can be seen in magnetophoretic effects as well as magnetic field enhanced structure changes of the filter cake. These mentioned effects result in a faster cake formation, a higher permeation rate through an already built filter cake and therefore an integral improvement of the overall cake filtration process. Next to the extensive experimental results this work also introduces a theoretical approach for the description of the cake formation with superposed magnetic fields. In addition, the work discusses scale up related issues and other potential hybrid separation processes using magnetic fields.

Introduction

As a classical unit operation the solid liquid separation can be found in most of the industrial production processes for particulate products. Due to that historical development dating back centuries, modern mechanical separation processes are settled on a high technical level. To extend the field of application for mechanical separation processes synergetic effects have to be used and hybrid processes have to be developed. In this development important milestones are represented by e.g. steam-pressure-filtration [1], steam-pressure-centrifugation [2], “hot” chamber press filtration and electro press filtration [3].

Considering the significant improvements in superconductivity and therefore the energy efficient creation of strong magnetic fields there are many more opportunities for magnetic field enhanced separation processes than the sorting in the mineral industry. In the last years for example the High-Gradient-Magnetic-Separation emerged in industry-scale filtration for the separation of low concentrated suspensions e.g. in the wastewater industry. In order to improve filtration kinetics for high concentrated suspensions a new application of magnetic fields, the magnetic field enhanced cake filtration [4] has been developed in collaboration between DuPont and the University of Karlsruhe.

In this new hybrid filtration process the improvement of filterability is achieved by magnetophoresis and magnetic self-assembly in the suspension and the filter cake. Magnetophoresis hereby decreases the rate of cake formation and magnetic self-assembly increases the permeability of the cake by structuring it.

In this paper both effects are experimentally investigated. On basis of Yukawa´s theoretical approach for the electrokinetic filtration [5] an equation for magnetic field enhanced cake filtration considering magnetophoresis is derived and experimentally confirmed.

Theory

The new developed process combines conventional separation technology with magnet technology. For the understanding it is therefore very important to discuss both aspects/technologies separately before going into detail about the magnetic field enhanced filtration. The theoretical part is kept very short in this work. More information can be found in physics books and in Fuchs [6].

Magnetic separation

According to their magnetic properties materials can be classified in three different main groups, as there are diamagnetics, paramagnetics and ferromagnetics. These materials differ significantly in their magnetic properties, which can be quantified using e.g. the magnetic susceptibility χ.

Considering magnetic separation the bottom line is that para- as well as ferromagnetic materials experience a force in the direction of the magnetic field gradient whereas diamagnetics experience a magnetic force in the opposite direction. The magnetic force can be calculated as follows.

$$F_m = \mu_0 \cdot V_p \cdot M_p \cdot \nabla H \qquad \textbf{eq. 1}$$

$$F_m = \frac{1}{\mu_0} \cdot \chi \cdot V_p \cdot B \cdot \nabla B \qquad \textbf{eq. 2}$$

Filtration

In general filtration processes are characterized by the retention of solids by a filtermedia or bridges of particles. During build-up of filter cake the liquid phase passes through the filter media due to a driving force like gas differential pressure, centrifugal pressure, hydrostatic pressure or mechanical pressure, whereas the solids are held back by the filter media or the accumulated filter cake.

For a laminar flow of a Newton fluid through an incompressible packed bed the flow rate can be calculated using Darcy's law.

$$\frac{dV_l}{dt} = \frac{A \cdot \Delta p_H}{\eta \cdot R} \qquad \textbf{eq. 3}$$

The combination of Darcy´s law with a mass balance results in the fundamental cake formation equation.

$$\frac{t}{V_l} = \frac{\eta \cdot r_c \cdot \kappa}{2 \cdot \Delta p_H \cdot A^2} \cdot V_l + \frac{\eta \cdot R_m}{\Delta p_H \cdot A} = a \cdot V_l + b$$ **eq. 4**

Just by experimentally determining slope a and interception b, the filter media resistance as well as the specific cake resistance can be calculated.

Idea of magnetic field enhanced cake filtration

The magnetic field enhanced cake filtration synergizes well known effects from magnetic separation [6] and classical cake filtration in differential pressure field in a not yet practised manner. The systematic use of homogeneous and inhomogeneous magnetic fields results for the former in magnetic volume forces preferably counter wise to the pressure force direction and for the latter in interparticle interactions that cause structural modification of the filtercake (Fig. 1). Both result in strong improvement of filtration kinetics. The magnetic force causes the solid phase to move with differential speed compared to the liquid phase. In case of counter wise orientation that leads to slower cake formation or even to prevention of cake formation at the beginning of a filtration process.

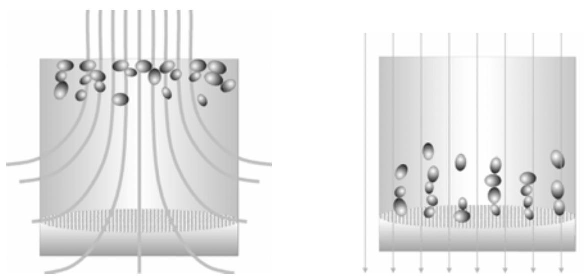

Fig. 1: Effect of macroscopic and microscopic magnetic force

Whilst macroscopic magnetic forces only exist in inhomogeneous external magnetic fields, structural modification of the filter cake is observed throughout any shape of magnetic fields. This originates in field induced microscopic particle-particle interactions [8], [9]. With the magnetization of the particles in external field the particles themselves act as microscopic magnets with North and South Poles. Once the gravitational force is not dominating over the interparticle forces, chainlike agglomerates with attracting force in external field direction and repulsing force orthogonal to the external field are formed [10]. Rosensweig [11] therefore defined the influence of a magnetic field on the structure of a packed bed with a characteristic magnetization number E_G, which describes the ratio of potential energy in the height of the particle diameter x and the repulsive magnetic energy.

$$E_G = \frac{24 \cdot \rho_s \cdot g \cdot x}{\mu_0 \cdot M^2}$$ **eq. 5**

He differentiates between $E_G<1$ for an open structure, $1<E_G<10$ for a partly structured bed and $E_G>10$ for a compact isotropic bed.

Experimental Apparatus and Product

The filter cell is a CUNO nutsche filter. The unit can be axially positioned within the warm bore of a 5T super conducting magnet. The position of the nutsche filter determines the direction and shape of the magnetic field. In the upper position the magnetic and pressure force are parallel, in the middle position no macroscopic magnetic force is acting and in the lower position the forces are acting in opposite directions. The product, called F&S, is a natural hematite with a median particle size of 4,7□m. More details about setup, product and experimental procedure an be found in Fuchs [6].

Experimental Results and Discussion

In Fig. 2 the results for the experiments in the lower position are plotted in the form of reciprocal flow rate t/V_l vs. filtrate volume V_l with the magnetic flux density B as parameter. The correlations between t/V_l and V_l are linear as shown in Fig. 2. With increasing magnetic field strength the slope of the curve decreases, which with respect to eq.(4) signifies a decrease of the specific cake resistance r_c and an acceleration of the overall filtration kinetics.

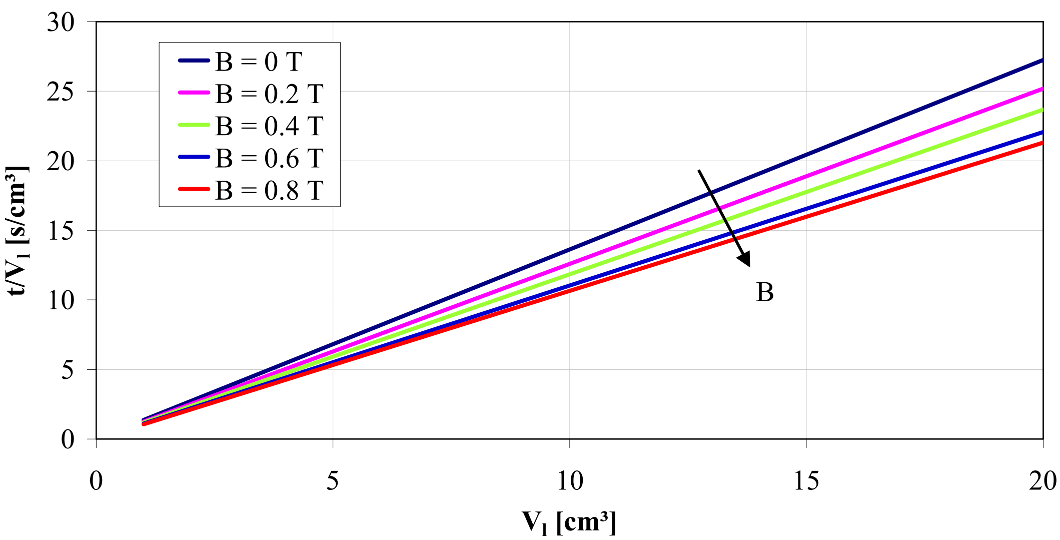

Fig. 2: Influence of magnetic field on filtration of natural ironoxide (Δp=0.8bar, product F&S)

For the product F&S an acceleration of the cake building kinetics by 22% was achieved superposing a magnetic field with B=0.8T, which is the product specific maximum flux density at which a homogeneous cake formation was still possible. Apart from the strong magnetic force on the particles the other reason for the investigated improvement at lower field strengths lies in the structural changes within the filter cake. Thus increased particle-particle interaction causes the formation of flow channels that enhance the permeability of the cake. For the lowest field strength of B=0.2T Rosensweig`s definition of E_G eq.(5) gives E_G=0.04 for the weak ferromagnetic product F&S, which still refers to an open structure of the cake. The formation of a structured filter cake with flow channels and therefore less flow resistance is also proofed by the structure of the filter cake surface. During filtration without external field smooth cake surfaces are observed, which are substituted by surfaces with periodic elevations for increasing magnetic field. Similar phenomenon was observed by Rosensweig [12] for magnetic fluids in external magnetic field. For higher field strength instabilities in the structure occurred that appeared as hexagonal patterns on the cake surface. Fig. 3 shows the slopes of the curves from Fig. 2 plotted versus the magnetic flux density B including the results for the experiments in the middle position where no macroscopic magnetic force is acting.

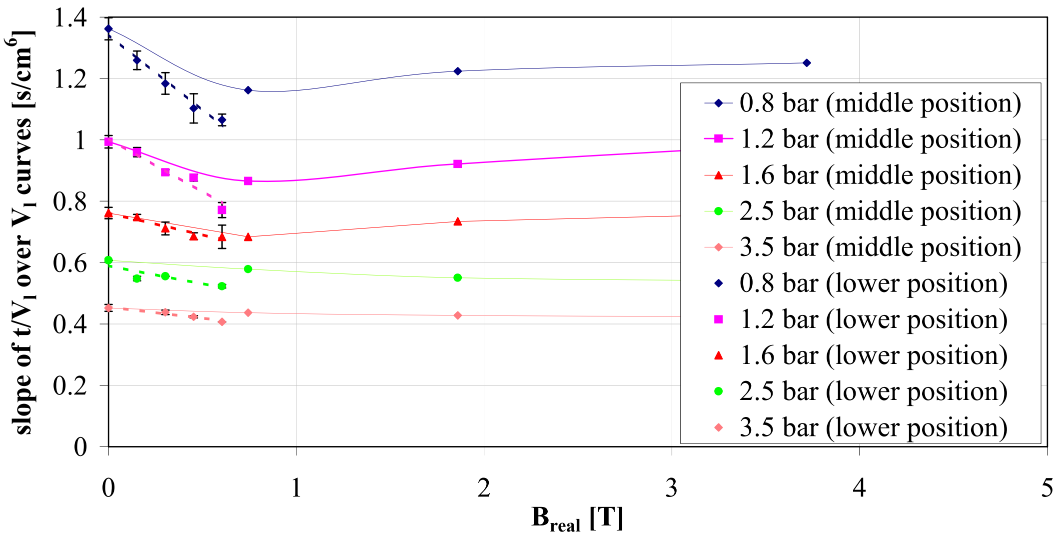

Fig. 3: Change of slope as function of magnetic flux density in middle and lower position at different filtration pressures (product F&S)

From comparison of middle and lower position at equal field strength it can be reasoned that the influence of cake structuring also has an effect in the lower position. However besides the structuring effect of the magnetic field the other important and indeed dominating mechanism is the magnetic force, which results in magnetophoresis and therefore a movement of the particles against the filtration direction in lower position. For higher field strengths (B>0.8T), as can be seen from Fig. 3 there is stagnation of filtration improvement in the middle position. When saturation magnetization of the sample is reached also the maximum of interaction potential between the chainlike structures of the cake is reached and cannot be increased beyond this point. Fig. 3 even shows a slight decrease of interaction potential, which has already been investigated by Svoboda [7].

Theoretical Approach

Fuchs [6] describes the development of a theoretical approach to quantify and predict the influence of an inhomogeneous magnetic field on the cake filtration performance. In the new fundamental cake formation equation the influence of the magnetic field is accounted for by implementing a magnetophoretic term.

$$\frac{t}{V_L} = \frac{\eta \cdot r_c \cdot \kappa \cdot \left(\frac{B^*_{crit} - B^*}{B^*_{crit}} \right)}{2 \cdot (\Delta p_H) \cdot A^2} \cdot V_L + \frac{\eta \cdot R_m}{\Delta p_H \cdot A} \qquad \textbf{eq. 6}$$

Wherein $(B^*_{crit}-B^*)/B^*_{crit}$ is the magnetophoretic quotient. The critical field force density B^*_{crit} can be calculated from the critical field strength B_{crit}, which is obtained by extrapolation, as shown in Fig. 4. Another method to determine B_{crit} is a force balance on a single particle.

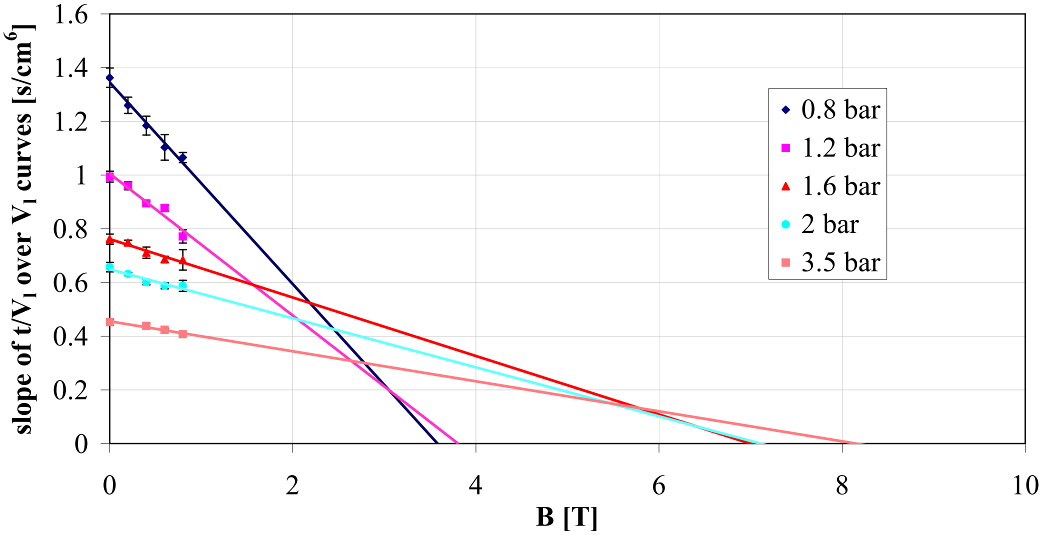

Fig. 4: Extrapolation to critical field strength for different pressures (product F&S)

A comparison of calculated slopes a of the t/V_l – V_l curves with experimentally determined ones can be seen in Fig. 5. The comparison shows a very good agreement and an error smaller than 3%.

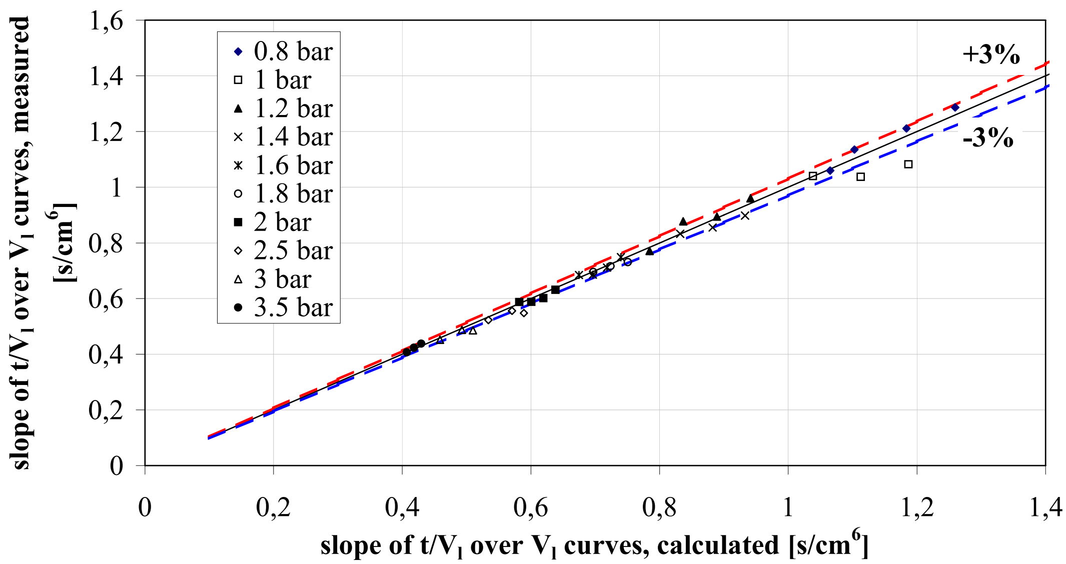

Fig. 5: Theoretical and experimental t/V_l – V_l plots for different pressures and field strength of F&S

Conclusions

The new hybrid process „Magnetic Field Enhanced Cake Filtration" was shown to be a high potential separation process for ferromagnetic and paramagnetic products. The improvement of filtration kinetics is achieved by two main effects, the external magnetic force and the interparticle magnetic force. The former results in cake formation slow down or even prevention and the latter leads to magnetic structuring of the filter cake, which increases permeability.

The dominating influences of external magnetic forces can be theoretically described. Hereby the particle movement and the resulting cake formation slow down is taken into account by implementing a magnetophoretic quotient.

Acknowledgments

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Nomenclature

Latin

A	$[A] = m^2$	cross-sectional area
a	$[a] = s/cm^6$	slope of t/V_l versus V_l curve
B	$[B] = T = N \cdot A^{-1} \cdot m^{-1} = V \cdot s \cdot m^{-2}$	magnetic flux density
B^*	$[B] = T = N \cdot A^{-1} \cdot m^{-1} = V \cdot s \cdot m^{-2}$	magnetic field force density
B^*_{crit}	$[B] = T = N \cdot A^{-1} \cdot m^{-1} = V \cdot s \cdot m^{-2}$	critical magnetic field force density
b	$[b] = s/cm^3$	y-intersection of t/V_l versus V_l curve
c_V	$[c_V] = 1$	volume concentration
E	$[E] = V \cdot m^{-1}$	electrical field strength
F_m	$[F] = N$	magnetic force
g	$[g] = m \cdot s^{-2}$	gravity constant
H	$[H] = A \cdot m^{-1}$	magnetic field strength
M	$[M] = A \cdot m^2 \cdot kg^{-1}$	magnetization
	$[M] = A \cdot m^{-1}$	magnetization
Δp	[□p] = Pa	filtration pressure
Δp_H	[□p_H] = Pa	hydraulic pressure
R	$[R] = m^{-1}$	flow resistance
r_c	$[r_c] = m^{-2}$	specific cake resistance
R_m	$[R_m] = m^{-1}$	filter media resistance
t	$[t] = s$	time
Δt	[□t] = s	time interval
V_l	$[V_L] = m^3$	filtrate volume
V_p	$[V_L] = m^3$	particle volume
$\dot{V}$	$[\dot{V}] = m^3 \cdot s^{-1}$	flux
x	$[x] = m$	particle size

Greek

κ	$[\kappa] = 1$	concentration coefficient
μ_0	$[\mu_0] = V \cdot s \cdot A^{-1} \cdot m^{-1}$	magnetic vacuum permeability
χ	$[\chi] = 1$	volume susceptibility
ρ	$[\rho] = 1$	density
η	$[\eta] = Pa\ s$	dynamic viscosity

Constants

$\mu_0 = 1{,}257 \cdot 10^{-6}\ V \cdot s \cdot A^{-1} \cdot m^{-1}$

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