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Magnetic field enhanced press-filtration

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Abstract

The proposed hybrid process represents a new application of a magnetic field which directly influences a classical press filtration. The new technology offers high potential in the field of magnetic pigment production and iron oxide processing as well as bio-separation with functionalized magnetic particles. Especially in the field of fine-scale particulate product systems high specific cake resistances result in slow cake building and dewatering kinetics, which leads to economic inefficiency.

Experimental and theoretical investigations show that the magnetic field has strong influence on cake building. Two major effects were observed: (I) In inhomogeneous magnetic fields magnetic particles experience a magnetic force counter directed to the pressure force, that results in slow down of cake formation; (II) Interparticle magnetic forces lead to structured cake formation.

This gives on one hand the possibility to uncouple fluid and magnetic particle motion to force a cake built-up in designated location of the filter chamber. The result is a big increase of the overall filtrate mass flow and therefore an improvement of filtration kinetics. On the other hand due to the particle's magnetization including the formation of an attracting north and south-pole chainlike agglomerates can be observed. This leads to a "structured" cake building and therefore higher permeability.

This work will show the effect of a superposed magnetic field on press filtration of ferromagnetic iron oxide particles (Fe_3O_4) in a lab-scale filter press.

Keywords: Cake filtration; Filtration; Field enhanced separation; Magnetic structuring; Magnetic field; Particle formation

1. Introduction

In most traditional and current industrial production processes, products accumulate in form of slurry. Due to the long historical development, modern mechanical separation processes are developed on high technical level. Increasing demands on the efficiency of production processes and the quality of their products require a continuous improvement of existing processes and the development of new process concepts. Especially in classical unit operations as solid–liquid separation the development of hybrid processes is of major interest. To extend the field of application for mechanical separation processes, new concepts have been developed. Important milestones of the development of hybrid solid–liquid separation processes are represented by steam-pressure-filtration (Gerl and Stahl, 1997), steam-pressure-centrifugation (Peuker and Stahl, 2001), "hot" chamber press filtration (Ruf and Stahl, 1997) and electro-press filtration (Weber and Stahl, 2002).

However on the way to nano- and biotechnology even harder requirements have to be fulfilled. A new approach to face these challenges and utilize synergetic effects lies in the superposition of magnetic fields. By taking advantage of the different magnetic properties of materials, additional and new parameters for the manipulation of separation processes can be developed. This enables the separation of submicron till nano-scale magnetic particles. Apart from classical applications of magnetic fields e.g. in the minerals industry for sorting, there are many more opportunities for field enhanced separation processes. One example for this advance is the high-gradient-magnetic-separation

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(Oberteuffer, 1974; Franzreb and Höll, 2000) which emerged in industry-scale filtration for the separation of low concentrated suspensions e.g. in the wastewater industry. The magnetic particles are separated by a non-remanent ferromagnetic matrix in an external homogeneous magnetic field. Due to the development of high gradients around the matrix, high magnetic forces in direction of the filter matrix act upon the particles (Gerber and Birss, 1983; Tsouris and Yiacoumi, 1997). As the matrix has a limited capacity the HGMS separation is only applicable to low concentrated feed streams. To improve filtration kinetics also for high concentrated slurries a novel application of magnetic fields, the magnetic field enhanced cake filtration (Fuchs et al., 2004) has been developed. It was shown that not only an external magnetic force on the particles but also an interparticle force that causes a self-assembled structure of the filter cake lead to improved filtration kinetics. Especially in magnetically stabilized fluidized beds these structural modifications reduce back mixing effects of solids and fluids (Rosensweig et al., 1981). While applying an external magnetic field the particles form chains with discrete flow channels in between. Due to the attractive magnetic forces the particle motion is reduced and the streaming velocity can be increased beyond the discharge velocity. Bolto et al. (1975) uses the chain-formation within a magnetic field as a switchable degree of freedom to vary the permeability of a filtermedia. By using granular magnetic particles as filter aid Bolto induced the formation of highly porous structures on top of the filtermedia by magnetization. This on one hand led to a reduction of turbidity of the filtrate and on the other hand to an acceleration of the filtration process. By a magnetic sorting step of the filter cake including the magnetic filter aid the particles can be recycled.

In combination with highly functionalized magnetic particles also an application of field enhanced filtration in specific bioseparation (Safarik et al., 2001) is easily possible and currently transferred to large scale production processes.

In the presented work, a new hybrid filtration process, the kinetics of dewatering is significantly influenced by magnetophoresis and magnetic self-assembly in the filter cake. Magnetophoresis hereby decreases the rate of cake formation and magnetic self-assembly increases the permeability of the cake by structural changes. In this paper both effects are experimentally investigated.

2. Theory

2.1. Magnetic properties of materials

Usually materials are classified according to their irritability by an external magnetic field. The quantitative measure of this irritability is the so called susceptibility χ. Depending on the magnitude of the susceptibility materials are coarsely grouped in diamagnetics, paramagnetics and ferromagnetics.

Diamagnetism ($\chi < 0$) is the weakest magnetic phenomenon. Although every substance is indeed diamagnetic, the phenomenon itself can only be observed when it is not superposed by the stronger paramagnetism ($\chi > 0$) or ferromagnetism ($\chi \gg 0$). Due to counter directed magnetic moments diamagnetic materials locally weaken the magnetic field and experience a magnetic force in direction of decreasing field gradient. The opposite effect can be observed in paramagnetic and ferromagnetic samples. They experience a force in the direction of the magnetic field gradient. This external magnetic force is indeed the bottom line of magnetic separation processes and represents to be an additional degree of freedom.

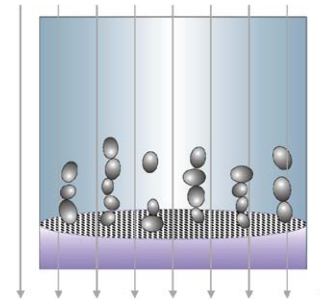

Fig. 1. Agglomerate chains.

Apart from external magnetic forces another important and up to now underrated role play interparticle magnetic forces, which are generated between particles. Due to the superposition of an external magnetic field the magnetic moments of the material are aligned according to the external field direction. The magnetized samples or particles hereby act as microscopic permanent magnets with North and South poles. Two approaching particles in an external magnetic field attract each other in direction of the magnetic field and repel each other perpendicular to the external field direction (Charles, 1988). This causes the formation of chainlike agglomerates as shown schematically in Fig. 1. The macroscopic dipole moment per volume unit of the sample is defined to be the magnetization M.

2.2. Forces acting on the particles

During filtration the interaction of different forces like gravitational, drag, external magnetic, interparticle and buoyancy forces are ruling the filtration process.

Gravitational and buoyancy forces shall be negligible in comparison to the magnetic and hydrodynamic forces represented by the drag force. The drag force can be calculated by the following equation:

$$F_D = \frac{\pi}{4} \cdot d_P^2 \cdot c_W(Re) \cdot \frac{\rho_f}{2} \cdot u_r^2. \tag{1}$$

For $Re < 0.25$, which is the case within the region of differential pressures used in this work, laminar flow can be assumed and Eq. (1) simplifies to the Stokes drag force.

$$F_D = 3\pi \cdot \eta_f \cdot d_P \cdot u_r. \tag{2}$$

The magnetic force on a particle depends on the magnetization, the volume of the particle, but also on the magnitude of the external field and its gradient ∇H as can be seen in Eq. (3),

$$F_m = \mu_0 \cdot V_p \cdot \rho_P \cdot M_p \cdot \nabla H. \tag{3}$$

There is no magnetic force without a magnetic field gradient. With the substitution of the magnetic field strength by the flux density it follows for Eq. (4):

$$F_m = V_p \cdot \rho_P \cdot M_P \cdot \nabla B. \tag{4}$$

The strong directed interparticle magnetic interactions lead to the above mentioned chain formation of magnetic particles in an external magnetic field. In magnetically stabilized fluidized beds this effect is taken advantage of to increase the fluid flow velocity and to prevent backmixing of the dispersed phase. The superposition of magnetic field and flow field results in a structured bed with discrete flow channels and a rather limited motion of the particles.

To quantify the structure of a magnetically stabilized fluidized bed Rosensweig (Rosensweig et al., 1981) recommends an energy ratio E_G.

$$E_G = \frac{E_{\text{pot}}}{E_M} = \frac{\frac{1}{6} \cdot \pi \cdot g \cdot \rho_P \cdot d_P^4}{\frac{1}{144} \cdot \pi \cdot \mu_0 \cdot \rho_P^2 \cdot M_P^2 \cdot d_P^3}. \tag{5}$$

Here the potential energy means the energy that is needed to lift the particle against the gravitational force by one particle diameter. The magnetic energy is the repulsive energy between two particles perpendicular to the external field direction. For $E_G < 1$ the structure is strongly ordered, for $1 < E_G < 10$ a partly structured bed and for $E_G > 10$ a unstructured bed is present.

By substituting the potential energy in Eq. (5) by the energy necessary to lift a particle against the drag force Eq. (6) is received.

$$E_S = \frac{E_{\text{drag}}}{E_M} = \frac{3 \cdot \pi \cdot \eta_f \cdot d_P^2 \cdot u_r}{\frac{1}{144} \cdot \pi \cdot \mu_0 \cdot \rho_P^2 \cdot M_P^2 \cdot d_P^3} = \frac{432 \cdot \eta_f \cdot u_r}{\mu_0 \cdot \rho_P^2 \cdot M_P^2 \cdot d_P}. \tag{6}$$

2.3. Basics of cake filtration

Filtration processes are characterized by the retention of solids by filtermedia or bridges of particles. During build-up of a filter cake the liquid phase passes through the built cake and 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 incompressibly packed bed Darcy's law (Eq. (7)) is applicable. With the common assumption that the resistance R consists of two serial resistances (Eq. (8)), the filter media- and the filter cake resistance, and the calculation of the cake height h_c from the filtrate mass signal (Eq. (9)), the classical cake building filtration equation (Eq. (10)) results.

$$\frac{\mathrm{d}V_L}{\mathrm{d}t} = \frac{A \cdot \Delta p_H}{\eta_f \cdot R}, \tag{7}$$

$$R = r_c \cdot h_c + R_m, \tag{8}$$

$$h_c = \frac{\kappa}{A} \cdot V_L \quad \text{with } \kappa = \frac{c_v}{1 - c_v - \varepsilon}, \tag{9}$$

$$\frac{t}{V_L} = \frac{\eta_f \cdot r_c \cdot \kappa}{2 \cdot \Delta p_H \cdot A^2} \cdot V_L + \frac{\eta_f \cdot R_m}{\Delta p_H \cdot A} = a \cdot V_L + b, \tag{10}$$

with V_L the filtrate volume, t the time, A the filter area, η the dynamic viscosity of the liquid phase, Δp the differential pressure, R_m the filter media resistance and the specific cake resistance r_c. Just by experimentally determining slope a and interception b from a filtration experiment, the filter media resistance as well as the specific cake resistance can be calculated. Even though Darcy's law is valid for incompressible cakes, which in reality is not always applicable, it gives proper results also for compressible structures by using integral values for porosity etc.

2.4. Idea of magnetic field enhanced press filtration

The magnetic field enhanced press filtration merges well known effects from magnetic separation (Svoboda, 1987) and classical press filtration in differential pressure field in a not yet practised manner. The systematic use of homogeneous and inhomogeneous magnetic fields results in magnetic volume forces and interparticle interactions that cause structural modification of the filter cake. Both result in strong improvement of filtration kinetics. The magnetic force causes a decoupling of solid phase motion from liquid phase flow. That leads to an additional degree of freedom regarding the solid phase motion. In case of press filtration magnetophoresis reduces the filtration process in an idealized approach initially to a single sided cake build-up.

Whilst external 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 particle–particle interactions (Svoboda, 1982; Tsouris and Scott, 1995). With the magnetization of the particles in an external field the particles themselves act as microscopic magnets with North- and South Poles. Once the gravitational force is not dominating the interparticle forces, chainlike agglomerates with attracting force in direction of the field lines and a repulsive force perpendicular to the magnetic field lines are formed (Chantrell et al., 1982). This combination of repulsion and attraction causes a structured cake formation which has higher permeability.

3. Materials and methods

Fig. 2-left shows a scheme of the experimental apparatus. The press filter cell consists of a filtration chamber built by a cake building ring which is bordered by filter plates. The cake building ring (3) features the feed inlet and the two filter plates (1, 5) the filtrate outlets on each side of the filtration chamber (3). For the filter media (2,4), which is placed between the cake building ring and the filter plate, a Pall Ultrapore membrane with 1.2 μm pore size and a specific permeate flux of 139 ml bar^{-1} cm^{-2} min^{-1} was chosen. The filtrate mass signal can be recorded for both filter plates individually.

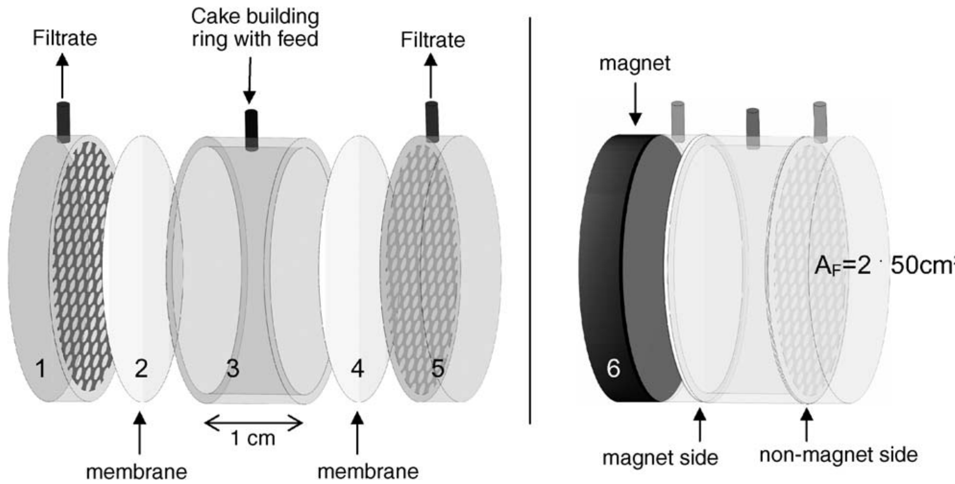

Fig. 2. Scheme of press filtration cell.

Table 1
Product properties of Bayoxide E8706 (Fe_3O_4)

Particle size		Density	Slurry	Magnetization		ζ Potential
X_{50} (measured)	$x_{predominant}$ (producer)	ρ	c_V	M_S (saturation)	M_r (remanent)	ζ (slurry)
1.3 µm	0.3 µm	4.98 g/cm^3	12%	90.5 Am^2/kg	5 Am^2/kg	−15 mV

The pressurized slurry is provided by a container. For the experiments with magnetic field a NdFeB-permanent-magnet (6) with 0.4T maximum field strength can be attached to one side of the press filtration cell, as shown in Fig. 2-right. Further on the filtration area, behind which the magnet is installed and which therefore experiences higher field strength, is called the magnet side, while the farther side of the filtration chamber is called the non-magnet side. Permeation tests where realized by a valve system that enabled the change-over from slurry supply to water supply.

A suspension of ferromagnetic iron oxide Bayoxide E8706 (Table 1) enters the filtration chamber through the feed inlet of the cake building ring. Due to the hydraulic pressure a filtration on either side of the filtration chamber takes place and the filtrate from both outlets is collected.

3.1. Experimental procedure

In case of classical filtration the filter cell is arranged within a press frame without the magnet. The slurry is supplied through the feed with a pre-adjusted pressure. During filtration the filter cell is continuously supplied with slurry. Simultaneously the filtrate mass versus the time is recorded. Once the filtration has ended, gravimetrical analyses of the filter cake followed to determine porosity and residual moisture.

In case of a permeation experiment, to investigate the structural integrity of the cake, after a specified filtration time the filtration is stopped and the cell is supplied with water. At first the permeation pressure is increased stepwise from 0.5 to 1.6 bar. To determine structural modifications during the permeation period the permeation pressure is then decreased in the same steps back to 0.5-bar.

4. Results

In Fig. 3 different mass signals for magnetic and non-magnetic filtration are shown for several differential pressures. As already proposed in the theoretical part, the chart shows the strong effect of an external magnetic field to the filtration of magnetic particles. Throughout all pressure steps a strong increase of filtrate flow especially at the beginning of the filtration process can be observed. Two effects are responsible for the accelerated filtration kinetics. On one hand the external magnetic force causes a stronger cake build-up on the magnet side of the filtration chamber at the beginning of the filtration which results in a slow down of cake building at the non-magnet side. That leads to lower resistance for the filtrate flow through the non-magnet side and therefore to an increase of filtration kinetics. By utilizing high speed video recording the initially stronger cake building on the magnet side could be visualized.

On the other hand, already mentioned internal magnetic forces, cause strong self-assembly of the particles in chain-like structures according to the external magnetic field shape. That results in a highly structured filter cake with much lower resistance and higher permeability (Fuchs and Stolarski, 2005).

By calculating the ratio of t/V from the mass signal shown in Fig. 3 the so called t/V vs. V chart (Fig. 4) can be drawn. It shows the significant acceleration of the filtration with superposed magnetic field. Due to the decoupling of particle

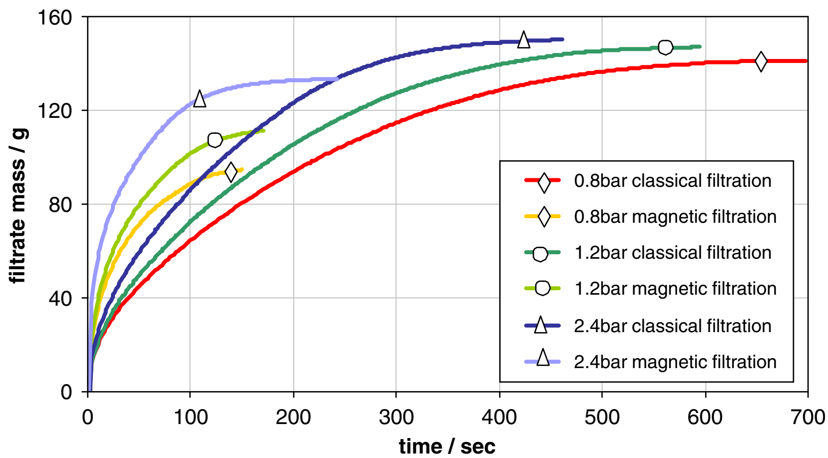

Fig. 3. Filtrate mass vs. time for different differential pressures with and without superposed magnetic field.

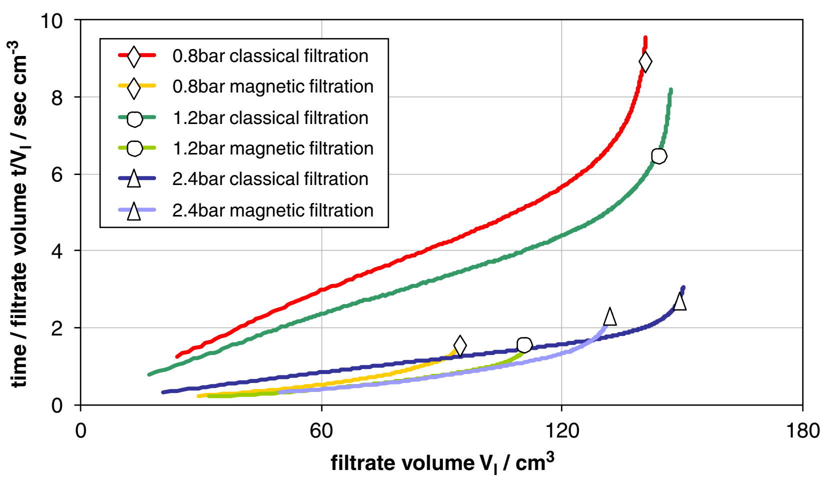

Fig. 4. t/V vs. V chart corresponding to Fig. 3.

motion and liquid flow the assumptions that lead to the classical cake building equation (Eq. (10)) are not appropriate anymore. Therefore magnetic filtration does not present as a linear function in the t/V vs. V chart.

According to the stated competing magnetic forces and the drag force the acceleration potential decreases with increasing differential pressure, which will be referred to later on.

As negative side effect of the filtration with superposed permanent magnetic field it has to be mentioned that the capacity of the filter chamber is much lower due to the structuring of the filter cake. As a matter of fact the porosity of the filter cake within magnetic field is depending on the differential pressure increased by 2–5%, which might also be of advantage in a subsequent cake washing step. To fully take advantage of the higher filtration kinetics in superposed magnetic field it is therefore recommended performing the filtration in a membrane filter press. That will enable the mechanical compression of the filter cake after a certain time of filtration. In classical press filtration of for instance fine pigment slurry the usual apparatus used indeed is a membrane filter press.

A more detailed view of the effects inside the cell gives the individual mass signals of each filtration area. Fig. 5 shows the mass signal of each filtrate outlet for 0.8 bar of the classical and field enhanced separation and Fig. 6 for 1.6 and 2.4 bar field enhanced separation. While in classical press filtration (Fig. 5-left) the filtrate flux is equal on both sides, for 0.8 bar magnetic field enhanced filtration (Fig. 5-right) the slow down of cake building on the non-magnet side is strongly visible from the increased filtrate collection in the first seconds. Throughout the whole duration of the filtration process the filtrate flux of the non-magnet side exceeds the one of the magnet side.

The first few seconds of the filtration at higher pressures (Fig. 6) conform indeed with the situation at 0.8 bar. There is higher filtrate flux through the non-magnet side, which is less blocked by particles due to the external magnetic force, but after a certain time the filtrate flux through the magnet side membrane exceeds the flux of the non-magnet side.

At the beginning of the filtration the cake building on the non-magnet side is slowed down, but it cannot be completely prevented. The interaction of forces initially leads to a preferred

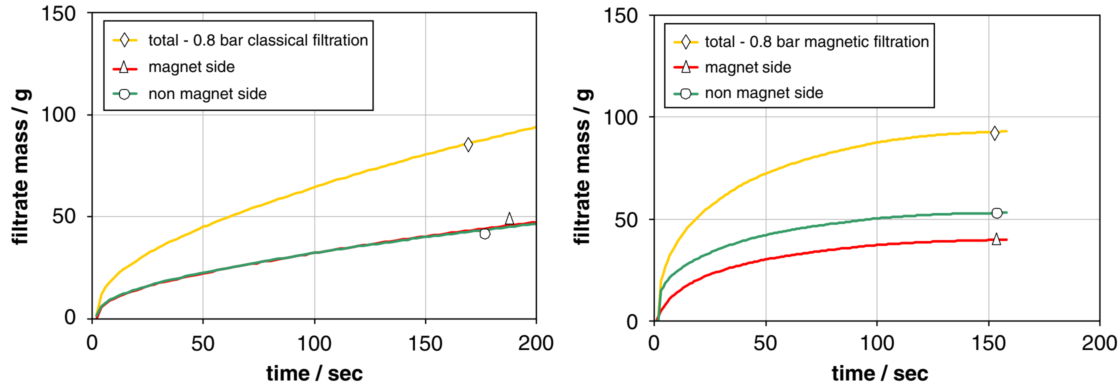

Fig. 5. Individual mass signals of each filtration area at 0.8 bar classical (left) and magnetic (right) filtration.

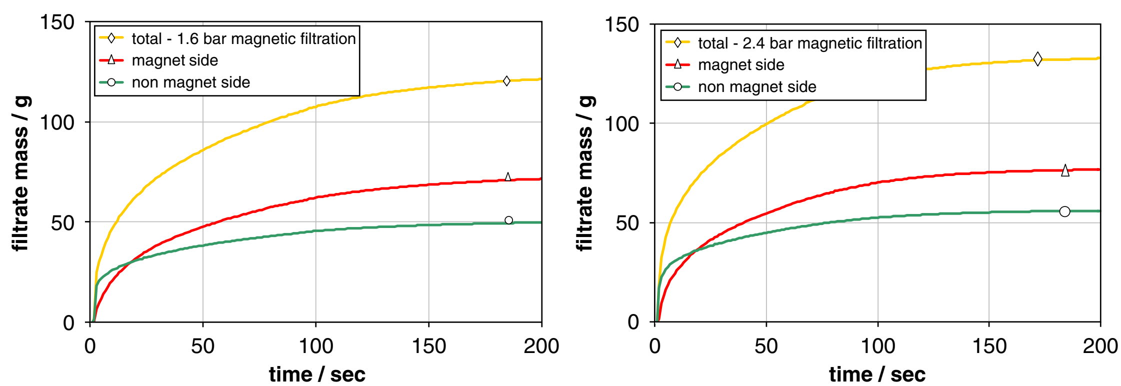

Fig. 6. Individual mass signals of each filtration area at 1.6 bar (left) and 2.4 bar (right) of magnetic filtration.

cake building on the magnet side, but after a time $t \approx 15$ s (at 1.6 and 2.4 bar) a strong decrease of the filtrate flux on the non-magnet side occurs. Taking into consideration the high-speed video recordings, where the cake build-up is especially in the first seconds proved that the cake building is in the magnet side, this can only be explained by the build-up of a more compact filter cake on the non-magnet side, where the influence of the magnetic field to the structure is weaker than at the magnet side.

Due to the drag forces particles precipitate at the non-magnet side, building a comparatively compact cake with high specific cake resistance. This can be shown by afore stated Eq. (6). For the determination of the drag force a relative differential velocity has been calculated from the manufacturer's water permeation value for the membrane. In this context the assumption has been made that a face-centered cubic latticed particle layer reduces the permeation area to 22% of the original filtration area. The calculation of the repulsive magnetic energy is based on the magnetization and field gradient in the actual position within the filter chamber. The obtained structure parameters E_G are shown in Fig. 7. The strength of a structure is at any differential pressure bigger in the region of higher magnetic fields. With one particle layer partly structured particle precipitation on the non-magnet side occurs for pressures higher than 0.8 bar, which have a higher flow resistance. At 0.8 bar on both sides structure modification by the magnetic field are stable, which

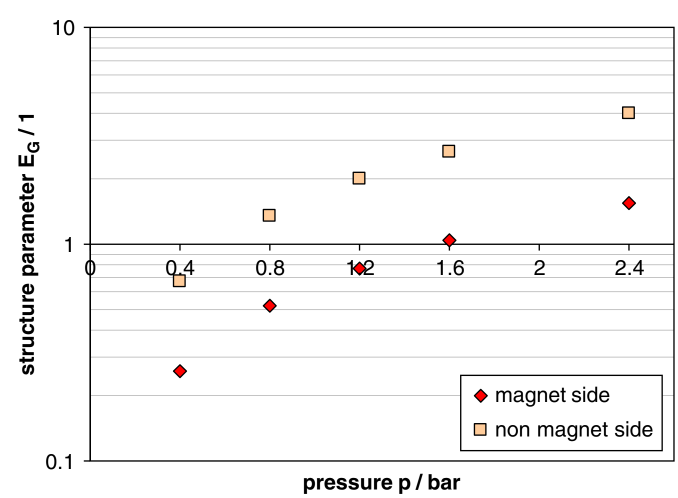

Fig. 7. Structure parameters obtained by Eq. (6) for several pressures at magnet and non-magnet side.

is the cause for the absence of the crossing point of the filtrate masses.

The different structures were also experimentally confirmed by measuring the permeability of the filter cake at each filtration area (see Fig. 8).

In the case of filtration without a magnet, the permeability is the same on both sides and the cakes do not show structural

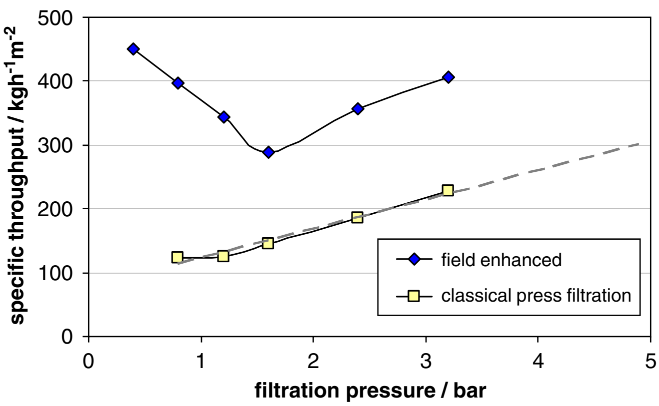

Fig. 8. Throughput of dry product mass calculated for continuous process.

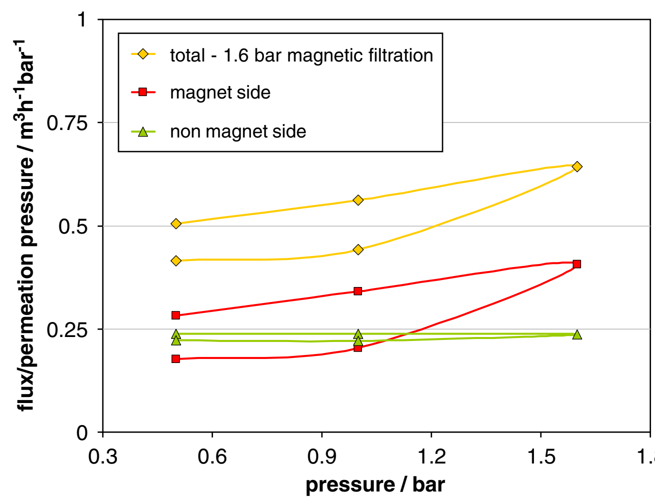

Fig. 9. Permeability of the cakes on each side of the filtration area and the total after 100 s filtration time at 1.6 bar (left: classical filtration, right: magnetic filtration).

changes induced by increased permeation pressure. Whereas in field enhanced filtration (Fig. 8) rising permeation pressures result in strong structural instability, which is shown by the mismatch in direction of increasing pressures in comparison to the decreasing permeation pressure. This mismatch is much higher at the magnet side. The restructuring is also concentrated on the magnet side and is partly irreversible, while the non-magnet side is nearly not affected. It can be concluded that the structure is much looser in the magnet side than in the non-magnet side.

Recapitulating, the results show that the external and inter-particle magnetic forces have positive impact to the filtration kinetics, but on first view negative impact on the capacity of the filter cell. Assuming a fill rate of 80% of non-magnetic filtration's fill rate for pressures higher than 1.2 bar an improvement of the filtration kinetics of approximately a factor of at least two can be calculated for the shown differential pressures, while the capacity decreases by less than 25%. The additional water can be removed by a membrane press step. To take advantage of the much higher kinetics, it is therefore recommended to do several short but highly efficient filtration steps instead of one inefficient.

To underline the substantial improvement in over-all filtration kinetics, Fig. 9 shows the calculated throughput of dry product as a function of differential pressure. The throughput for each differential pressure has been calculated on the basis of the dry cake mass collected at the end of the filtration process in equilibrium condition.

Especially remarkable is the increase of throughput at lower pressures in magnetic press filtration. While for classic filtration the throughput decreases when decreasing the filtration pressure in magnetic filtration the opposite is the case. The particles are experiencing hydrodynamic as well as magnetic forces. Depending on the acting differential pressure and the magnetic field either one of these forces dominate the motion of the particles. At low pressures the magnetic forces are strong enough to initially strongly slow down cake building at the non-magnet side. The result is an increase of unblocked filtration area and therefore higher liquid flow velocity, as the filtrate does not have to penetrate through a big cake. Additionally to that the structure that builds-up at the non-magnet side is according to Fig. 7 well structured and much more permeable. For even higher flow velocities hydrodynamic forces strongly dominate over external magnetic forces, so that there is nearly no difference in slope between magnetic and non-magnetic filtration at high differential pressures where the particles due to the high drag force tend to follow the liquid flow. Apart from external forces, the effect of internal magnetic forces, which causes structuring of the cake and results in a shift to higher throughputs due to higher permeability, is observed through the whole spectra of differential pressures. However by superposing a magnetic field, it is indeed possible to gain the same throughput at much lower differential pressure for the used permanent magnets as follows from Fig. 9. That means the energy consumption for compression can be decreased significantly. Nevertheless one has to take in consideration that Fig. 9 shows indeed throughputs for filtration processes, where the dead time in between the filtration cycles is neglected. However in reality the ratio of filtration time and dead time is usually much smaller than one. Considering an additional membrane press step, it will still be in that region.

It is evident that there is a big exceed of throughput for magnetic products by superposing a magnetic field, which can be easily realized by integration of permanent magnets into the filter chamber separations. The application of permanent magnets does have some advantages over the use of electromagnets. On one hand, even especially designed permanent magnets are very cheap in comparison to electromagnets and do not produce further energy cost. On the other hand, modern permanent magnets provide highest field strength at little geometry. Especially this fact enables an easy and cheap installation into existing filter presses. An advantage of electro magnets is indeed the possibility to switch them off, but the big geometries make it difficult to integrate them into a filter press without loosing a big amount of filtration area. Nevertheless magnet coils offer the possibility to control the magnitude

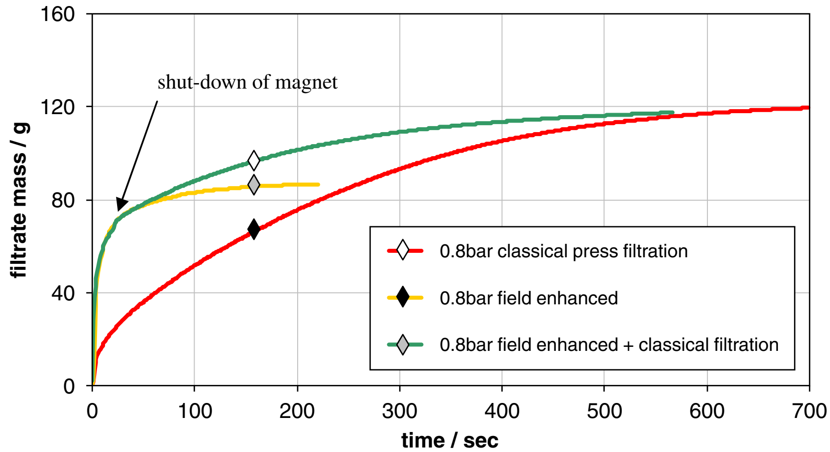

Fig. 10. Mass signal for magnetic filtration with electro-magnet field and its power-down after the first 20 s of filtration time.

of the structure in the filter cake. By deactivating the external magnetic field the magnetic structure collapses due to the hydraulic pressure and the porosity sinks to the level of classical press filtration. This enables the product specific process management and to benefit from higher filtration kinetics at increased capacity compared to the permanent magnetic process at the same time. The operating point can be freely chosen between highest kinetic but high residual moisture or low kinetic and low residual moisture depending on the demand (Fig. 10). Also for a subsequent washing step the ability to adjust the filter cake's porosity might be an interesting and beneficial opportunity.

Depending on constructive matters also the use of switchable permanent magnets (Watson and Beharell, 1997) should be considered, because those combine the advantages of both magnet field sources.

However for special applications as the separation of proteins, virus, DNA, etc. by functionalized magnetic carriers, where the throughputs are comparably small, the use of electro magnets is strongly justified and is currently proved in magnetic field enhanced cake filtration (Fuchs and Stolarski, 2005).

Also for the processing of nano-scale magnetic particles the new approach offers to be a technology platform. The superposition of a magnetic field leads to the formation of bigger particle agglomerates (Tsouris and Scott, 1995) that are more affected by the magnetic volume forces. In combination with especially designed magnetic fields an efficient filtration of finest particles can be realized.

5. Conclusion

The hybrid process, "magnetic field enhanced press filtration" was shown to offer high potential in the field of magnetic particle processing. Due to external magnetic forces, which slow down cake building, and interparticle magnetic forces, which cause structured cakes with higher permeability, a big acceleration of filtration kinetics can be realized. Initially the external forces are acting but at a later point of time the filtration kinetics are ruled by the structure of the built filter cake, which is strongly affected by the interparticle magnetic forces. Throughout all differential pressures the throughput can be increased significantly while compression power demand is decreased down to a fractional amount of non-magnetic filtration.

Due to strong interactions of magnetic particles, that leads to agglomerate formation the "magnetic field enhanced press filtration" is also believed to have high potential in the field of nano-scale magnetic products processing.

Notation

a	slope of t/V vs. V, s m^{-6}
A	filtration area, m^2
b	interception of t/V vs. V, s m^{-3}
B	magnetic flux density, T
c_V	volume concentration, 1
c_W	drag coefficient, 1
d_P	particle diameter, m
E_{drag}	drag energy, J
E_G	structure parameter (Rosenzweig), 1
E_M	magnetic repulsion energy, J
E_{Pot}	potential energy, J
E_S	modified structure parameter, 1
F_D	drag force, N
F_m	magnetic force, N
g	gravitation coefficient, m s^{-2}
h_c	cake height, m
H	magnetic field strength, A m^{-1}
M_P	particle magnetization, A m^2 kg^{-1}
M_r	remanent magnetization, A m^2 kg^{-1}
M_S	saturation magnetization, A m^2 kg^{-1}
p_H	pressure, bar
r_c	specific cake resistance, m^{-2}
R	resistance, m^{-1}
Re	Reynolds number, 1
R_m	filter media resistance, m^{-1}
u_r	relative velocity, m s^{-1}

V_L filtrate volume,m^3
V_P particle volume, m^3

Greek letters

ζ zeta-potential, mV
ε porosity, 1
η dynamic viscosity, Pa s
κ concentration coefficient, 1
μ_0 magnetic vacuum permeability $\mu_0 = 1.256 \times 10^{-6}\,\mathrm{V\,s\,A^{-1}\,m^{-1}}$, $\mathrm{V\,s\,A^{-1}\,m^{-1}}$
ρ_f fluid density, $\mathrm{kg\,m^{-3}}$
ρ_P particle density, $\mathrm{kg\,m^{-3}}$
χ volumetric susceptibility, 1

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