Limits of mechanical filter cake deliquoring

H. Anlauf

The mechanical deliquoring of filter cakes can be realized either by reducing the pore volume, by displacing the pore liquid with gas or by a combination of both. However the mechanical deliquoring is physically limited. Depending on the deliquoring forces an equilibrium state or an ultimative limit can be reached. In the presented paper the state of the art regarding the methods of measuring the limits of mechanical deliquoring and their interconnections are summarized, the related laboratory techniques are described, still open questions are formulated and technical examples are given.

1. Introduction

The mechanical displacement of liquid from the pore system of filter cakes is limited by physical means. Its residual moisture content at the final end depends on particle characteristics, liquid properties, the structure and behaviour of the filter cake and the type and extent of the acting forces. A certain lower limit of cake moisture content cannot be underrun unless by thermal drying. This mechanically not removable liquid is bound in the pore system in form of interstitial liquid at the particle contact points, as adhesive liquid at the particle surfaces and as inner liquid in case of micropores inside the particles themselves.

The respective physical limit of mechanical demoisturing gives important hints about the filtration behaviour of the slurry to be separated as well as for the choice and the operational parameters of the apparatus to solve a given separation problem.

The demoisturing of filter cakes takes place either by displacement of the capillary liquid by gas (desaturation), by reduction of the pore volume (consolidation) or by a combination of both mechanisms. For cake filtration therefore very different apparatuses like discontinuously oder continuously operating vacuum filters, gas overpressure filters, press filters with hydraulic or mechanical cake squeezing or filter centrifuges are applied. For this reason from the physical point of view as well as from historical tradition very different methods are existing to measure and describe the respective accessible limits of deliquoring.

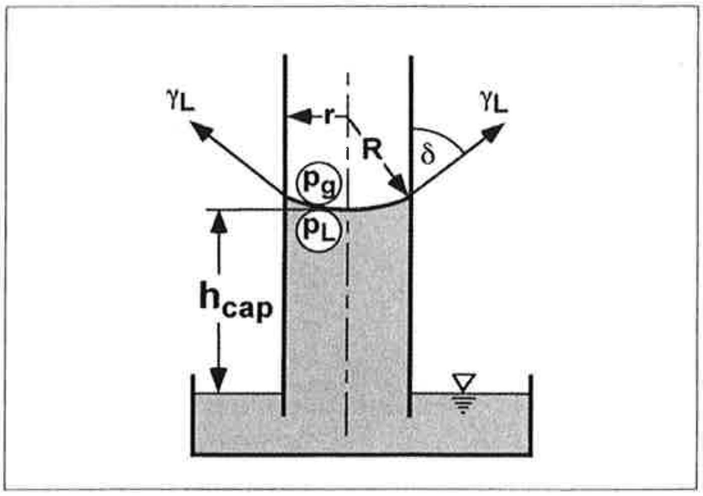

Fig. 1: circular model pore

2. Desaturation of incompressible filter cakes

2.1 Capillary pressure and capillary pressure distribution

A comprehensive description of capillary effects in porous systems of solid particles is given in [1]. If two molecular mutually not miscible fluids, such as liquid and gas, have a common and freely movable phase boundary, an interfacial tension of $\gamma_{L,g}$ originates. If the boundary surface is bent, the pressures p_g in the gaseous phase and p_L in the liquid are different. The resulting pressure difference (p_g - p_L) is called capillary pressure p_{cap}. In the case of lower pressure in the phase of higher spec. weight (liquid) the capillary pressure is defined as positive. A moist filter cake in gaseous environment represents a three-phase system of solid, liquid and gas. Where solid, liquid and gas are meeting a three-phase contact line originates and the angle with which the liquid touches the solids is called wetting contact angle δ. A virtual transformation of the porous system in a filter cake to circular-cylindrical model pores leads to the equilibrium situation shown in fig. 1. The formulation of a force balance in the vertical direction leads in this case to the simplified form of the so-called "Laplace equation", which describes according to eq. (1) the capillary pressure p_{cap} in dependence of the capillary radius r, the wetting contact angle δ, the surface tension γ_L and the radius of boundary surface curvature R.

$$p_{cap} = p_g - p_L = \frac{2 \cdot \gamma_{L,g}}{R} = \frac{2 \cdot \gamma_{L,g} \cdot \cos\delta}{r} \qquad (1)$$

If one calculates after measurement of the capillary pressure the radius of an arbitrarily formed filter cake pore from eq. (1), the resulting capillary radius corresponds to the radius of a circular pore with the same capillary pressure, like the measured one. Hence this radius is called equivalent or hydraulic pore radius. Between the hydraulic pore radius and the radius of a

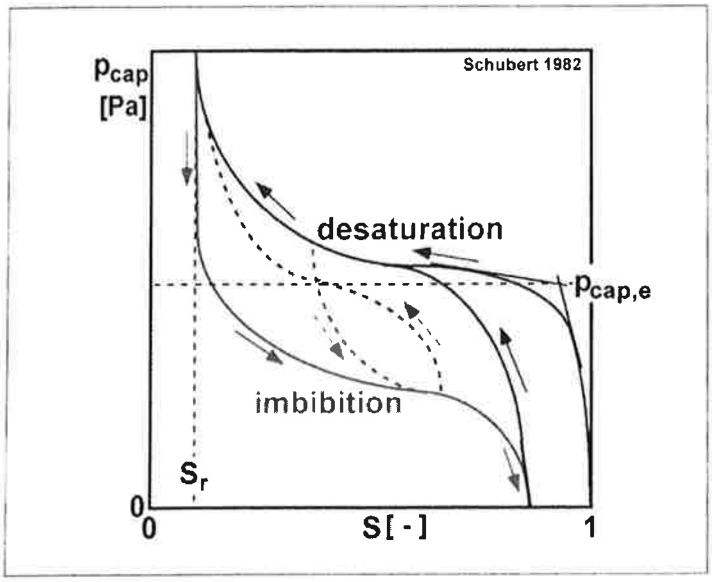

Fig. 2: capillary pressure curve (according to [1])

sphere, which just can penetrate this pore, an explicit relationship exists with knowledge of the pore geometry [2]. One makes use of these physically definite correlations in particular in the pore size analysis of filter media by means of bubble point tests [3], forward flow tests [4] or in general for porous bodies by mercury intrusion [5], [6].

If liquid rises up in a capillary to an equilibrium value, this capillary height h_{cap} can be calculated by a force balance between capillary pressure and hydrostatic pressure according to eq. (2).

$$h_{cap} = \frac{p_{cap}}{\rho_L \cdot C \cdot g} = \frac{2 \cdot \gamma_L \cdot \cos\delta}{r \cdot \rho_L \cdot C \cdot g} \tag{2}$$

In this equation p_L means the spec. liquid weight, g the earth acceleration and C multiples of g during centrifugation. As a result of a stochastic arrangement of particles in a filter cake, a pore size and thus a capillary pressure distribution exists. The capillary pressure distribution in a filter cake of approximately incompressible, homogeneous and isotropic structure is characterized usually by the so-called "capillary pressure curve" shown schematically in fig. 2.

This function shows for mechanical equilibrium the relationship between capillary pressure p_{cap} and liquid saturation degree S. For filter cakes with constant pore geometry the liquid saturation degree is particularly well suited, because it describes the moisture content very clearly and also varies as standardized parameter within the fixed limits of 0 and 1. The liquid saturation degree is defined as relation of the actual liquid volume V_L in the filter cake to its total void volume V_{void}.

$$S = \frac{V_L}{V_{void}} [-] \tag{3}$$

To be able to quantify the void volume in the filter cake the porosity ε as ratio of void volume to the total volume of the filter cake V_{tot} has to be determined.

$$\varepsilon = \frac{V_{void}}{V_{tot}} = \frac{V_{void}}{V_s + V_{void}} \tag{4}$$

If the porosity changes like in the case of squeezing the liquid loading θ can be used. It represents the relation of liquid volume in the cake to its solid volume.

$$\theta = \frac{V_L}{V_s} \tag{5}$$

However, beside the saturation degree and the liquid loading θ other definitions, like the easy to measure residual moisture content *MC* or dry substance *DS* can characterize the liquid content of the filter cake.

The moisture content relates the actual mass of liquid m_L to the total mass of the moist filter cake (m_L+m_s).

$$MC = \frac{m_L}{m_L + m_s} \cdot 100 [\%] \tag{6}$$

The dry substance uses the relation of solid mass m_s to the total mass of the moist filter cake (m_L+m_s).

$$DS = \frac{m_s}{m_L + m_s} \cdot 100 [\%] \tag{7}$$

At full saturation the liquid covers the cake surface in form of a flat boundary surface. This means, that the pressure on both sides of the boundary layer is equal and thus no capillary pressure exists. With a gradual increase of the differential pressure the liquid between the particles first is pressed a little bit into the cakes surface, what leads to a marginal reduction of saturation without real desaturation of pores. As can be seen in fig. 2 a significant reduction of the saturation can be registered only after exceeding the capillary entry pressure $p_{cap,e}$. With further increasing differential pressure smaller and smaller pores can be emptied. The capillary entry pressure is defined as intersection of two tangents attached to both curve segments at the beginning of desaturation. If finally the complete hydraulically connected capillary liquid is displaced by gas, the mechanical limit of desaturation S_r is reached. Further increase of the differential pressure does no longer decrease the saturation degree, because according to fig. 3 the remaining liquid in the filter cake is now hydraulically isolated and bound at the contact points of the particles as liquid bridges, on the surface of the particles as adhering layer and inside of micropores in the solid matter as internal liquid.

If the liquid can penetrate back into the filter cake due to stepwise reduction of the pressure difference, an

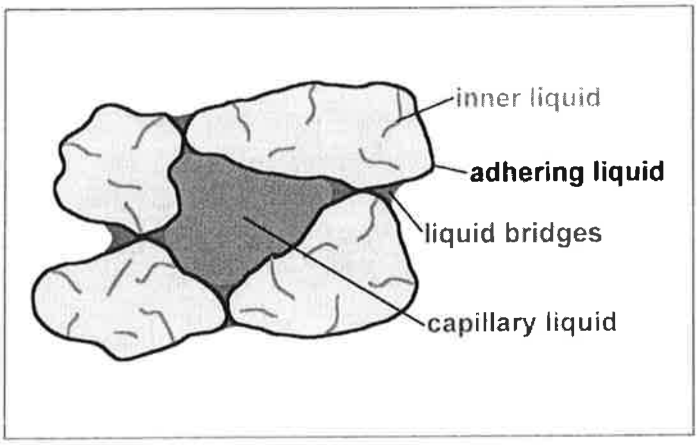

Fig. 3: different bound components of liquid in the cake

imbibition curve below the desaturation curve results according to fig. 2. A complete remoistening of the filter cake does not succeed due to unavoidable gas inclusions during the resaturation process. If desaturation is started again after maximal imbibition, the new desaturation curve meets the initial desaturation curve at a certain point and a hysteresis loop develops. Within this hysteresis loop any point can be set in the equilibrium state by appropriate de- and resaturation. To have an unambiguous definition the capillary pressure curve has to start from full saturation $S=1$ and ends at the mechanical limit of desaturation $S=S_r$. The capillary pressure curve is independent of the filter cake dimensions and the procedure of desaturation. It is a material characterizing function of the respective filter cake.

2.2 Desaturation of incompressible filter cakes by gas pressure difference

For vacuum and gas overpressure filters like continuously operating drum, disc, belt and pan filters or discontinuously operating stirred nutsch filters, candle and sheet filters the gas pressure difference for cake deliquoring generally is held constant. Thus in case of sufficient time all hydraulically with the filter medium connected pores and a capillary pressure, which is lower than the gas pressure difference can be deliquored. Fig. 4 illustrates this case, but shows also consequences of an inhomogeneous cake structure, as can occur due to different sedimentation velocity of particles during cake formation. On the left side of fig. 4 one can see the principal course of time dependent demoisturing. It starts for constant pressure difference at full saturation and then runs horizontally to the left until the equilibrium value on the capillary pressure curve has reached. With higher pressure difference an accordingly lower equilibrium value of the saturation is accessible. The right side of fig. 4 makes clear, that the capillary pressure curve can change its course remarkably with changing cake structure.

If caused by segregation effects in the slurry a filter cake with a top layer of finest particles forms, its capillary entry pressure can rise dramatically in comparison to a homogeneously structured filter cake and in the worst case, fully saturated mud is discharged from the filter. In the case of such a bottleneck also the mechanical limit of deliquoring is shifted to higher saturation degrees. While overcoming locally the capillary entry pressure of the fine particle layer a spontaneous desaturation of the underneath located coarse pored particle layer occurs. Thereby hydraulically isolated zones in the fine particle layer are remaining fully saturated.

The capillary pressure curve must be measured as a material function till this day for every case separately. For this measurement of gas pressure deliquoring two methods are available. Both of them require a pressure filter cell with a filter area of at least 20cm² like it is described in the VDI guideline 2762 [7] for the filter

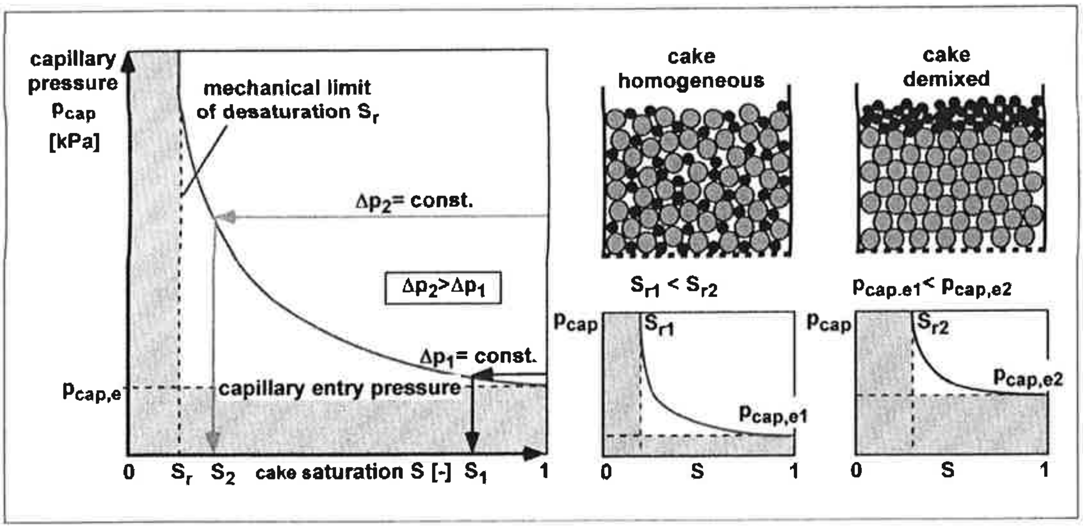

Fig. 4: capillary pressure curves for gas pressure filtration

cake formation and is shown exemplarly in fig. 5. The first method is based on a filter cake formed in the filter cell. Starting from fully saturated pores the pressure is increased stepwise from zero to the maximal value. The pressure of each stage is maintained until no more filtrate is registered on a balance. Because this measurement needs some hours no gas flow through already emptied pores is allowed to avoid thermal drying. This can be achieved by using a microporous membran as filter medium. Its capillary entry pressure must be higher than the maximum of the applied pressure difference. The long measurement times require an automated measurement procedure.

The second method is related very close to the technical practice. Several independent filter experiments with different filtration pressures have to be carried out and conventional filter fabrics can be used. Each experiment is stopped after some minutes, when no more filtrate flow can be observed. The thus determined data are located on the capillary pressure curve, which than can be approximated by an appropriate mathematical function.

Both methods should have an identical course to the greatest possible extent.

The question arises how the particle size distribution influences the capillary pressure curve. Experiments with limestone particle fractions of different mean particle size and variance, which had been stable dispersed in water, have proved, that all measured capillary pressure curves could be represented by one master curve [8], [9]. For this purpose the RRSB (Rosin-Rammler-Sperling-Bennet) distribution, well known from the characterization of particle size distributions, turned out to be useful. This equation must be adjusted by three physically interpretable parameters.

$$S_\infty^* = \frac{S_\infty - S_r}{1 - S_r} = 1 - \exp\left[-\left[\frac{\overline{p}_{cap}}{p_{cap}}\right]^{\frac{1}{\xi}}\right] \qquad (8)$$

They can be interpreted as limit of mechanical desaturation S_r, mean characteristic capillary pressure $\overline{p}_k$ and pore size distribution index ξ. S_∞ represents the measured equilibrium saturation degree for the respective capillary pressure p_{cap}. A detailled investigation how each of these three parameters is depending on the particle size distribution is still missing. Fig. 6 shows the result of the above mentioned capillary pressure measurements for different lime stone fractions, which can be distinguished by the Sauter mean diameter $D_{3,2,i}$ and the geometric variance $\sigma_{g,3}$.

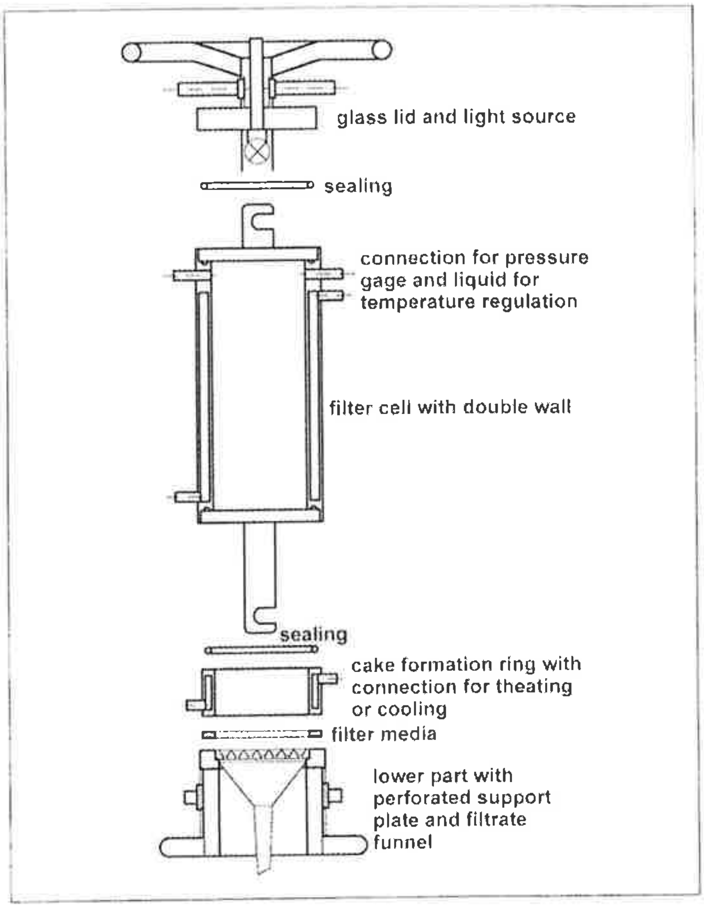

Fig. 5: laboratory pressure filter cell

2.3 Desaturation of incompressible filter cakes in the centrifugal field

During the deliquoring phase of centrifugal filtration processes like continuously operating pusher, worm screen or vibrating centrifuges or discontinuously operating peeler or inverting centrifuges the rotation speed besides few exceptions normally remains constant. The sieve basket of filter centrifuges is cylindrical, cylindrical-conical or concial with enlarging radius towards the solids outlet. This facilitates not only the product transport due to the component of the centrifugal force in transport direction but the centrifugal force itself is increased by increasing the radius. The centrifugal acceleration a_{cent} depends according to eq. (9) on the radius r and the square of the angular velocity ω respectively the rotational speed n.

$$a_{cent}(r) = r \cdot \omega^2 = r \cdot 4 \cdot \pi^2 \cdot n^2 \qquad (9)$$

Fig. 7 shows for a beaker of a lab scale filter centrifuge the essential parameters to describe the filtration process.

According to eq. (9) the centrifugal acceleration rises from the inner radius r_i at the cakes surface to the outer radius r_o at the filter medium. If the cake thickness h_c is

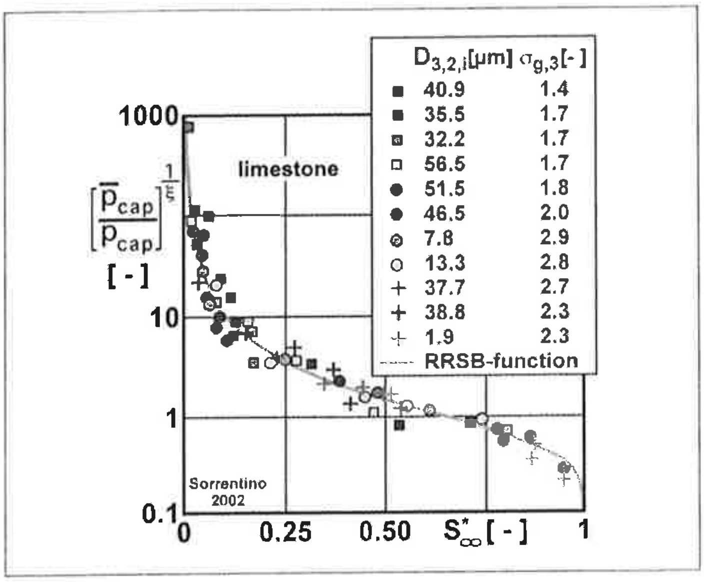

Fig. 6: representation of capillary pressure curve by RRSB-function (acc. to [9])

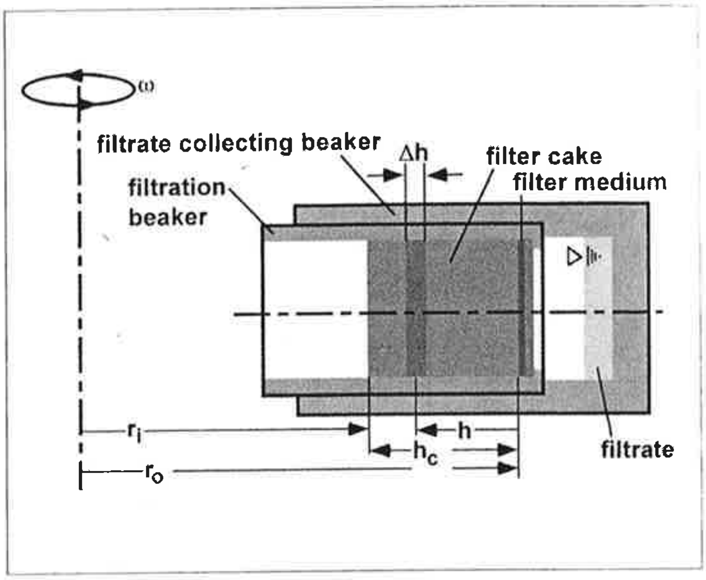

Fig. 7: filter cell of a laboratory beaker centrifuge

small in comparison to the outer radius r_o, the so called "long arm approximation" with constant mean centrifugal acceleration $a_{cent,m}$ can be applied.

$$a_{cent,m} = r_m \cdot \omega^2 = \frac{(r_o + r_i)}{2} \cdot \omega^2 \tag{10}$$

The filtration pressure Δp_{cent} originates from the hydrostatic pressure of the liquid column h in the centrifugal field, whereby the spec. weight of the gas ρ_g is neglected.

$$\Delta p_{cent} = (\rho_L - \rho_g) \cdot a_{cent,m} \cdot h \approx \rho_L \cdot a_{cent,m} \cdot h \tag{11}$$

Fig. 8 makes clear, that the most extensive deliquoring takes place at the surface of the cake at $h=h_c$, because there the length of the liquid column h is maximal.

The more the liquid is displaced from the pores of the cake, the more the liquid column is shortened, the smaller the centrifugal pressure becomes and the less pores can be emptied. Thus in comparison to the gas differential pressure deliquoring the filter cake shows now a saturation gradient along the cake height in the equilibrium state. At $h=h_{cap}$ (cf. eq. (2)) the capillary entry pressure $p_{cap,e}$ is no longer overcome and the cake remains completely saturated.

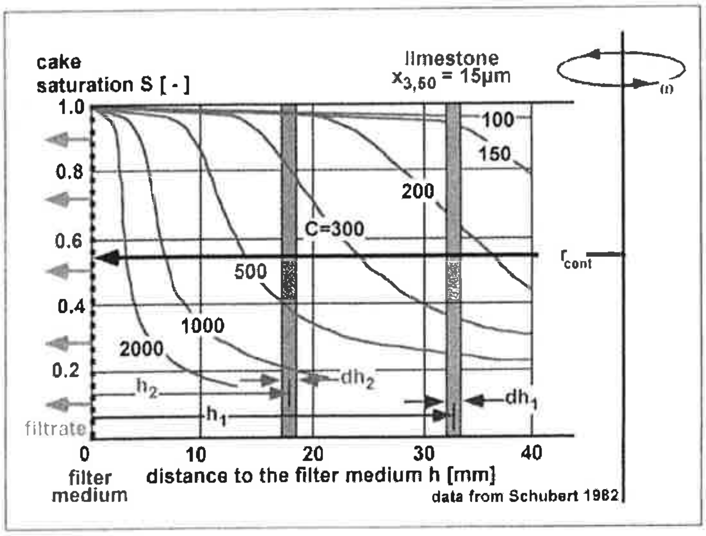

Fig. 8: equilibrium moisture profiles in centrifuge cakes (acc. to [1])

This allowes a comparatively quick and so called "incremental" measurement of the capillary pressure curve in principle by one experiment with constant rotational speed (cf. [1]). After reaching equilibrium state the cake must be discharged quickly to avoid liquid migration in the cake and cut radially into thin slices. Each slice then represents one point on the capillary pressure curve $p_{cap}(S)$.

The capillary curve also can be measured by the so called "cumulative" method by several independent experiments with constant cake height but varied rotational speed. After reaching equilibrium the integral mean saturation degree $\bar{S}$ has to be determined and the centrifugal pressure has to be calculated for $h=h_c$. This "capillary pressure curve" is not identical with the true capillary pressure curve and allows no longer an explicit correlation of capillary pressure and saturation degree due to the averaging of the saturation gradient in the cake. Fig. 9 illustrates, how the true capillary curve $S(p_{cap})$ however can be found from the experimentally determined function $\bar{S}(p_{cent,hc})$ (cf. [1]).

At point C on the measured curve a tangent is applied. To point C are belonging point A on the ordinate and point D on the abszissa. A parallel shift of the tangent from point C to point A leads to an intersection point B on the straight line CD. Finally point B is located on the true capillary pressure curve. A related theoretical derivation of this graphical method can be found in [1].

Capillary pressure curves, which are measured by gas differential or centrifugal pressure from the physical point of view should be comparable, if the cake structure is identical. This unfortunately often is not the case and so the analytical experiments should be carried out with the technique, which is forseen for the practice.

For centrifuge operators it is common for reasons of easy use to represent integral equilibrium saturation degrees $\bar{S}$ as function of the so called "Bond number" Bo. This number corresponds to a centrifugal force, which is made dimensionless with a capillary force [10]. The filter cake is considered here as a bundle of parallel circular tubes of same diameter in the direction of the centrifugal field. The pore size distribution of the filter cake is characterized by a mean hydraulic pore diameter d_h.

$$d_h = \sqrt{\frac{32}{\varepsilon \cdot r_c}} \qquad (12)$$

This pore diameter is calculated from a combination of the Darcy equation to describe the flow through a porous packed bed and the Hagen-Poiseuille equation to describe the flow through a circular pipe. As material function the experimentally determined spec. filter cake resistance r_c (cf. [7]) and the porosity ε (cf. eq. (4)) is implemented into the equation. The Bo number is calculated as ratio of the mean capillary force F_{cap} to the counteracting mass force F_{cent}, which is calculated with the cake height in the centrifugal field.

$$Bo = \frac{4 \cdot F_{cent}}{F_{cap}} = \frac{4 \cdot h_c}{h_{cap}} = \frac{\rho_L \cdot g \cdot C \cdot d_h \cdot h_c}{\gamma_L \cdot \cos\delta} \qquad (13)$$

This kind of representing the measurement results of the saturation degree is no more independent on the cake height. The capillary height remains constant for cakes of different thickness. However the integral moisture content of the filter cake is decreasing with increasing cake height, because the portion of deliquored cake becomes greater. Fig. 10 shows the representation of the Bond curve.

In the range (I) the cake remains fully saturated. In the declining range (II) a capillary height remains in the cake, which becomes smaller for increasing Bond numbers. For constant Bond numbers the integral cake moisture decreases with increasing cake thickness. In range (III) the hydraulically interconnected pores of the cake are desaturated to the greatest possible extent, the capillary height disappears and the saturation degree reaches the mechanical limit of deliquoring. At very high Bond numbers in the range (IV) under circumstances a very small part of the liquid bridges, which are bound very strongly by high capillary forces at the contakt points of the particles, can be removed.

3. Consolidation of compressible filter cakes by expression

If the particles to be separated are becoming smaller than about 10μm and if the attracting van der Waals forces are predominating the repelling electrostatic forces, the particles are agglomerating and compressible filter cake structures are formed. Such suspensions in the area of cake filtration commonly are separated with press filters like discontinuously operating chamber, diaphragm or piston filter presses or continuously operating screw or double belt presses. The pressure difference necessary for the cake formation and deliquoring (consolidation, expression) is realized either hydraulically by the feeding pressure of the slurry pump or mechanically by a pressing tool. Beside the uniaxial compression of the filter cake (chamber, diaphragm, piston filter press) an additional shearing of the cake structure can be effected by applying a shear stress τ (screw and double wire presses). This can promote a further cake compaction. A deliquoring of the

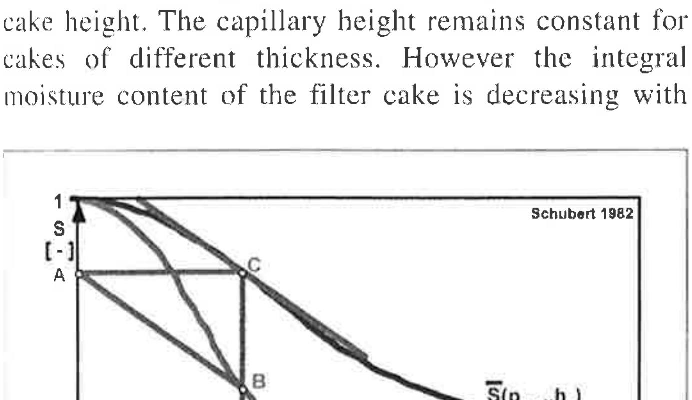

Fig. 9: cumulative centrifugal method and real capillary pressure curve (acc. to [1])

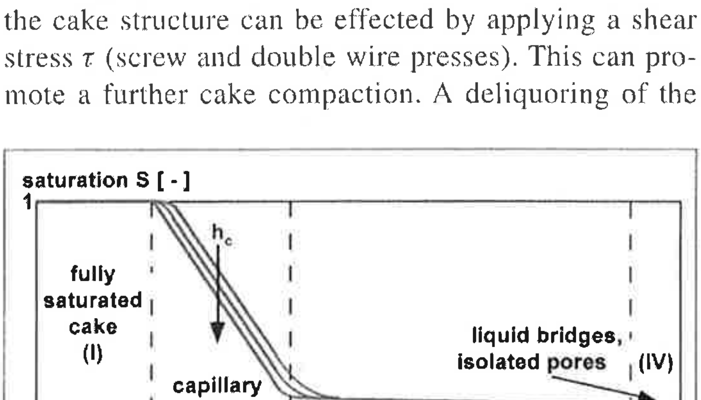

Fig. 10: Bond curve

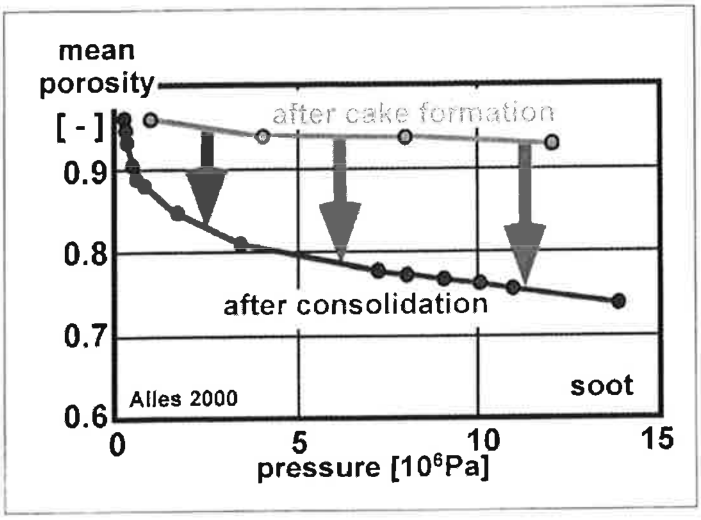

Fig. 11: porosity before and after consolidation

filter cake in every case takes place only by reducing the pore volume and not by desaturation. For this reason the quantification of the remaining liquid in the cake by the saturation degree S (cf. eq. (3)) here is senseless. However the residual moisture content MC (cf. eq. (6)), dry substance DS (cf. eq. (7)) and especially the liquid loading θ (cf. eq. (5)) can be used.

After the filter cake formation compressible cakes exhibit a strong porosity gradient over the cake height. The porosity at the filter medium already corresponds approximately to the consolidation equilibrium for the applied pressure, whereby the cake surface is significantly more porous. As can be seen in fig.11 the integral mean porosity for different filtration pressures differs relatively little directly after the cake formation.

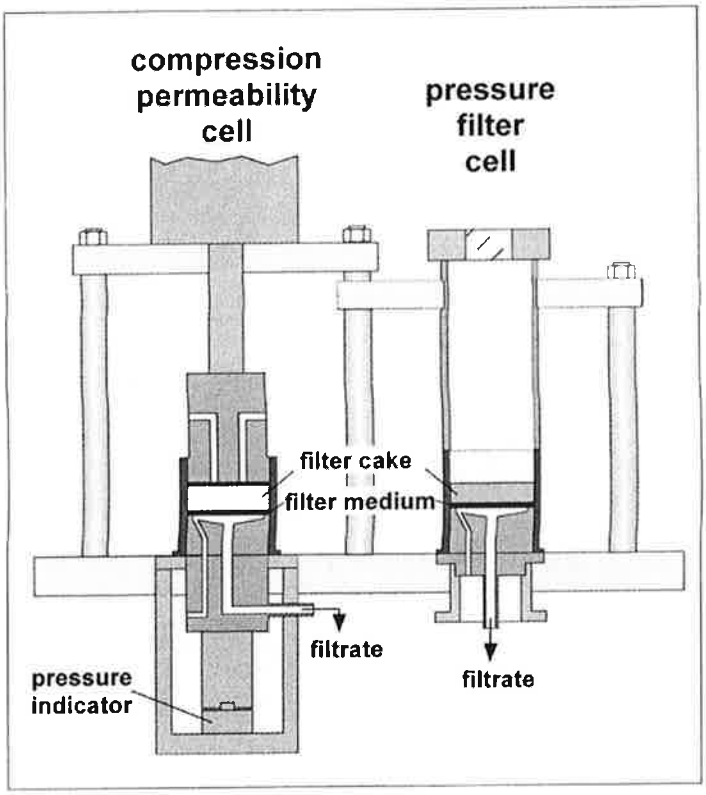

Fig. 12: CP-cell and gas pressure filter cell in tandem design

A clear difference in the cake porosity arises for varied pressure not before the consolidation equilibrium, when the cake structure is homogeneous and the porosity minimal [11]. This pressure dependent function of the quilibrium porosity normally is approximated by an exponential approach with an exponent G, which is a measure for the compressibility of the filter cake [12].

$$(1-\varepsilon) = (1-\varepsilon_0) \cdot \left[1 + \frac{\Delta p}{\Delta p_0}\right]^G \tag{14}$$

For compressible filter cakes porosity ε and flow resistance α are correlated. Both are measured in the laboratory by means of a so-called "CP-cell" (CP = Compressibility-Permeability).

Fig 12 shows the CP-cell mentioned above in a tandem arrangement with a pressure filter cell for gas pressure filtration experiments [13].

A filter cake can be formed with gas differential pressure and afterwards consolidated with the piston in the CP-cell. In the CP-cell the filter cake is consolidated between two porous plates and can be permeated to determine its flow resistance. The measuring cell is mounted floating on a load cell to measure the real pressure on the cake, because some pressure gets lost due to friction. As has been mentioned above deviations from the result of pure uniaxial compaction can occur due to further overlayed stresses of the cake structure. To that subject matter yet no systematic studies are available. But even if the purely uniaxial stressing of a filter cake is considered, different consolidation mechanisms can be identified according to fig. 13. These are depending on the respective particle properties and the amount of applied pressure [14].

In range (1) at low compaction the particles still have a relatively great mobility and can easily be rearranged. In range (2) structures are destroyed, which had been formed before under the influence of adhesive forces. In range (3) the attacking forces are high enough to destroy the particles themselves by breakage. The dotted lines indicate, that the respective functional course can vary dependent on the material.

4. Combined consolidation and desaturation of filter cakes - shrinkage

Beside the exclusive desaturation of incompressible and the consolidation of compressible filter cakes a broad intermediate field exists for applications of vacuum and gas overpressure filters, in which moderately compressible filter cakes are deliquored according to both mechanisms. This case is also relevant for batch filter centrifuges and sediments on the conical part of decanter centrifuges. These filter cakes are frequently compressible on one hand, but the capillary entry pressure is exceeded on the other hand. Because they have a boundary surface to the surrounding gaseous atmosphere, this is acting like an impermeable diaphragm, if the capillary entry pressure is not exceeded. The consolidation becomes manifest in form of a cake shrinkage. The resulting tensile stress in the cake structure can be reduced, if the particles are able to rearrange themselves. This is easily possible at the beginning of the deliquoring phase with high porosity at the cake surface. With proceeding liquid removal and especially desaturation the inner resistance of the cake against deformation rises fast and strongly. With desaturation during the start of cake demoisturing also the tensile strength of the cake rises steeply. If during this phase locally a critical tension in the cake structure is exceeded, shrinkage cracks are originating, which are dreaded in the filter technology. The equilibrium moisture dependent on the respective acting pressure difference can be determined according to the methods for measuring the capillary pressure curve described in chapter 2.2. Alternatively to the mechanical method of liquid removal by stepwise increase of the gas differental pressure could be demonstrated, that careful thermal drying leads to nearly identical results [14].

The relationship between consolidation and desaturation in the equilibrium state can be illustrated like to be shown qualitatively in fig. 14, whereby here no informations about the capillary pressure are included.

Here the pore number e is plotted over the liquid loading θ. If exclusively consolidation takes place any reduction of liquid loading corresponds with an equivalent reduction of the pore volume and all measured points are located on a straight line through the origin, which represents the saturation degree $S=1$. If the measuring points deviate upwards from the straight line, the capillary entry pressure is exceeded and the cake is consolidated and desaturated simultaneously. Within the range marked as "dangerous" shrinkage cracks can occur in the filter cake. Finally towards low moisture content the curve passes into a horzontal straight line. This means, that in this case liquid is removed from the now incompressible cake only by gas displacement. The diagram shown in fig. 14 was determined in its original form for consolidated cakes in the equilibrium state and following thermal drying. The numbers from 1 to 6 indicate in each case higher pressure during the preconsolidation. For example at pressure "5" the cake already has reached the limit of shrinkage by preconsolidation and is afterwards only desaturated. An apparative example for combined expression and following desaturation by gas differential pressure is the diaphragm filter press. The danger of shrinkage cracks is given, if desaturation starts before sufficient stabilisation of the cake structure.

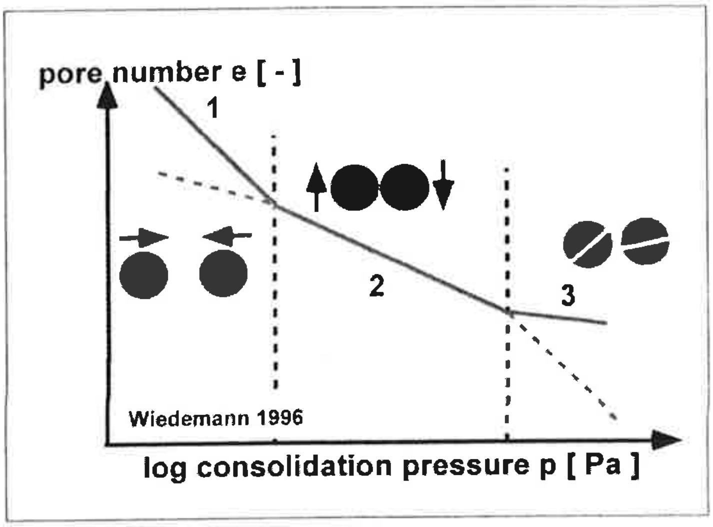

Fig. 13: consolidation mechanisms (acc. to [14])

Parallel occurring consolidation and desaturation are influencing each other. Currently unfortunately no detailled data are available on this subject. However under the aspect of optimal transferability of the lab scale data to a technical gas pressure filter it is recommended to carry out the lab scale experiments as similar as possible to the technical process. This means that cake formation and deliquoring gas pressure difference should be held constant for each experiment.

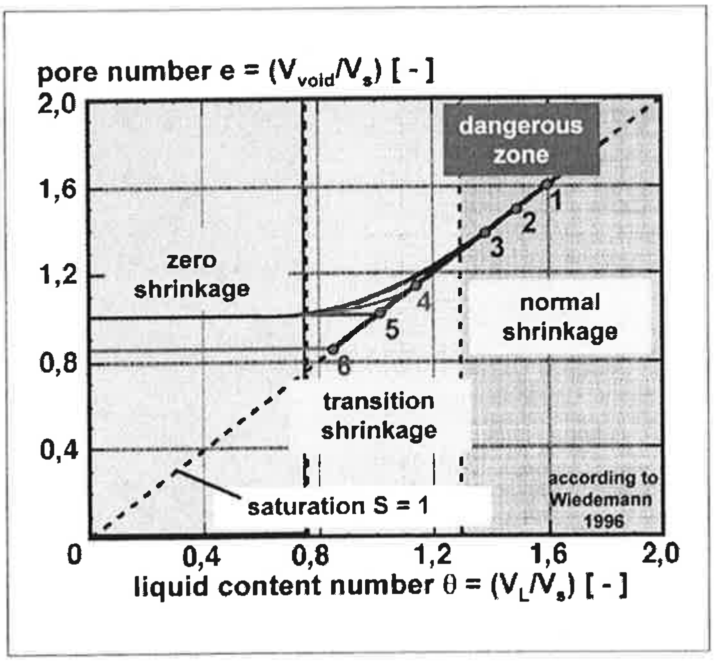

Fig.14: consolidation and desaturation in the „shrinkage-diagram" (acc. to [14])

5. Summary

The mechanically achieved minimum residual moisture content of a filter cake in the equilibrium state depends beside the properties of the filter cake itself and the magnitude of the driving forces on the applied process. By mechanical means it is principally not possible to produce a completely dry solid material. The variety of boundary conditions, which can be given for a mechanical deliquoring of filter cakes, is reflected in different measurement methods and representations of the test results. These are comparable and transferable only with restrictions. The security for a successful prediction of technically achieved deliquoring results increases to the extent, in which the measuring procedure is orientated on the technical process. Today still no general guidelines are existing to measure the deliquoring of filter cakes and there is still a lack of knowledge regarding the answer to some basic questions.

6. Notation

Latin letters

a	$[m \cdot sek^{-2}]$	acceleration
Bo	$[-]$	Bond-number
d	$[m]$	pore diameter
D	$[m]$	Sauter-diameter
g	$[m \cdot sek^{-2}]$	gravity acceleration
G, N	$[-]$	material parameters
m	$[kg]$	mass
n	$[sek^{-1}]$	rotaion frequency
p	$[Pa]$	pressure
r, R	$[m]$	radius
r	$[m^{-2}]$	spec. filter resistance
MC	$[-]$	moisture content
S	$[-]$	saturation
DS	$[-]$	dry substance
V	$[m^3]$	volumen
x	$[m]$	particle diameter
C	$[-]$	centrifugal factor

Greek letters

α	$[m \cdot kg^{-1}]$	spec. filter resistance
γ	$[N \cdot m^{-1}]$	surface tension
δ	$[rad]$	wetting angle
Δ	$[-]$	difference
ε	$[-]$	porosity
η	$[Pa \cdot sek]$	dyn. viscosity
θ	$[-]$	liquid content number
ρ	$[kg \cdot m^{-3}]$	spec. weight
σ	$[-]$	variance
τ	$[N \cdot m^{-2}]$	shear stress
ξ	$[-]$	pore size index
ω	$[rad \cdot sek^{-1}]$	angular velocity

Subscripts

c, k	cake
cap	capillary
cap,e	capillary entry
$cent$	centrifugal
g	gas
g	geometric
h	hydraulic
L	liquid
m	mean
o, i	outer, inner
r	remanent
s	solid
tot	total
0	reference value
∞	equilibrium

7. Literature

[1] H. Schubert, Kapillarität in porösen Feststoffsystemen. Springer-Verlag, Berlin 1982

[2] H. Anlauf, Chem.-Ing.-Tech. 1996, 68 (11), 1476-1479

[3] DIN ISO 4003, Beuth Verlag, Berlin

[4] A. Jena, K. Gupta, Fluid/Particle Separation Journal 2002, 14 (3), 227-241

[5] H. Juntgen, M. Schwuger, Chem.-Ing.-Tech. 1966. 38 (12), 1271-1278

[6] M. Stiess, in: Mechanische Verfahrenstechnik – Partikeltechnologie 1 (Editor: M. Stiess), Springer Verlag, Berlin 2009, 498

[7] VDI-Richtlinie 2762, Blatt 2, Beuth Verlag, Berlin

[8] J.A. Sorrentino, Advances in correlating filter cake properties with particle collective characteristics, Shaker Verlag, Aachen 2002

[9] H. Anlauf, J.A. Sorrentino, Chemie Ingenieur Technik 2003, 75 (9), 1254-1258

[10] G.Ph. Mayer, Die Beschreibung des Entfeuchtungsverhaltens von körnigen Haufwerken im Fliehkraftfeld, Dissertation, Universität Karlsruhe (TH) 1986

[11] C. Alles, Prozessstrategien für die Filtration mit kompressiblen Kuchen, Dissertation, Universität Karlsruhe (TH) 2000

[12] F.M. Tiller, N.B. Hsyung, Water Science and Technology 1993, 28 (1), 1-9

[13] C. Alles, H. Anlauf, F & S Filtrieren und Separieren 1998, 12 (5), 220-222

[14] Th. Wiedemann, Das Schrumpfungs- und Rissbildungsverhalten von Filterkuchen, VDI-Verlag, Düsseldorf 1996

[15] H. Anlauf, Entfeuchtung von Filterkuchen bei der Vakuum-, Druck- und Druck/Vakuumfiltration, VDI-Verlag, Düsseldorf 1986

Dr.-Ing. Harald Anlauf
Karlsruhe Institute of Technology (KIT), Institute of
Mechanical Process Engineering and Mechanics (MVM)
Straße am Forum 8, D-76131 Karlsruhe
harald.anlauf@kit.edu.de