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CENTRIFUGAL FILM DRAINAGE IN PACKED BEDS

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ABSTRACT

The model of centrifugal dewatering describes the course of measurements by any variation of the determining factors.

In comparison to models and measurements of literature also a equilibrium saturation can be calculated and has not to be measured for very long times in a centrifugal force field. The model is not only proofed for glass spheres but also for packed beds of irregular particles such as coal or quartz sand.

I. INTRODUCTION

Dewatering of packed beds in the centrifugal force field is in industry a mostly applied method for solid liquid separation; not finally because of the low costs compared to the costs of thermical dewatering.

In spite of variety of existing centrifuges and their manyfoldly use in different products, there is no model in literature that allows a shure precalculation of the humidity of packed beds in the centrifugal-force field by any variation of the determining parameters.

The following model points out, that by use of two dimensionless parameters the moisture content, dependent on time, can be precalculated. In comparision to literature can be demonstrated too, that existing models have validity only in a certain sphere of parameter's variation.

2. PARTS OF FLUID IN PACKED BEDS

The whole fluid existing in a wetted packed bed will be subdivided into four different parts in order to precalculate them as shown in figure 1.

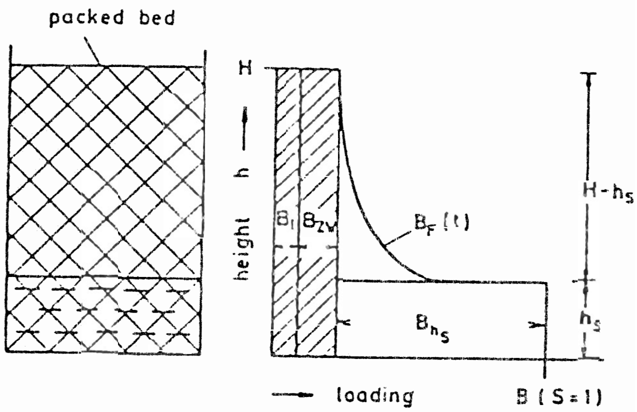

Fig. 1. Parts of fluid in packed bed (Schema)

The first part of fluid is bound in very fine pores in the particle itself. Because of the very high capillary forces this fluid only can be removed by thermical dewatering. For mechanical solid-liquid separation can be assumed that this part of fluid is a material constant value.

The caused loading (in the dimensions kg fluid/kg solid) and the saturation can be written as

$$m_{L,I} = \text{constant} \tag{1a}$$

$$B_I, S_I = \text{constant} \tag{1b}$$

The second part of fluid existing in a wetted packed bed is caused by a capillary rise (BATEL, SCHUBERT). According to equation 2 the height of the capillary rise h_s depends on the centrifugal acceleration factor C_m, the surface tension σ, the contact angle δ and capillary radius. The capillary radius is determind by particle size and porosity and will be defined by equation 3

$$h_s = \frac{4\sigma\cos\delta}{\rho_L g C_m r_K^2} \quad (2)$$

$$r_K = \frac{1}{3}\,\frac{\varepsilon}{1-\varepsilon}\,\bar{x} \quad (3)$$

As the height of the capillary rise in a packed bed is caused by the balance of forces (centrifugal force and capillary force) the quantity of fluid can be assumed as a function of centrifugal acceleration factor and M_1 (equation 5a) at which M_1 means a quantity part of quantity M (equation 4) that contents all parameters that might influence the humidity of a packed bed.

$$M = \{\ \bar{x},\ S_v,\ \sigma,\ \cos\delta,\ \varepsilon,\ \eta\ \ \ldots\} \quad (4)$$

$$m_{hs} = f_1(C_m,\ M_1) \quad (5a)$$

$$B_{hs},\ S_{hs} = f_1(C_m, M_1, H) \quad (5b)$$

The loading and saturation caused by m_{hs} however depends to the height of the packed bed. With increasing mass of the solid material and with this, the height of the packed bed, the constant value of capillary fluid is less important. Therefore can be assumed an function corresponding to equation (5b).

The third part of fluid is the so-called "wedge fluid" at the contact points of the different particles. For the dependence of this fluid can be assumed a function (eq. (6a))

$$m_{L,ZW} = f_2(C_m,\ M_2) \quad (6a)$$

respectively for loading and saturation

$$B_{ZW},\ S_{ZW} = f_2(C_m,\ M_2) \quad (6b)$$

The last part of fluid is defined to be the only one that is dependent on time in the centrifugal force field. Generally can be taken a function

$$m_{L,F} = f_3(C_m, M_3, t, H) \quad (7a)$$

respectively

$$B_F(t), S_F(t) = f_3(C_m, M_3, t, H) \quad (7b)$$

The acceptance of time-constant parts of fluid according to equation 5a and 5b only contradicts apparantly to what one can see if watching the variation of fluid at the different contact points (figure 2).

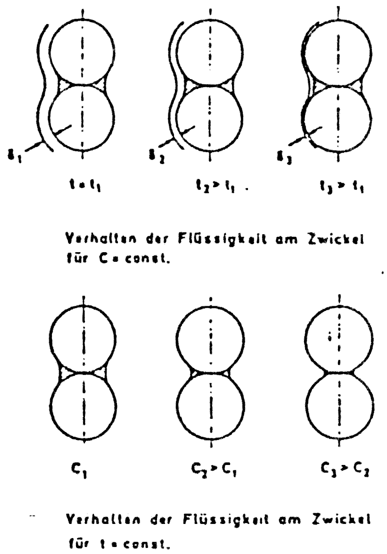

Fig. 2. Behaviour of fluid at the contact point of two particles

In fact, the equilibrium fluid at the contact points is built at the beginning of any dewatering in its value corresponding to the acceleration factor. This fluid only can be changed by variation of the centrifugal force. The fluid above, which slowly reaches the surface of particle and the wedge fluid belongs to the part of fluid that is described by equation 6b.

Totally the saturation of a packed bed can be described by equation 8a. In cases in which there is no capillary rise in a packed bed at all, equation 8b can be taken

$$S = h_s/H + S_{ZW}\left(\frac{H-h_s}{H}\right) + S_F(t)\ \left(\frac{H-h_s}{H}\right) \quad (8a)$$

$$S = S_F(t) + S_{ZW} \quad (8b)$$

As the kinetic cause of the variation of fluid dependent on time a model of film flow is assumed. In the case of metal plates which were dipped in an "oil-bath" BIKERMAN proofed in 1956 JEFFREYS equation, that there is a dependence on time by $1/\sqrt{t}$ (figure 3).

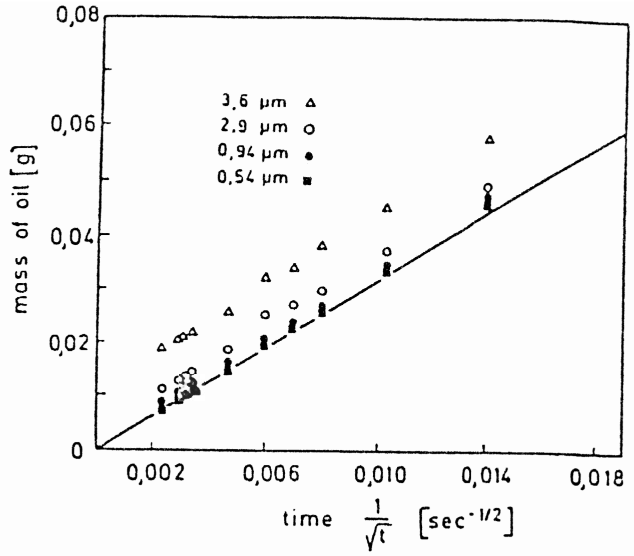

Fig. 3. Mass of oil versus time on a vertical metal plate

By this, metal plates of different rugostities were pulled out and the mass of fluid was measured at different times.

Indeed the theoretical course was not reached but the measurepoints indicate a parallel shifting. The quantity of deviation is corresponding to the surface roughness of the plates.

Solving the problem for a centrifugal dewatering analogeously, but instead of a plate for a cylindrical capillary, starting from equation 9 (fig. 4).

$$\rho_L g\ r\ d\varphi dr\ dh = \tau\ r\ d\varphi\ dh -$$

$$- \ (\tau + \frac{\partial \tau}{\partial r}\ dr)\ \ (r+dr)\ d\varphi\ dh \qquad (9)$$

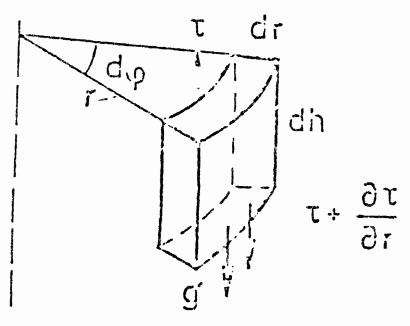

Fig. 4.

the following partial differential equation will be get

$$\frac{\partial g}{\partial t} = -g\ /\nu\ \{\ \frac{1}{2}\ r_k^2\ -\ \frac{1}{2}(r_k - \delta)^2\ -$$

$$-\ (r_k - \delta)^2 \ln \frac{r_k}{r_k - \delta}\ \}\ \frac{\partial \delta}{\partial h} \qquad (10)$$

A particular solution of equation (10) expressed as saturation for the case of a capillary is given in equation 11

$$S_F(t)\ =\ 4/3\ \sqrt{\lambda_M}\ -\ \lambda_M/2 \qquad (11)$$

whereas

$$\lambda_M\ =\ \frac{4\ \eta\ \bar{H}}{\rho_L g\ C_m d_h^2 \cdot t} \qquad (12)$$

Equation (12) describes the time-dependant course of saturation in a packed bed.

3. EXPERIMENTAL DATAS

Looking at typical measurements with glass spheres which were got in a special centrifuge (tumbler centrifuge) and compared to the theoretical course expressed by equation (8) there is similar to the results of BIKERMAN a shifting found out. In figure (5) this is demonstrated for three different values of the centrifugal acceleration factor C_m.

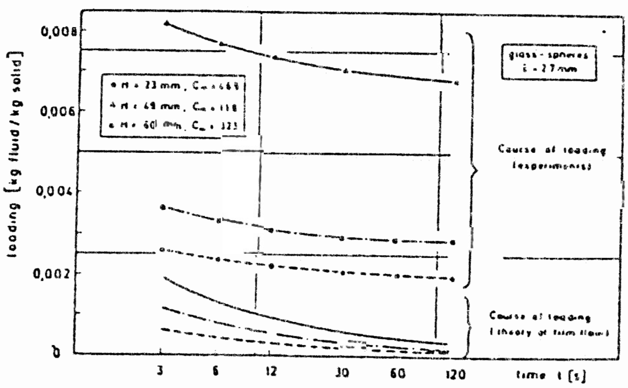

Fig. 5. Comparison of theoretical and experimental course of loading for three different values of acceleration factor C_m

Subtracting the theoretical values of saturation or loading at certain times from a lot of experimental values the time-constant differences shown in figure (6) are found out.

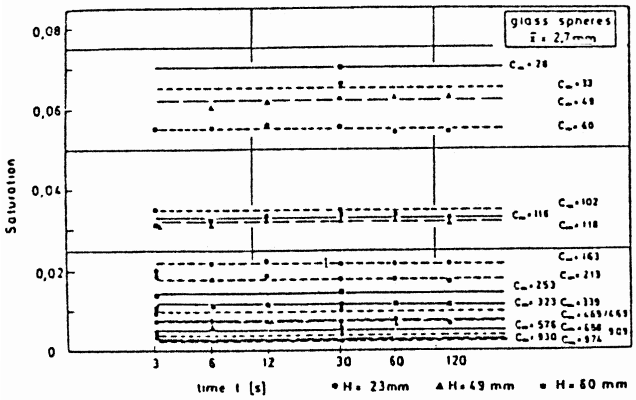

Fig. 6. Time-constant differences of saturation for different values of C_m (glass spheres, $\bar{x}$ = 2,7 mm)

Dependent to the equilibrium between centrifugal force and capillary force in a packed bed, which is known in literature as Bondnumber (MERSMANN)

$$F_c/F_\sigma \sim \frac{d_h^3 \rho_L g \; C_m}{\sigma \; \cos\delta} = Bo_2 \qquad (13)$$

for all varied porosities, centrifugal acceleration factors, heights of packed beds, particle sizes and particle size distributions all points of measurements can be seized by one course only (figure 7).

In this figure the third and fourth field of the Bond-diagram is presented which can schematically be explained in figure 8.

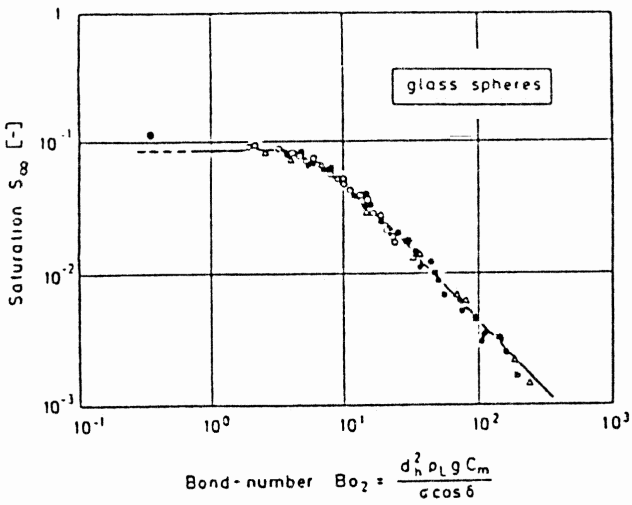

Fig. 7. Equilibrium saturation S versus Bond-number Bo_2 (glass spheres, different particle sizes)

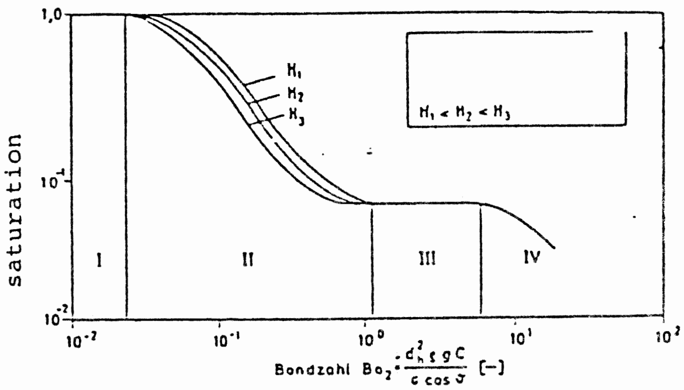

Fig. 8. The four fields of the "Bond-diagram"

In field one the capillary force is higher than the centrifugal force and the capillary rise (also for C_m > 1) is higher than any height of a packed bed that can be realized in a centrifuge. The saturation S still remains at value one.

In the second field the capillary rise has a value greater zero but less than the maximum height of a packed bed. That means that for height H_1 a saturation S = 1 is possible but for the same acceleration factor C_m and height H_2 or H_3 the saturation is less than one.

In cases in which a capillary height h_S is no longer existent there is a constant value of equilibrium saturation between Bondnumber of 0,5 and about 5. After this the saturation decreases once more.

This course can be interpretated as a, in pressure-filtration wellknown capillary-pressure course. Field one and two is valid for the coarse capillary system, the course of field three and four is valid for the wedge-capillary system.

By comparison of the course correspondant to equation (7) to the course of known models of dewatering in literature (e.g. figure 9) the following can be established.

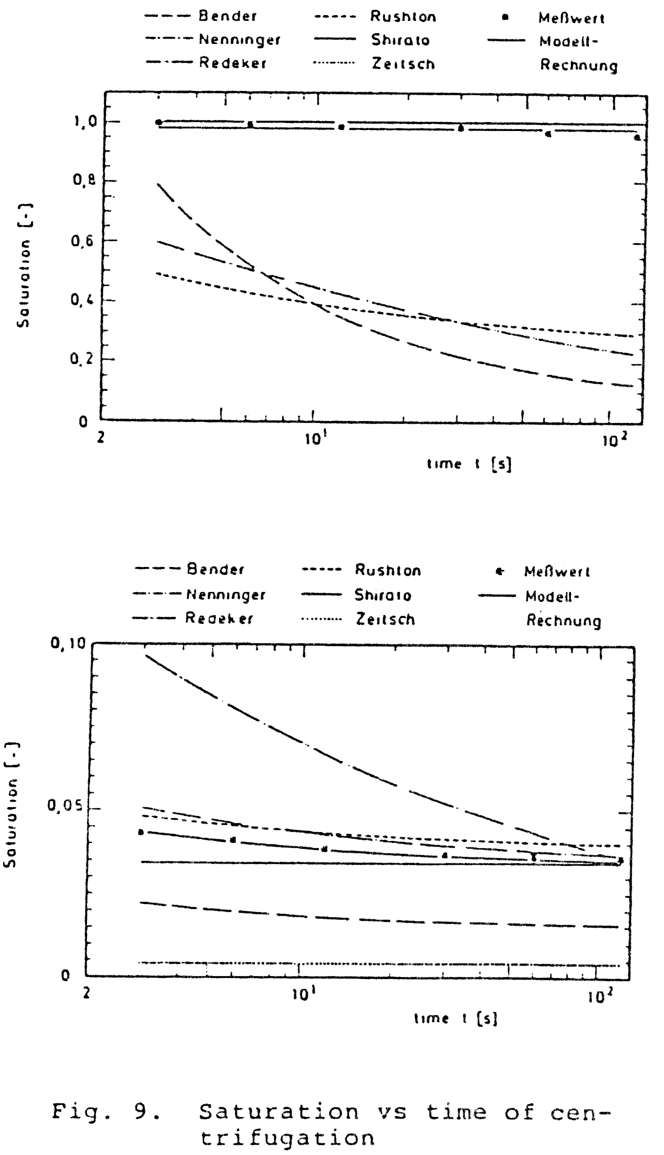

Fig. 9. Saturation vs time of centrifugation
a) $Bo_2 = 0{,}01$
b) $Bo_2 = 15$

Many authors found out that the equilibrium saturation depends on a power - 0,25 to the centrifugal acceleration factor C. They had done experiments in all fields of the Bond-diagram and the experimental datas are seized by regression in a fair good manner by this power.

In fact the power of C_m changes from 0 or -1. Therefore, this shows figure 9, dependent to the field in the Bond-diagram, there can be a very good correspondance to the experimental datas. In cases in which the power of C_m is not in the region of -0,25, there is a considerable deviation between theory and experimental datas.

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SYMBOLS

Bo_2	=	Bondnumber
C	=	Centrifugal acceleration factor
F	=	force
H	=	height
S	=	saturation
S_V	=	specific surface
V	=	volume
d_h	=	diameter of capillary
h_S, h_{SC}	=	head of capillary rise
m	=	mass
r_K	=	radius capillary
t	=	time
x	=	particle size
δ	=	thickness of film
$\cos\delta$	=	cos of contact angle
ε	=	porosity
η	=	viscosity
λ_M	=	parameter
ρ	=	density
σ	=	surface tension