New Concept on Centrifugal Filtration

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Journal: AIChE Journal

Manuscript ID Draft

Wiley - Manuscript type: Research Article

Date Submitted by the Author: n/a

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Keywords: Centrifugal filtration, Specific filling flow rate, Filling load, Preconsolidated cake

1. Introduction

In the recent years, the scientific interpretation and the industrial practice of process centrifugal filtration moved off from each other although the application of filter centrifuges mainly in the fine chemical and the pharmaceutical industry became more important regarding the generally received cyclical production and the GMP prescriptions.

According to the up-to-date industrial practice a typical cycle of a batch-wise operated filter centrifuge involves the following main process steps:

1. The acceleration of the empty basket up to the filling revolution.
2. Filling the suspension into the basket continuously or intermittent running. Preferably applying constant volumetric flow rate.
3. Drainage of the tail of the filtrate after the basket has been full.
4. Washing and drying the cake.

Other steps, e.g. the inertization, changing revolution between two process phases, discharging the basket, are out of the scope this article because they do not influence the hydrodynamic processes. The cake washing was neither investigated.

Most of the cases the decisive process step among the above listed ones, is the filling from the point of productivity. In other words how can be charged into the basket most of the solid relatively in the shortest time. Hultsch and Wilkesmann[1] described three filling methods, the choice from them “should be based on experimentation”. Then there was no more saying about the experimentation. The description of the starting point for modelling the system as follows: that is an

annular layer of consolidated cake submerged in a clear liquid (Zeitsch[2]). This simplified model serves no more than to ensure the possibility of a mathematical solution of a situation, which nowadays has no practical use at filling the basket, but at the very most, at washing. At that point, the charge of the centrifuge is finished and the flow through a consolidated cake layer can be investigated while the liquid layer is decreasing. One can say that it is a not too important episode of the cycle.

2. Experimental method

The precise measurement of the instantaneous value of the filtrate flow rate is difficult because the holdup of the centrifuge casing and its drainage system is rather high and incalculable. That partly generates an integrating effect, partly causes delay when measuring the flow rate in the discharge nozzle. To overcome this difficulty instead of the discharge flow rate the instantaneous value of the volume held up in the basket was measured. For this purpose a special tool, a mechanic level gauge was constructed and built into the centrifuge. This is shown in Fig. 1.

Fig.1

A horizontal beam (1), tipped with a small curved blade can revolve around a vertical axis. The curvature of the sliding plate and the positioning of its axis ensure that the face of the blade is always tangent to the cylindrical free surface inside the basket in case of any layer thickness (between 0 and 34 mm) and the plate is sliding on the surface of the rotating liquid like a water sky. The bearings of the vertical shaft (2), which holds the revolving beam, are built into the cover of the machine. Inside the bearing box, a small helical spring exerts a slight

momentum to force the sliding plate onto the liquid surface. The shaft is led out of the centrifuge through the cover and by means of the indicator (3). The instant volume of the slurry in the basket can be read off on an angle graduated volume scale (4). If the results of the measurement are plotted as a function of time, the instantaneous filtrate flow rate is given:

$$v_f = v_{fill} - \frac{dV_h}{d\tau} \qquad (1)$$

The inside diameter of the basket of the experimental centrifuge was 0.35m and the filter surface of it, A = $2r_B$H = 0.25m^2. The range of the revolution extended from 1000 to 1840 min^{-1}. That means a range of acceleration from 1919 to 6496 ms^{-2}. The maximum value on the volume scale was 9×10^{-3} m^3. The filling was stopped generally at reaching the volume of 8×10^{-3}m^3. That means 34mm layer thickness and a value of $r_O/r_B = 0.8$. The total geometrical volume of the basket was 10×10^{-3}m^3

The experimental results

The experiments were carried out as follows: The centrifuge with empty basket was started. When the rotation stabilized at the preset revolution, the feed pump was also started simultaneously with the timer. The time was read at each whole unit (10^{-3}m^3) of the scale. The zero value of the hold up volume on the scale and the volumetric flow rate of a progressing cavity feed pump were checked before starting each experiment. The pump was stopped when reaching the aimed volume. Then the times belonging to the values of the decreasing volume was also read.

To the first series of experiments a sort of aluminium-hydroxide slurry (Al-OH-I) was used which was precipitated from a solution of aluminium-sulphate. The solid content of it was 8.8 m% (g solid/100g suspension). Four different filling flow rates

were applied. The results are presented in Fig.2. The peculiarity, that catches the eyes on the plot at first, is the linear increase of the holdup volume in the basket,

Figure 2.

independently from the filling flow rate. It follows that the filtrate flow rate is also constant (see Eq.1). At the time instants when the filling was stopped a sharp break in the trend of the volume change (from increase to decrease) can be observed. It proves the very high sensitivity of the level gauge. The measured and calculated results of four experiments are presented in Table1.

Table1.

It can be seen that the filtrate flow rate does not depend on the time but it does depend on the filling flow rate. From the figures in Table1, one can note that increasing the feed flow rate the filtrate flow rate becomes higher. At the same time, it also should be noted that the total volume filled into the basket became not more but less and less, exceeding a certain value of the filling flow rate. By other words, applying higher filling flow rate a bigger portion of the filled slurry is held in the basket relatively to the discharged filtrate. The total volume fed into the basket can be expressed as follows:

$$\Sigma V_{fill} = v_{fill}\tau_{fill} = \dot{v}_{fill}A\tau_{fill} \qquad (3)$$

Here τ_{fill} is the period of the continuous filling, as v_{fill} is the volumetric filling flow rate, still $\dot{v}_{fill}$ is the same relatively to the filter area of the basket. In such cases when the filling was stopped (for the sake of sparing the experimental material), at a smaller hold up volume as the usual ($8\times10^{-3}m^3$); the extrapolated total volume was evaluated calculating the mass balance. In Table1, it was

reasonable to give not only the filling volumetric flow rate but also the filtrate flow rate in specific unit of measure relative to filter surface of the basket. The filtrate flow rate does not depend on time; on the contrary, it is a function of the specific filling flow rate. That perception opens a brand new, undiscovered field of investigation. The independent variable of the experimental investigation (instead of time) became the filling flow rate, which was termed to “filling load”.

To confirm these recognition further experiments were carried out. The next series of experiments were made with another type of aluminum-hydroxide containing slurry (Al-OH-II). That was an industrial by-product, which originated from etching high purity aluminum foils for electrolyte condenser production. The solid content of the slurry was 14.2 m%. The industrial processing of that material was done applying manually discharged pendulum type filter centrifuges because the filtration protracted for very long time. The filtrate flow rates proved also to be constant as it is shown in Fig. 3.

Figure 3.

In case of two experiments of these series, the feed was restarted after the holdup volume diminished. Note that during the second filling period, the filtrate flow rate also remained constant but its value became much lower relative to the first filling run. In case of the highest filling flow rate, during the second run the basket became full in such a short period that the second filtrate flow rate was not evaluable (proved to be practicable zero). These results may be interesting when the influence of the heel cake on the filtrate flow rate has to be taken account filtering the next charge or in the cases when the technologically expected quantity of the solid in the basket can be accumulated by restarting many times the filling. The operator has to know that during the second, third, etc. refilling the filtrate flow

rate becomes lower and lower. The experimental results are summed in Table 2. The change of the filtrate flow rate in dependence of the filling is rather moderate, so the calculated values of the total filled volume are not so unambiguous as in case of the preceding series of experiments (maybe due to measurement errors).

Table 2.

The third sort of slurry used for the experiments was 10 m% solid content brewery yeast (suspended in water). It also exhibits similar characteristics like the preceding slurries. The results are summed in Table 3.

Table 3.

The values of the filtrate flow rates listed in Tables1; 2 and 3, are plotted against the filling flow rates. These result the characteristic diagrams shown in Figures 4; 5 and 6. In these figures, both the filling volumetric flow rate and the filtrate flow rate are given in specific unit of measure.

Figures 4; 5 and 6.

Discussion

The change of the filtrate flow rate is function of the filling flow rate. The use of the same measure of unit is evident. The experimental results above and its interpretation can be regarded as a revelation, because they have no antecedents. There are not experimental results made using such technics. The specific filling flow rate, as independent variable, is termed to “filling load” analogously to the liquid or gas load, which are generally accepted technical terms in the gas (or vapor)-liquid transfer processes. Each line representing the change of the filtrate flow rate (in Fig. 4 and 6) starts from the origin and then each has a typical break point. That point is a distinguished place. Here and within the range below it, the

measured filtrate flow rates are proportional to the filling flow rates. It is enhanced by drawing the $\dot{v}_f = \dot{v}_{fill}$ diagonal. Applying the terminus of filling load in this range, the filter area is „under-loaded" expression is proper. The mentioned proportionality is noticeable mainly in Fig.4 and Fig.6. In case of Fig.5, all of the four experimental points fell into the range of the higher range of filling flow rates beyond the break point that is in the „over-loaded" filling range. Maybe the lowest filling rate is near to the break point, so its value was estimated. The under-loaded filter area means that the ratio of the filtrate to the holdup volume is constant (independently from the filling flow rate). Coming from that, the solid concentration of the holdup has to be also constant in this range. Presumable the solid concentration of the holdup is analogous to (maybe identical with) the gel point concentration, as it is interpreted by Stickland et al.[3]. According that, the gel point concentration in case of a solid-liquid dispersion means that the individual particles get contacts to each other so the slurry will be able to withstand mechanical effects. That process is in relation with the volume proportion of the particles relative to the whole suspension. The evolution of the solid concentration in the holdup within the under-loaded range, for the sake of distinction, it is named here to "pre-consolidated" cake. However, it has to know that inside the layer, which builds up in the basket starting from zero and reaching certain thickness after a period, a distribution evolves regarding the volumetric rate of the solid in dependence of the radius. The average solid content of the pre-consolidated cake can be calculated from the material balance of the basket in an optional time instant of the filling.

Detracting from the filled slurry the quantity of filtrate proportional to the $\dot{v}_f / \dot{v}_{fill}$ ratio, the material balance results for the holdup:

$$A(v_{fill}\rho_{sl} - v_f \rho_f)c_{prec} = v_{fill}\rho_{sl}c_{sl}A \tag{4}$$

The concentration of the pre-consolidated slurry in the basket (in the under-loaded filling range) can be expressed as follows:

$$c_{prec} = \frac{c_{sl}}{1 - \frac{v_f^{opt}}{v_{fill}^{opt}} \frac{\rho_f}{\rho_{sl}}} \tag{5}$$

Applying this formula for calculations, the ρ_f / ρ_{sl} quotient generally can be taken to one if the solid density is not too high (most of the materials investigated here that was the case).

Right side from the break point, in the range of the higher (over-loaded) filling flow rates; the proportionality between the filtrate and the filling flow rates, does not exist more. The filtrate flow rate keeps on increasing but its quantity relative to the holdup becomes gradually smaller. A more and more high portion of the slurry charged into the basket will be held up there. Coming from them the average solid content of the holdup become lower than the concentration given by Eq.5. The specific hold up flow rate can be calculated from the experimental result:

$$\dot{v}_h = \frac{v_h}{A} = \dot{v}_{fill} - \dot{v}_f \tag{6}$$

Where v_h in case of a given experiment is the slope of the strait line representing the increase of the holdup e.g. in Fig.2.or Fig.3.

To interpret generalized way the change of the filtrate flow rate in dependence of the specific filling flow rate, and to explain processes involved, let us regard Fig.7.

Figure 7.

In the range of the low filling flow rates, the filter surface of the given centrifuge is under-loaded by the filling. What does it mean? As an extreme case let us imagine a centrifuge which is charged by dripping small quantities of slurry into the basket. If the frequency of the basket rotation will be integral multiple of the frequency of the dripping, the droplets will fall onto the same spot at all times. On that spot, the solid content of the droplets will be very fast settle onto the filter surface while the liquid will find its way through or away the sediment to leave the basket within a very short time. Easy to see that it is merely a question of time that the basket becomes unbalanced. In a not so extreme case, if the slurry is filled by very low flow rate into the basket, it loses fast its liquid content. The rapid settling sediment is not able to spread out forming a smooth layer. That gets unbalanced the basket that is, the rugged cake layer in the basket and in consequence, the vibration of it, are signs of the under-loading filling.

The user manual of a Ferrum centrifuge (Ferrum AG, Switzerland) writes about this phenomenon, without giving thorough explanation of the processes involved as follows: *"An asymmetric cake is built during filling should continuous vibrations identical to the basket speed occur. To help putting this right for the next charge the basket speed shall be reduced and/or the filling quantity respectively the time unit needs to be raised."* These measures result the filter surface less under-loaded or become over-loaded. In other words, the occurrence of the unbalanced state, which is a side phenomenon of the under-loading filling, can be avoided by increasing the filling volumetric flow rate (that is the filling load) and/or decreasing the revolution of the basket (the driving force of the filtration).

At the break point, a noteworthy operational state arises. It termed to be an optimum and means that applying the filling flow $\dot{v}_{fill}^{opt}$ (see Fig.7) the solid quantity filled into the basket in one run reaches the possible maximum. Increasing further the filling flow rate the filter surface of the centrifuge becomes over-loaded. In this operational range, the absolute value of the filtrate flow rate keeps on increasing but a decreasing portion of the charged slurry leave instantly the basket in contrast to the under-loaded state. Therefore, the unbalance phenomenon disappears when the filling turn to over-load. Applying higher filling flow rates, more and more liquid surplus accumulates in the basket. Coming from that, the total quantity of the slurry filled into the basket by one run, will be less and less (see Tables1; 2 and 3). The liquid surplus does better the flowing characteristics of the batch mainly within the layers near to the free surface. Beyond the optimum point, the average solid content of the slurry layer in the basket becomes gradually lower. Since the concentration is changing along the radius, its value near to the free surface will be more liquid-like until in the deeper layers, close to the basket wall, the consolidation goes ahead.

However, let us remember that because of the continuous filtrate discharge, the average solid content of the charge in the basket has to be significantly higher than the feed concentration. Therefore, the sharp separation of the layer, to a liquid ring, in which the pressure is increasing and to a consolidated cake, in which the pressure decrease, respectively, practically cannot evolve. Instead of that, the whole charge in the basket has to be treated to a unified continuum inside of it, the concentration and the permeability of the batch and the centrifugal field generated pressure, as well, has to be unbroken function of the radius. The distribution of the characteristics is helped by the stirring effect of the

continuously incoming mass of feed and the "rising tide" action in the batch (the radial component of the velocity on the free surface is directed against the centrifugal force). These effects are going on during the whole period of filling. Coming from them, as the free surface radius, r_O will coincide with the border of the sediment and the sediment-cake transition does not appear like a sharp line, the pressure inside the layer will be positive, increasing from the free surface then reaching a maximum, it decreases to the ambient pressure at the basket wall. The gradient of that over-pressure should be much lower than in the centrifugal field generated pressure in the liquid layer. Summarizing, the pressure distribution in the basket is similar to the one in Zeitsch's model[2], but there, at the case of $r_O = r_C$, the pressure inside the cake, is negative because he counted with a consolidated cake.

If the centrifuge is considerably over-loaded, the basket becomes full within a very short period. Then stopping the feed, after a little while the slurry will be separated to a cake and a clear liquid layer because of the sedimentation. This is the standard starting-point of the classic model of centrifugal filtration: A layer of consolidated cake submerged in an annulus of clear liquid[1-6].

There is no evidence that anybody would have tried to modify this generally accepted basic condition although it has not too much practical use. The main inadequacy of this model is not in that the starting point is, in time and space, uncertain but it is also obscure how the cycle will be continued. Under such circumstances, the centrifugal field generates significant pressure in the liquid layer. By the compression of the liquid pressure slows down the filtration. Not too far from here, (in the filling-load scale), as the extreme case of the over-loading, an unpleasant and dangerous vibration occurs. Hultsch and Wilkesmann[1] termed

it to liquid shock. This phenomenon appears (mainly in horizontal machines) when the slurry is difficult to filter and the concentration of it is rather low. Applying high filling flow rate the batch in the basket reaches the full level within a relatively short time. In such a case, when a deep layer of liquid covers a thin layer of cake, a circumferential wave motion emerges in the clear liquid. The frequency of it much lower than the revolution of the machine. It starts after the full indicator has stopped the feed, so there is no tool to intervene when a horizontal machine, let us say of 15 tons, begins to shake on the support structure. The prosecution of the filling could dump this vibration but the basket is full at that moment. Alternatively, the increase of the revolution could eliminate the shocks but probable, in this earthquake-like situation, which can last long minutes, the operator does not risk this step. The centrifuge producers (e.g. Ferrum AG.) know that phenomenon and describe it in the user manual.

The optimum filling as a distinguished point of the process

Instead of the extreme cases, the attention has to be focused on the optimum termed break point, which means the transition from the under-loading to the over-loading filling range. That is a well-defined and experimentally reproducible place. The specific filling flow rate belonging to the optimum definitely appears in the plots, $\dot{v}_{fill}$ vs. $\dot{v}_f$, although the inherent process is a very moderate transition. It is regarded optimum because the utmost solid can be charged in one run during relatively shortest time (see Fig.7). To quantify the optimum point, a more simple apparatus may also be enough taking account that the filtrate flow rate does not depend on time. Measuring filtrate volumes by cubage, discharged from a small-scale centrifuge, within a shorter period maybe enough. Suitable

results can be gained in a technically well-furnished up-to-date production plant, too.

For drawing conclusions, let us regard the model of the process. Starting out the differential equations set up by Zeitsch[2]:

$$v_f = \frac{2\pi KH}{\mu_f}\left(\rho\omega^2 r - \frac{dP}{dr}\right) \tag{7}$$

Taking account that v_f is constant, on the contrary K is function of the radius, the modified differential equation will be:

$$dP = \left(\rho\omega^2 r - \frac{v_f \mu_f}{2\pi H}\frac{1}{K(r)}\frac{1}{r}\right)dr \tag{8}$$

Providing that for the dependence of K(r) a suitable distribution function will be found, and applying the $r_O = r_C$ boundary condition, the solution of Eq.8 will give the pressure distribution in the unified continuum layer. The radius dependence of the permeability can be written, as follows:

$$K(r) = f(r)K_B \tag{9}$$

In case of a correct solution, moreover applying the $v_f = v_f^{opt}$ substitution, the relation between the optimum of the filtrate flow rate and the permeability of the consolidated cake can be established. Insomuch as the above presented new concept on centrifugal filtration is accepted, this statement has to be regarded a conjecture.

The role of the concentration of the slurry to be filtered

It is not a guess but a practical experience[1] that a higher magnitude of solid content of a suspension to be filtered get more easily the process. As during

washing, the characteristics of the cake forming particulate solid exert decisive effect on the process (beyond the magnitude of the centrifugal field). In filling a centrifuge, other parameters (the specific filling flow rate, the time schedule of the filling) have decisive influence on the outcome of the cycle. The low solid content and the filling method jointly can result such a situation that rather much liquid has to be forced through a consolidated cake layer. To handle too much liquid beside the solid, in most of the cases, construction resolutions are known. The use of lateral filter surface or peeling tube can ensure escape possibility if too high liquid layer cumulates on the "bad side" of the cake (e.g. the sidewall basket centrifuge, Zeitsch[2]). Other design, as the rotary syphon centrifuge with the peeler tube ensure an auxiliary depression to accelerate the filtrate flow through the cake (Hultsch and Wilkesmann[1]). The latter design is usual also nowadays in the market and in the production but exclusively in the starch production. The probable cause of that is the depression generated by the syphon and the peeling pipe, easily reach the boiling point of the mother liquor if it is not aqueous solution.

The constructions introduced in Asmatulu's theses[5] provide a pressure difference surplus between the inside and the outside space of the filter surface of the basket. The disadvantage of Asmatulu's resolutions that building a mechanical sealing into the process room of the centrifuge is anxious. In a clean technology that is impossible. It is meaningful that these resolutions were born not in the recent years so the fact that they, except one: the rotary syphon centrifuge, did not become widespread.

It is easy to see thus, that among different solid content slurries from the same particulate solid and liquid, the higher solid content one will prove easier to filter

than the other with lower solid content. To clarify this question, two series of experiments were carried out. Using a slurry of 11 m% solid content, the $\dot{v}_{fill}$ vs. $\dot{v}_f$ plot was made as usual. The name of the solid material was Albendazol, a veterinary ingredient made by acidy precipitation. Thereafter the residue of the original slurry was diluted to double with the filtrate collected from first series of experiments. The second series of experiments were fulfilled consuming this diluted slurry. The $\dot{v}_{fill}$ vs. $\dot{v}_f$ plots are represented in Fig.8.

Figure8

The optimum values of the filtrate flow rates proved to equals, within an acceptable measurement tolerance in case of the original and the diluted slurries. The line from the origin to the $\dot{v}_2^{opt}$ point is approximately bisector of the angle enclosed by the $\dot{v}_f = \dot{v}_{fill}$ diagonal and the origin to $\dot{v}_1^{opt}$ line. The rate of the holdup flow rates $\left[\dot{v}_h^{opt}\right]_1 / \left[\dot{v}_h^{opt}\right]_2$ is about 2.35. This means that filling the same basket volume with the optimum flow rate; it takes more than double period if the concentration is half of the original (see Fig.7 and Fig.8). Coming from them if there is any method to increase the concentration of the suspension to be filtered, it will results significant cut in the filling time. Doubling the filling concentration can results a cut in the filling period to one-half to two-third, depending on the difference between the filling and the pre-consolidated cake concentration.

Table 4

The evaluated results are summed in Table 4, which contains also the calculated values of the pre-consolidated cake concentrations for both the original and the diluted slurries (32.8 and 33.3 m%, resp.). The good agreement of the two

figures seems to verify the provided dependence between $\dot{v}_f^{opt}$ and the permeability of the cake. The effect of the pre-thickening on the solid capacity of the centrifuge is the higher if the filling solid content is the nearer to the pre-consolidated concentration.

The similarity aspects of the process

An important point of this experimental analysis that the gained results are valid or not at scaling-up. The geometrical similarity is trivial. The identity of the magnitude of the centrifugal field is also suitable. However, the three-five times difference in the layer thickness may question the transfer of experimental results to big industrial machine.

There were only restricted possibilities to make experiments in industrial scale. Two different suspension were available. One was a fungicide (named BCM-N), the other was a crystallized active ingredient (named Trasicor). The applied method was that after fulfilling the small-scale series of experiments, at discrete points, (aiming the optimum) were made large-scale measurements. The results are shown in Fig.9.

Figure 9.

Fig.9 is a combined diagram. The experimental results of BCM-N (two large-scale points) and the Trasicor (one large-scale point) are represented in a mutual figure. For the sake of better distinction, the results of BCM-N appeared separately in the right down corner of the figure, too. Both big machines were one-meter diameter but the revolutions differed from each other (960 min^{-1} in case of BCM-N and 900 min^{-1} regarding Trasicor, respectively). The similarity was ensured by the identity of the centripetal acceleration 5053 and 4433 ms^{-2}, respectively. The large-scale results amount to the small-scale ones with

acceptable deviations with special regard that the experimental slurries came from different batches in case of the small scale and the large experiments. The filtrate quantities from the big machines were measured by cubage and the values gained showed right small spread. The Trasicor was an easy to filter crystalline material with a rather high solid content (32 m%). The period of filling was less than three minutes. During that three volumetric samples were taken, each of them 40s lengths of period.

Filtering the BCM-N in large scale the filtrate flow rate was calculated from the average of 8×90s' collected filtrate volume. The total filling time of the 11 m% slurry took 15min. These two suspensions differ from each others significantly from the point of filterability, the distinction can not regarded to be exceptional (really Trasicor can regarded as a best to filter material).

Figure10.

Just as an interesting contribution to the scale-up and shading the foregoing, in Fig.10 the mass decrease of a crystallizer from a production plant is shown. From that reactor a Comi-Condor centrifuge of 1400 mm diameter was filled. The quasi-continuous filling of the gross 0.4 m^3 basket lasted 100 minutes while the mass loosing of the reactor was 1190 kg (practically 1.4 m^3 iso-propanol based suspension). It is represented in Fig.10, by line 5 between points A and B. As a sensitive product was involved, more information may not be given.

The effect of centripetal acceleration

The investigations of the effect of the centripetal acceleration did not give unambiguous results. In respect of the under-loading filling, there can be no doubt about the results. In case of a given material the filtrate flow rates values fallen on

the same line. That means that the pre-consolidated cake concentration does not depend on the acceleration. The optimum point appeared at smaller filling flow rate if the acceleration is lower and this point displaced higher when the acceleration is higher, but the correlation not enough clear. In case of two materials, the relative disposition of the optimum proved more or less proportional to the acceleration but in a third case (Albendazol) the change does not follows the proportionality. Maybe the compressibility plays a role here. The results are summarized in Table 5.

Table 5.

Conclusions

It is hoped that the interpretation of the presented experimental results is a novelty in the field of process centrifugal filtration. Maybe it is not an overstatement that the authors who persist in the traditional model, shut themselves in such a physical reality the occurrence of which is realistic but the relevance of it nowadays is questionable. The up till now not revised theory lead back to the pristine processing when the suspension was filled into the static basket then it began to revolve. Speaking on plant scales, a well sophisticated, for optimum planned filling can last, in an average case, 15-30 minutes but (as it is shown in Fig.10) it can take much longer period. After this, stopping the filling, the batch begins to consolidate by shrinking. The shrinking lasts not too long, the measure of it 10-20%. During that process, a notable liquid layer (tail) does not evolve above the cake. In the course of a second filling period the filtration slows down considerably therefore more than two filling periods is not reasonable. The verification of the relation between the cake permeability and the optimum of the filtrate flow rate needs further theoretical and experimental work.

Notation

A filter area [m^2]

C_{sl} slurry concentration [m%] (g solid/100g suspension)

C_{prec} concentration of the pre-consolidated cake [m%] (g solid/100g cake)

$f(r)$ distribution function representing the dependence of permeability on the radial coordinate [-]

H length of the cylindrical basket [m]

K, K_B permeability of the cake layer [m^2]

n revolution of the basket [min^{-1}]

P, ΔP pressure, pressure difference [Pa]

$P(r)$ pressure distribution inside the basket [Pa]

P_C pressure in the liquid at the slurry/cake boundary [Pa]

r radial coordinate [m]

r_B inside radius of the basket [m]

r_C radius of the slurry/cake boundary [m]

r_O radius of the free liquid/slurry surface [m]

v_f volumetric filtrate flow rate [m^3s^{-1}]

$\dot{v}_f$ specific volumetric filtrate flow rate [$m^3s^{-1}m^{-2}$]

v_{fill} volumetric filling flow rate [m^3s^{-1}]

$\dot{v}_{fill}$ specific volumetric filling flow rate [$m^3s^{-1}m^{-2}$]

V_h holdup volume of the basket [m^3]

v_h volumetric holdup flow rate [m^3s^{-1}]

$\dot{v}_h$ specific volumetric holdup flow rate [$m^3s^{-1}m^{-2}$]

Greek letters

μ_f dynamic viscosity of the filtrate [Pas]

ρ_f density of the filtrate [kgm^{-3}]

ρ_{sl} density of the slurry [kgm^{-3}]

τ time [s]

ω angular velocity [s^{-1}]

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