SIMULATION OF LIQUID PHASE ACCUMULATION FOR THE CENTRIFUGAL DEWATERING OF ACTIVATED SLUDGE

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Centrifugation of activated sludge is a frequently used dewatering process but, in spite of this, there is a need for a fitting function for moderate and high sludge concentrations. Liquid phase accumulation kinetics during centrifugation may be used as a source of information about the sedimentation properties and the governing mechanisms during cake formation. For this purpose, activated sludge at different concentrations was investigated on a laboratory centrifuge with a centrifugation factor of 2667. The following sludges were used in the experiments:
1. Activated sludge from thickener (with and without flocculant treatment)
2. Sludge taken after an industrial centrifuge decanter, treated with Floctag 252-A flocculant and collected from a dumper pond
3. Sludge (2) after anaerobic treatment
4. Sludge (2) with a dispersed solid additive.

Using the experimental data for an asymptotic analysis, a dimensionless fitting function was obtained that adequately describes the dependence of liquid volume vs. time for the centrifugation of activated sludge. For the highly concentrated sludge it was found that the dewatering occurs through cake compression. Analysis of deformation models leads to the conclusion that for the compressible cake it is necessary to introduce a parameter characterising the cake plasticity dependence on the centrifugation time. The developed model was validated by fitting numerous experimental data. The main advantage of the proposed model is the possibility to fit the liquid phase accumulation kinetics during centrifugation over a wide range of activated sludge concentration values, from suspensions up to structured and paste-like cake consistency.

INTRODUCTION

The analysis of suspension sedimentation and centrifugation is present in numerous works. The existence of different physico-chemical factors involved in the centrifugal decanting process does not favour obtaining a general solution for the problem. Frequently, models are based on data for defined initial and boundary conditions. Nevertheless, with changing sludge properties, for instance with activated sludge, model predictions can significantly deviate from experimental measurements. This is the reason for the application of semi-empirical models for sedimentation and centrifugation. In many industrial applications information about the "dewatering potential" of a centrifugation process at certain technological conditions is required, e.g. sludge concentration, centrifugation factor, treatment condition, etc. Laboratory centrifuge tests, where experiments are performed up to the point where equilibrium between the sediment and fugeate is achieved, may be used to get this data.

Centrifugation kinetics can be represented in the form of the fugeate (liquid phase) volume V, accumulation vs. time of centrifugation t, or in a normalised volume form as \( v = V/V_0 \), where V and V* are the decanted liquid volumes at time t and at equilibrium, respectively.

Applying the normalised volume v, the simplest kinetic dependence has the form

\[ v = 1 - \exp(-kt) \]  

(1)

where ki is a coefficient comprising parameters dependent on the centrifugal force and sludge properties. The centrifugal force is usually represented in the form of the centrifugation factor

\[ K_c = \frac{\omega^2 r}{g} \]  

(2)

where \( \omega \) is the rotation speed, r is a radius of rotation, characterised as the distance of a sludge particle at a certain time from the axis of rotation and g is the acceleration due to gravity. As particles are randomly distributed in the suspension at the beginning of the centrifugation process and, when equilibrium is reached, accumulate in the sediment, in industrial applications \( K_c \) is considered as an average value.

Another model, proposed for an activated sludge, takes the form of a double exponential decay

\[ \frac{dv}{dt} = A \exp(-k_1t) + B \exp(-k_2t) \]  

(3)

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where $A$, $B$, $k_2$, and $k_3$ are coefficients.

Centrifugation of activated sludge is a frequently used dewatering process but, due to the wide range of sludge properties, relating accurately describing the dewatering kinetics data are still missing. There is a need for a fitting function for moderate and high sludge concentrations, in particular, for the liquid phase accumulation kinetics during centrifugation.

**EXPERIMENTS**

Activated sludge obtained from an industrial wastewater treatment plant at different solids concentrations determined as dry solids (DS) and solid composition content was investigated at room temperature. The wastewater treatment plant treats sewage water from a petrochemical refinery plant and municipal wastewater from a city with a population of around 70,000. The characteristics of the used sludge were:

1. activated sludge from the thickener (with and without flocculant treatment)
2. sludge samples taken after the industrial centrifuge decanter, treated with Florezware 262-4 flocculant and collected from the dumping pond
3. sludge (2) with and without food waste after anaerobic treatment
4. sludge (2) with a dispersed solid additive

Centrifugation experiments were performed on a laboratory tubular centrifuge with a 30 cm diameter rotor and 8 tubes each having a sample volume of 30 ml (sample height = 4.5 cm). The average centrifugation factor $k$, was 2667.

**RESULTS AND DISCUSSION**

Analysis of the Centrifugation Kinetics and Model Determination

Based on the experimental data obtained (and presented later in Figures 6, 8 and 9) the following assumption was made, the setting of the solid phase and cake compaction depends on the hindered settling velocity and sediment compression. Due to the applied centrifugal force, a primary cake skeleton from particular aggregates and flocs is formed leading to free water being displaced from the space between the aggregates/flocks (inter-floc liquid). This stage is followed by compaction of the sediment with the water being displaced from the pores of the flocs (intra-floc liquid) by a filtration mechanism until an equilibrium condition is reached at $t = \infty$.

The liquid volume for hindered sedimentation and sediment dewatering can be represented in the form $V = V(t)$, where $r \leq 1.0$. Therefore, in log-log coordinates, the kinetics of liquid accumulation must have a linear dependence $log(V) = log(V)_{eq}$ if the process is controlled by a single mechanism, or comprise a series of different linear functions if during dewatering one mechanism changes to another. This assumption was confirmed for different types of activated sludge. In Figure 1, for example, the dependence of the liquid volume on time for different types of activated sludge is shown. It is seen that the observed dependences are well fitted by linear relationships.

A model that may cover the entire range of concentrations for activated sludge is developed below. In this model, the liquid phase volume $V$ obtained during centrifugation is assumed to be the main variable. Using asymptotic analysis, in the function form $F(V)$ that satisfies the conditions

$$\lim_{t \to \infty} F(V) = \infty$$
$$\lim_{t \to 0} F(V) = \infty$$

**Figure 1:** Experimental data for the centrifugation of activated sludge. (a) 1 - with 1.6 % DS, 2 - treated by Florezware flocculant (11.9 mg/l DS), 3 - centrifuged on an industrial centrifuge after anaerobic treatment with 16.64 % DS, 4 - the sludge with 11.07 % DS, 3 - the sludge with 11.7 % DS + cement to the amount of 90 % DS.

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the dimensionless general fitting function is obtained:

\[ \frac{V}{V_i} = \frac{(t/t')^2}{a + (t'/t)^p} \]  \hspace{1cm} (4)

where, in our case, \( F_2(V) = 0 \) and \( F_1(V) = V \); \( v \in (0, 1) \), \( a, t' \) and \( p \) are the model parameters. At \( (t'/t)^2 \rightarrow \infty \), \( V \rightarrow 0 \).

Due to the specific properties of the activated sludge, parameters \( a \) and \( t' \) are variable. For instance, the activated sludge settling properties are affected by the coagulation/flocculation pretreatment, the ratio of organic/non-organic components in the solid phase, etc. and, therefore, the settling kinetics will be different. However, if the centrifugal dewatering plays a key role, the settling kinetics in the coordinates \( V - t \) will result in a series of similar curves (see Figure 2). Assuming equation (4) to form the basis of the model, the values of the model parameters \( a, t' \) and \( p \) are combined below for different modelling approaches.

**Centrifuge Settling**

Based on the analysis of the settling process, it may be considered that in the initial stage of centrifugation a dependence \( V = f(V-V_i) \) may be applied. Hence, the volume of fugate obtained can be represented as:

\[ V = V_i - k_i (1 - V) t \]

(5)

where \( k_i \) is a parameter dependent on the average centrifugal factor \( (K_i) \) and sludge properties, has the dimension of \( \text{[day]} \) and can be considered as the proportional velocity constant.

As follows from equation (5), the experimental data must be fitted by the relation \( V = (1 - V) \alpha t \), at least in the initial dewatering stage. Figure 3 presents the experimental data for the activated sludge centrifugate together with the expected linear trend. Rearranging equation (5) gives the equation for hindered settling:

\[ V = \frac{k_i t}{1 + k_i t} \]

(6)

Comparing equations (4) and (6), the following values of the model parameters are found: \( a = 1.0 \), \( p = 1.0 \), and \( t' = 1/k_i \). At the initial settling stage, when \( k_i t < 1 \), \( V = k_i t \). Moreover, if \( t = t' \) then \( V = 0.5 \), hence, parameter \( t' \) corresponds to the time when \( V = V_i/2 \).

**Centrifugal Dry-Squeezing**

From the structural cake, squeezing under centrifugal force can remove an additional volume of liquid. In this dewatering phase the cake porosity becomes a function of time. The dewatering for highly concentrated sludge occurs as cake compaction with a changing plasticity. Analysis of deformation models

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**Figure 2:** Dependence of \( V \) on \( t \) for the activated sludge presented in Figure 1(a).

**Figure 3:** Experimental data and linear relations for \( V(t) \) vs. \( t \) obtained from the data presented in Figure 1 (see legends also shown in Figure 1).
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leads to the conclusion that for the compromise case, the time coefficient \( f' \) becomes dependent on the dewatering time \( t \). It is possible to assume \( f'_m = f''_m \), where \( 0 \leq m \leq f' \) is the parameter that characterises the cake plasticity dependence on the centrifugation time. For the case of \( p = 1.0 \), equation (4) becomes:

\[
v = k_f^{f''_m} \left[ 1 - \frac{k_f}{k_{f}^{f''_m}} \right]
\]

(7)

When \( m = 0 \), then \( f'_m = f' \), equation (7) becomes the hindered settling relation (6). The value of \( m \) can be calculated from the dewatering kinetics data at any \( t \)-th point by:

\[
m = 1 - \frac{\log \left( \frac{1}{1 - v_i} \right)}{\log(f')} \]

(5)

or determined by a fitting procedure.

The effect of the parameters \( f' = 1/k_{f}^{f''_m} \) and \( m \) on \( v \) is shown in Figure 4. As can be seen, with an increase in the hydraulic resistivity \( f_{m} \) (increase of \( 1/k_{f} \)), the time needed to reach a defined centrifugate volume increases and the initial dewatering velocity decreases.

In the initial dewatering stage, the inequality \( k_{f}^{f''_m} \ll 1.0 \) is valid and equation (7) becomes

\[
v = k_f^{f''_m} k_{f}^{f''_m}
\]

(9)

Equation (9) has similarities with the empirical filtration equation \( V = k_f^{f''} \), where the parameter \( b \) characterises the filtration complexity (for instance, cake pores blocking) and \( a \) in the range 0.4 – 0.98. The limiting value \( b = 1.0 \) corresponds to the aeration of pure liquid through a stationary cake (washing regime). Parameter \( b \) has a similar meaning and, therefore, when \( m = 0 \), then \( b = 1.0 \) and the dewatering process in this condition is characterised by liquid removal from the inter-particle (inter-floc) space.

At \( b < 1.0 \), the dewatering process occurs as the squeezing of structured cake aggregates with a corresponding change in cake porosity with time and the release of infracake liquid. Knowledge of the dewatering velocity \( dv/dt \) is important for process control and optimisation. Dewatering velocity \( w \) is obtained from equation (7) at \( m > 0 \):

\[
w = \frac{dv}{dt} = k_f \left( 1 - m \right) \frac{f''_m}{1 - f''_m}
\]

(10)

When \( m = 0 \), equation (10) describes the dewatering velocity for the hindered settling regime and \( w = k_f / (1 + k_f^{f''_m})^2 \).

In Figure 5 the dependence of the dewatering time is presented (a) at \( k_f = 1.0 \) (1 min), for different values of \( m \) and (b) for different regimes, respectively. The effect of variation is shown in Figure 5(b) at \( m = 0 \) and 0.2. From Figure 5, it follows that the dewatering kinetics are characterised by two periods of moderate and fast reduction of the dewatering velocity \( w \) dependence on \( k_f \) and \( m \). The considered model confirms conventional observations that the dewatering efficiency increases with \( m \) to 0 and with the reduction of the sediment (cake) hydraulic resistance \( 1/k_f \).

Figure 6 represents the dependence of the decanted fluid volume on time, for activated sludge at low and moderate solid concentrations (DS). In these situations.

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there is no plasticity effect.

The dependence of $f = 1/k$, on the flocculant dosage is given in Figure 7 together with corresponding fitting functions. As may be seen, the parameter $f$ is well correlated with flocculant concentration making it possible to define the optimal dosage for maximum dewatering of the sludge.

The validity of the model for high concentration slurry, as described by equation (7), is shown in Figure 8 for anaerobic treated mixtures of activated sludge and potato peels. The volumetric proportion between the sludge and peels is 1:1. Samples 2 to 4 were treated by using Sedipure flocculant with respective dosages of 0.7, 5.4, and 4.8 g/h g DS. Centrifuged slimes are represented by a non-homogeneous structured system that significantly hampers the dewatering process. Due to the complexity of the direct determination of the plasticity parameter for industrial grade activated sludge, the values of $m$ were obtained by a non-linear least squares fitting procedure for the model described by equation (7) as 0.25, 0.28, 0.4, and 0.53 and these correspond to the experimental situations described in Figure 8 as (1) to (4). The model was also evaluated using published data $^{13}$, which is also shown in Figure 9. Figure 9(b) shows results for the flocculated activated sludge with 8.3% DS $^{13}$ treated with different dosages of flocculant.

The dependence of $1/k$, on DS is shown in Figure 10 (a). An increase in the parameter $1/k$, is observed until 7-8% DS activated sludge is reached after which it remains constant for larger DS values. The data is fitted by the function

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NOMENCLATURE
\( a \) model parameter in equation (41) (-)
\( b \) power order in filtration formula (-)
\( b_1 = 1 - m \)
\( F_r(V) \) asymptotic function
\( g \) gravity constant (m/s\(^2\))
\( K_c \) centrifugation, average centrifugation factor (-)
\( K \) centrifugation, average centrifugation factor (-)
\( m \) coefficient (1/s)

\[
\frac{1}{K} = \frac{1.512}{S} \quad \exp\left(\frac{(DS - 3.4)}{0.79}\right)
\]

with a regression coefficient of 0.973. It was determined that up to 7-8% DS, the value of the parameter \( m \) for activated sludge dewatering in a centrifuge can be assumed to be zero. Starting from 7-8% DS, a transition from a settling regime to the filtration (squeezing) regime with \( m > 0 \) is observed which corresponds to the qualitative change in the cake structural properties. Moreover, experiments show that anaerobic treatment of highly concentrated slurry or when a high amount of organics is present in the solid phase of more than ~5% DS leads to the parameter value \( m > 0 \) (see Figure 10(b), branch (II)).

CONCLUSION
Using asymptotical analysis, a fitting function was obtained that describes the centrifugation of activated sludge with a high solid phase concentration. For this case it was found that dewatering occurs due to cake compaction. The main advantage of the proposed model is the possibility to fit liquid phase accumulation kinetics during centrifugation for a wide range of the activated sludge solids concentration, from suspension up to structured and plate-like cake consistency. However, the extension of this model to other slurries requires further investigation.

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![Figure 9: Fitted experimental data V vs. t obtained for activated sludge from (a) Agraivic\(^2\) and (b) Chu & Lee\(^3\). Points correspond to experimental data and lines to data fitting according to equation (7) for different situations. (a): 1 - 3.5% DS; 2 - primary settler's sludge, 9.7% DS; 3 - anaerobic sludge, 4.5% DS; 4 - for these situations \( a = 0 \) was unsuitable. (b): 1 - 0.3% DS without flocculant (\( e = 0.4 \)); 2 - 0.3% DS with 5 mg/L DS (\( e = 0.55 \)); 3 - 0.3% DS with 25 g/kg DS (\( e = 0.5 \)); 4 - 0.3% DS with 50 mg/L DS (\( e = 0 \)). FILTRATION. 8(1), 2008]
$k$, parameter in equation (5), dependent on ($K_n$) and sludge properties ($\eta_s$)

$m$, parameter that characterizes the cake plasticity

dependence on centrifugation time ($\eta$)

$n$, power value, $n \leq 1.0$

$q$, model parameter in equation (4) ($-\Delta$)

$r$, radius of rotation (m)

$s$, time of centrifugation (s)

$t$, model parameter in equation (4) ($a$)

$\phi$, $\phi = F/V_n$

$V$, filtrate (liquid phase) volume ($m^3$)

$V_0$, liquid volume at equilibrium ($m^3$)

$v = V/V_0$, normalized liquid volume ($-\Delta$)

**REFERENCES**


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