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SIMULATION OF LIQUID PHASE ACCUMULATION AT CENTRIFUGAL DEWATERING OF ACTIVATED SLUDGE

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ABSTRACT

Centrifugation of activated sludge is a frequently used dewatering process but there is a need for a fitting function for moderate and high sludge concentrations. In particular, liquid phase accumulation kinetics during centrifugation may be used as a source of information about sedimentation properties and governing mechanism of the cake formation. This will allow the obtention of the optimal parameters for the dewatering control and process optimisation.

For this purpose, activated sludge at different concentrations was investigated on a laboratory centrifuge with centrifugation factor 2667. The following sludges were used in the experiments: 1) activated sludge from thickener (with and without floculant treatment); 2) sludge after industrial centrifuge decanter *Flottweg Z62-4* collected from dumping pound; sludge (2) after anaerobic treatment; sludge (2) with a dispersed solid additive.

Based on the obtained data, the following assumption was made: settling of the solid phase and cake compaction depends on the hindered settling velocity and sediment compression. Due to the applied centrifuge force, a primary cake skeleton from particular aggregates and flocs is formed. During this stage, free water is displaced from the space between aggregates/flocs with a further transition to the compaction of the sediment with the water being displaced from the pores of the flocs by a filtration mechanism until an equilibrium condition is reached.

The liquid volume V vs. time t at hindered settling and sediment dewatering can be represented in the form $V \propto t^n$, where $n \leq$ 1.0. Therefore, in log-log coordinates, the kinetics of liquid accumulation have a linear dependence $\lg(V) \propto n \lg(t)$ in both settling and compaction stages. This assumption was confirmed for different types of activated sludge.

Using asymptotical analysis in the function form $F(t,V)$, a dimensionless fitting function was obtained that describes the centrifugation of activated sludge. For highly concentrated sludge, it was found that the dewatering occurs as 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.

Developed model was used for fitting numerous experimental data. The main advantage of proposed model is the possibility to fit the liquid phase accumulation kinetics during centrifugation in a wide range of the activated sludge concentration, from suspension up to structured and paste-like cake consistency. The extension of this model to other slurries requires further investigation.

KEYWORDS
Activated Sludge, Centrifugation, Dewatering, Filtration, Simulation

Introduction

Analysis of suspensions sedimentation and centrifugation is presented in numerous works [1-4].

The existence of different physico-chemical factors involved in the centrifugal decanting process is not favourable for the obtention of a general solution of the problem. Frequently models are based on data for defined initial and boundary and a large volume of experimental measurements is required. Nevertheless, with changing slurry (for instance, activated sludge) properties, model predictions can significantly deviate from experimental. That is the reason for the application of semi-empirical models for sedimentation and centrifugation [5].

In the work [6] the sediment growth velocity is given as

$$dh/dt = k_1(h - h_\infty) \tag{1}$$

where h is the sediment thickness, t the sedimentation time, h_∞ is the equilibrium thickness of the sediment at $t \to \infty$, and k_1 is the coefficient.

In Eq. (1) $h - h_\infty$ may be considered as a measure of the dispersed system deviation from the equilibrium. If we consider the sedimentation in the form of a normalised variable $v = V/V_\infty$, where V and V_e are the decanted liquid volumes at time t and at equilibrium, respectively, then $-k_1 t = \ln(1 - v)$ and

$$v = 1 - \exp(-k_1 t) \tag{2}$$

Another model, proposed for an activated sludge, takes the form of double exponentional decay [7]

$$dv/dt = A\exp(-k_1 t) + B\exp(-k_2 t) \tag{3}$$

where A, B, k_1 and k_2 are coefficients.

Centrifugation of activated sludge is a frequently used dewatering process but, due to the wide range of sludge properties, relations adequately 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.

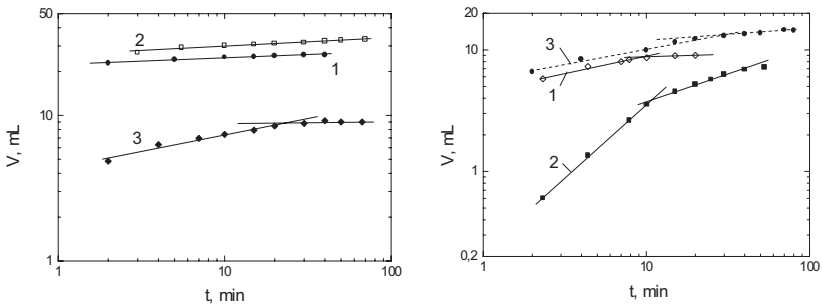
Activated sludge at different concentrations was investigated on a laboratory centrifuge with centrifugation factor K_c = 2667: 1) activated sludge from thickener (with and without floculant treatment); 2) sludge after industrial centrifuge decanter *Flottweg Z62-4* collected from dumping pound; sludge (2) after anaerobic treatment; sludge (2) with a dispersed solid additive.

Analysis of the centrifugation kinetics and model determination

Based on the obtained data, presented below in Figs 6 - 9, the following assumption was made: settling of the solid phase and cake compaction depends on the hindered settling velocity and sediment compression. Due to the applied centrifuge force, a primary cake skeleton from particular aggregates and flocs is

formed. During this stage, free water is displaced from the space between aggregates/flocs with a further transition to the compaction of the sediment with the water being displaced from the pores of the flocs by a filtration mechanism till an equilibrium condition is reached at $t \to \infty$.

The liquid volume at hindered sedimentation and sediment dewatering can be represented in the form $V \propto t^n$, where $n \leq$ 1.0. Therefore, in log-log coordinates, the kinetics of liquid accumulation must have a linear dependence $\lg(V) \propto n \lg(t)$, if the process is controlled by a single mechanism, or composed by 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 Fig. 1, as an example, the dependence of the liquid volume on time for different types of activated sludge is shown, where TDS means the total dissolved solids.



(a) (b)

Figure 1. Experimental data on the centrifugation of activated sludge. (a): 1 – activated sludge with 1.6 % TDS, 2 – activated sludge treated by flocculant *Sedipure* (11.9 mg *Sedipure*/g TDS), 3 – activated sludge centrifuged on an industrial decanter centrifuge after anaerobic treatment with 16.64 % of TDS. (b): 1 – activated sludge centrifuged on an industrial decanter centrifuge with 10.6 % TDS, 2 – the same with 11.67 % TDS, 3 – the same with 11.7 % TDS + cement in amount of 50 % of TDS.

As may be seen, Fig. 1, the observed dependences are well fitted by a linear relation. A model that may cover the entire range of concentrations of the activated sludge will be developed. In this model, the liquid phase volume V obtained during centrifugation is assumed as the main variable.

Using asymptotical analysis in the function form $F(t,V)$ satisfying the conditions $\lim_{t\to 0} F = F_0(V) \neq \infty$ and $\lim_{t\to \infty} F = F_\infty(V) \neq \infty$, the obtained dimensionless fitting function is

$$V / V_\infty = v = (t / t^*)^p / [a + (t / t^*)^p] \qquad (4)$$

Where, in our case, $F_0(V)$ = 0 and $F_\infty(V) \equiv V_\infty$; $v \in$[0, 1]; a, t^* and p are the model parameters. At $(t / t^*)^p \to \infty$, $v \to$ 1.0.

Due to the specific properties of the activated sludge, parameters a, t^* and p are variable. For instance, the activated sludge settling properties are affected by the coagulation/flocculation pre-treatment coagulation/flocculation, the ratio of

organic/non-organic components in solid, 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 series of similar curves, Fig. 2.

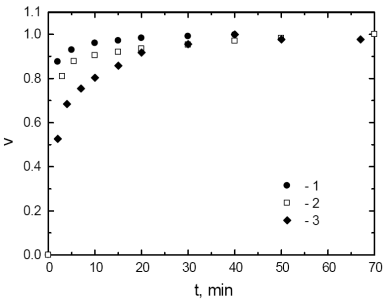


Figure 2. Dependence of v on t for the activated sludge presented in Fig. 1a.

Assuming Eq. (4) as the basis of the model, the values of the model parameters a, t^* and p are obtained.

Centrifuge settling. Usually in the sedimentation model, the main variable is the sediment (cake) thickness, Eq. (1). By analogy, in centrifuge dewatering, the volume of the obtained fugate can be represented as:

$$v = k_s(1-v)\cdot t \tag{5}$$

where k_s is a parameter dependent on the centrifugal force and sludge properties, has the dimension of $[1/t]$ and can be considered as the process velocity constant.

As follows from Eq. (5), the experimental data must fit the relation $v/(1-v) \propto t$, at least in the initial dewatering stage. Fig. 3 presents the experimental data for the activated sludge centrifugate together with the expecting linear trend.

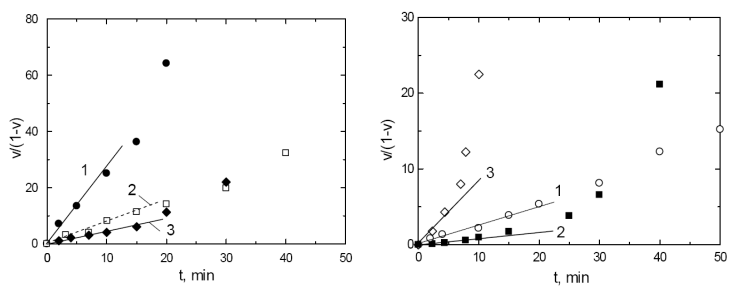


Figure 3. Experimental data and linear relation $v/(1-v)$ vs. t obtained from the data presented in Fig. 1. Legend see in Fig. 1.

Rearranging Eq. (5) the equation for hindered settling is obatined:

$$v = k_s t/(1+k_s t) \tag{6}$$

Comparing Eqs (4) and (6), the following values of the model parameters are obtained: a = 1.0; p = 1.0 and $t^* = 1/k_s$. At the initial settling stage, when $k_s t << 1$, $v \approx k_s t$. Moreover, if $t = t^*$ then v = 0.5, hence, parameter t^* corresponds time when v = 0.5 or $V = V_\infty / 2$.

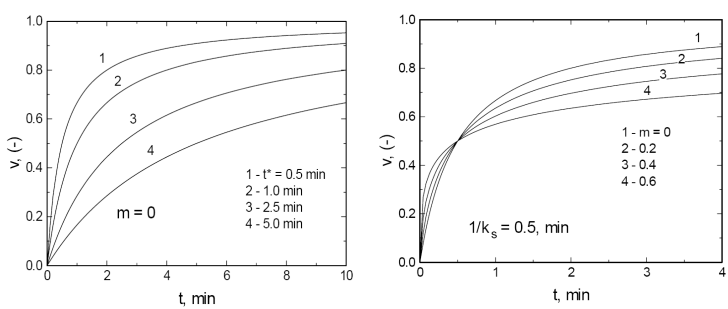
Centrifugal squeezing. From the structured cake, squeezing under centrifuge force can remove an additional volume of liquid. In this phase, the cake porosity becomes a function of the time. The dewatering for highly concentrated sludge occurs as cake is compressed and its plasticity changes. Analysis of deformation models leads to the conclusion that for the compressible cake, the time coefficient t^* becomes dependent on the dewatering time t. It is possible to assume $t_p^* \propto t^m \cdot t^* = t^m / k_s$, where $0 \le m \le 1$ and when m = 0 then $t_p^* \equiv t^*$. For the case of p = 1, Eq. (4) becomes:

$$v = k_s t^{1-m}/(1+k_s t^{1-m}) \tag{7}$$

Parameter m characterises the cake plasticity dependence on the centrifugation time and needs further investigation and analysis. The value of m can be calculated from the dewatering kinetics data at any i-th (t_i, v_i) point by:

$$m = 1 - \frac{\lg[v_i/(1-v_i)/k_s]}{\lg(t_i)} \tag{8}$$

Effect of parameters t^* $(1/k_s)$ and m are shown in Fig. 4. As can be seen, with an increase in the hydraulic resistance (increasing of $1/k_s$) the time needed to reach a defined centrifugate volume increases and the initial dewatering velocity decreases.



(a) (b)

Figure 4. Dependence v on t^* at (a) m = 0, hindered settling regime, and (b) $m \le 0$, $1/k_s$ = 0.5 min, squeezing regime.

In the initial dewatering stage, the inequality $k_s t^{1-m} << 1.0$ is valid and Eq. (7) becomes

$$v = k_s t^{b_1=1-m} \tag{9}$$

Equation (9) has similarities with the empirical filtration equation $V = kt^b$, where parameter b characterises the filtration complexity (for instance, cake pores blocking) and is in the range 0.4 – 0.98. The limiting value b = 1.0 corresponds filtration of pure liquid through stationary cake (washing regime). The parameter b_1 has the similar meaning and, therefore, when m = 0 then b_1 = 1.0 and the dewatering process in this condition characterises by the liquid removal from interparticle (inter-flocs) space by pores.

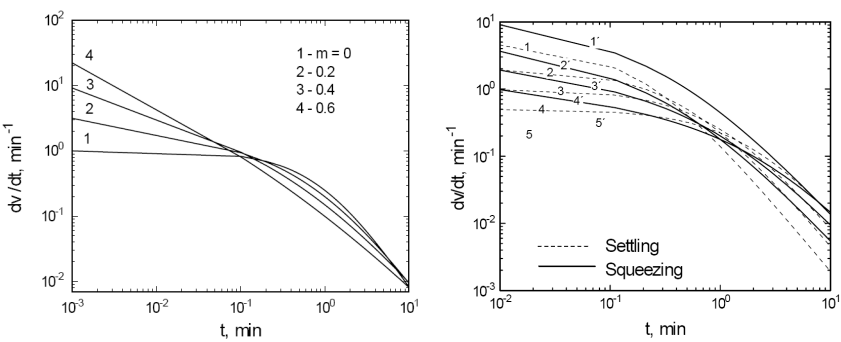
At b_1 < 1.0 the dewatering process transforms to the squeezing of structured cake aggregates with changing the cake porosity with time and releases inta-flocs liquid.

The knowledge of the dewatering velocity dv/dt is important for the process control and optimisation. Dewatering velocity w is obtained from Eq. (7) at m > 0:

$$w = dv/dt = k_s(1-m)/[t^m(1+k_s t^{1-m})^2] \tag{10}$$

When m = 0, Eq. (10) describes the dewatering velocity at hindered settling regime $w = k_s/(1+k_s t)^2$. In the limited case of $m \to 1.0$, $w \to 0$.

In Fig. 5 the dependence of dv/dt on the dewatering time is presented (a) at k_s = 1.0 (min^{-1}), for different values of m and (b) at different regimes, respectively. Effect of k_s variation is shown in Fig. 5b at m = 0 and 0.2.



(a) (b)

Figure 5. (a) Dependence of dv/dt on t, Eq. (10), (a): for k_s = 1 min^{-1} for different values of m and (b) effect of k_s on dv/dt; curves 1 – 5, m = 0 (settling regime) and curves 1´– 5´, m = 0.2 (squeezing). Values of k_s are the following: 1 and 1´ – 5.0; 2 and 2´ – 2.0; 3 and 3´ – 1.0; 4 and 4´ – 0.5; 5 and 5´ – 0.2.

From Fig 5, it follows that the dewatering kinetics is characterised by two periods of moderate and fast reduction of the dewatering velocity w dependence on k_s and

m. Considered model confirms conventional observations that the dewatering efficiency increases with $m \rightarrow 0$ and with the reduction of the sediment (cake) hydraulic resistance $1/k_s$.

Fig. 6 represents the dependence of the decanted fluid volume on time, for activated sludge at different concentrations. The dependence of $t^* = 1/k_s$ on the flocculant dosage is given in Fig. 7 together with corresponding fitting functions. As may be seen, parameter t^* is well correlated with the flocculant concentration making possible to define the optimal dosage for maximum dewatering of the sludge.

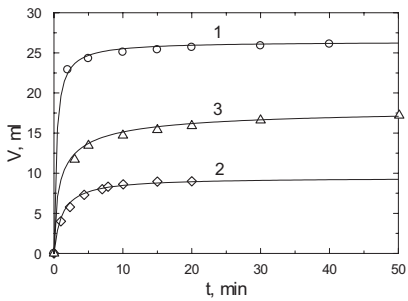


Fig. 6

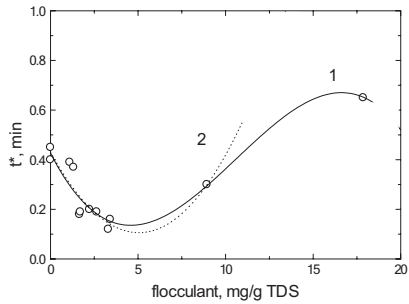


Fig. 7

Figure 6. Dependence of the decanted fluid volume on t for activated sludges with different TDS: 1 - 1.8% TDS; 2 - 10.6% TDS; 3 - 17.76 % TDS (obtained by mixing equal volumes of dumped sludge with 32.96 % TDS and sludge with 2.56 % TDS treated by flocculant *Sedipure* at a 0.19 g/kg concentration). Solid lines correspond to Eq. (7) at m = 0 (lines 1 and 2) and m = 0.25 (line 3).

Figure 7. Dependence of t^* (Eq. 6) on the flocculant concentration in the activated sludge with 2% TDS. Lines 1 and 2 are, respectively, cubic and square fitting functions.

It was determined that up to TDS 7 – 8% the value of the parameter m for activated sludge dewatering in centrifuge can be assumed equal zero. Dependence of t^* on TDS is shown in Fig. 8. An increase in the parameter $1/k_s$ is observed until 7 – 8 %TDS activated sludge, remaining constant for larger TDS values. The data is fiited by the function $1/k_s = 1.512/\{1+1/\exp[(s_0 - 3.4)/0.79]\}$ with a regression coefficient of 0.973. Starting from 7 – 8% TDS, a transition from settling regime to the filtration regime with m > 0 is observed corresponding to qualitative change in the cake structural properties.

The validity of the model described by Eq. 7 validity at high TDS concentration is shown in Fig. 9 for anaerobic treated mixtures of activated sludge and potato peels. Volumetric proportion between sludge and peels is 1:1. Samples 2 to 4 are treated by flocculant *Sedipure*. Centrifugated slurries are represented by a non-homogeneous structured system that significant hampers the dewatering process. Values of m were: 1 – 0.25, 2 - 0.28, 3 – 0.4, and 4 – 0.53.

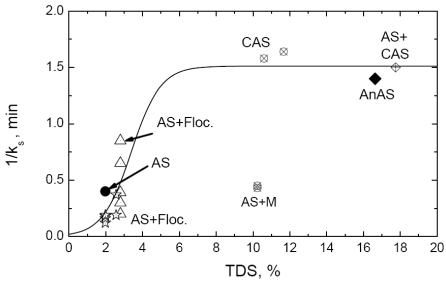


Fig. 8

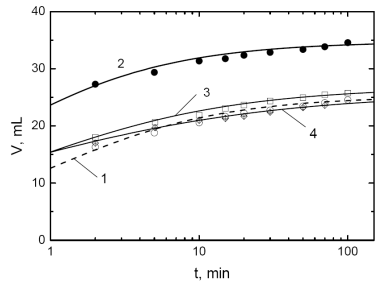


Fig. 9

Figure 8. Dependence of $1/k_s$ on TDS: AS – activated sludge; AS+Floc – AS treated by flocculant; CAS – AS after industrial centrifuge decanter; AnAS – anaerobic AS; AS+M – mixture of AS with clay (1:3); AS-CAS – mixture AS and CAS (1:1volume).

Figure 9. Centrifugation kinetics of an anaerobic treated mixture of activated sludge and potato peel (1:1 volume). 1 – organic fraction 0.47 in 5,78% TDS; 2 – the same as (1) treated by 8.7 g flocculant/kg TDS; 3 – organic fraction 0.26 in 28.58% TDS with 5.4 g flocculant/kg TDS; 4 – organic fraction 0.25 in 31.99% TDS with 4.8 g flocculant/kg TDS.

The main advantage of the proposed model is the possibility to fit the liquid phase accumulation kinetics during centrifugation in a wide range of the activated sludge concentration, from suspension up to structured and paste-like cake consistency.

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