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Phenomenological Sedimentation Model for an Industrial Circular Settling Tank

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The paper presents a study of the influence of integral parameters of an industrial settling tank on the process of sedimentation. An organic water suspension was used in the experiment where the impact of the suspension age on sedimentation was determined experimentally and by computer-aided visualization. Measurements of the inlet- and outlet suspension concentration, the difference in the level of suspension between the reservoir and settling tank as well as the suspension volume flow rate were carried out on a newly developed continuous sedimentation tank. The results of the measurements served as the basis for a phenomenological multi-regression model that was developed to determine the functional dependence of the ratio between inlet- and outlet suspension concentration on the independent parameters of the process. According to the obtained results of the model, the most influential parameters of the sedimentation process are the inlet concentration and the mass flow of the suspension.

Keywords: wastewater, sediment, purification, sedimentation

0 INTRODUCTION

Settling tanks are the oldest, but nevertheless utterly simple and efficient devices for mechanical separation of substances. Solids removal mechanics governs the separation of the suspension on concentrated settled particles and pure fluids. Such a process that is based on simple physical laws is very important in praxis. Accordingly, in order to define the phenomenological theory of settling, various experimental and theoretical studies have been conducted for more than a century. Different areas of usage require different types of sedimentation devices, which are important not only in purifying stations for drinking- and waste water, but also in diverse branches of industry, such as the pharmaceutical-, chemical-, paper- and textile industry, not to mention some other areas and activities (e.g. geological research, etc.).

Collecting and draining of meteoric water goes back as far as antiquity. Collecting waste water began in at the beginning of the 19th century, followed by a systematic handling of waste water together with its (mechanical) purifying at the end of the 19th and the beginning of the 20th century. With an experiment, Seddon [1] showed that the gravitation as a driving force affects particles according to their size. Early theories about the efficiency of the settling tanks were developed by Hazen at the beginning of the 20th century [2], commencing with the theory of behaviour of the individual particle in the uniform flow. Later research [3] showed that the flow of suspension differs significantly from the uniform flow due to a distinctive stratification in settling tanks. Kynch, who studied the settlement of the suspension particles of the same size, introduced a theory that served as a basis for various other authors [4]. He assumed that the sedimentation velocity depends mainly on the concentration of the suspension. Accordingly, he divided the entire suspension into 4 zones from top to bottom: the top layer of the fluid, the starting concentration layer, the layer of the higher concentration and the bottom layer (consisting of the concentrated sediment). Apart from the assumption of the concentration influence on sedimentation velocity, the other important assumption is that the individual particle is exposed only to forces which occur due to the fluid velocity between the particles, while the forces due to fluid acceleration are negligible. Kynch also neglected the momentum of suspended particles. Later authors [5] continued his research by including the particle momentum and showed that the sedimentation velocity depends on a concentration gradient as well. Fitch [6] proved that the differential equation for the equilibrium of forces acting on the particle can be derived

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from different theories already described in literature. He had to neglect certain factors in the equation and introduced some assumptions, which relate to determining pressure gradients in the fluid and the pressure on the contact surfaces between particles. Fluid pressure could be determined by Darcy's law for the flow through porous materials. Michaels and Bolger [5] found with this model that pressures in the fluid as well as pressures between particles depend only on concentration of the suspension, while Kos [7] treated both quantities as functions of pressure gradients. Later studies [8] to [11] showed that pressures depend not only on local concentration, but also on the rate of concentration changing and particle properties (e.g. rheological properties, etc.).

Intensive research which originated from basic principles of mechanics showed that movement and behaviour of particles in fluids present a problem which cannot, even now, be adequately numerically simulated as a whole. Some of the applied techniques, such as finite element- and finite volume methods, can decently describe the particle behaviour inside the suspension [12] to [14], but several limitations are still present (small number of particles, low Reynolds numbers, etc.). For this reason, measurements still need to be carried out on different physical models and pilot devices as well as on prototypes, e.g. on operating purifying stations.

A study described in the paper presents an experimental determination of integral parameters that influence the process of separation of suspended substance in waste water. The main difference between previously published similar studies [15] and [16] and this study is that the presented paper deals with a phenomenological model that is directly derived from experimental results rather than from a theoretical mathematical model. Furthermore, the analysis of the influence of the organic suspension age was carried out for a case of simple sedimentation due to gravity force – it is known [17] that physical properties of a suspension such as density, viscosity and surface tension can change over time and thus influence the settling process of particles. The measured integral parameters such as inlet suspension concentration volume flow rate of the suspension and suspension level difference were used to establish a phenomenological model of the influence of these parameters on the efficiency of the presented settling tank.

1 EXPERIMENT

The fluid used in the experiment was water suspension with 3% mass concentration of ground nut kernels. Bulk density of dry ground nut kernels equalled 604 kg/m^3. When suspended in water, the specific weight of particles slightly exceeds the specific weight of water. Since the solid particles in the suspension consisted of organic substance, it was expected that the sedimentation properties of the particles suspended in water could change over time. For that purpose, the influence of the suspension age on sedimentation, especially on its speed, had to be established before the main integral parameter measurements.

1.1. Influence of Suspension Age on Settling Velocity

An assessment of the impact of the suspension age was carried out in stationary conditions, i.e. when the suspension was exposed to gravity force only. The whole experiment was carried out by means of computer-aided visualization. The main idea adopted here was that the decrease in suspension concentration due to sedimentation allows more light to penetrate through the suspension, because it is the particles in the suspension that obstruct the light. More light penetrating the suspension means brighter images of the suspension with higher values of greyscale intensity. Therefore, values of greyscale intensity A are in proportion with the values of the concentration N of the particles in the suspension:

$$.A \propto (1 - N) \qquad (1)$$

Greyscale intensity values can be easily determined from the digitized images using readily available software packages.

Fig. 1 shows the experimental setup. Freshly made suspension was poured from the reservoir into a 0.5 l test tube. A light source with the power of 100 W was placed near the test tube in order to provide sufficient and stable lighting needed to illuminate the suspension in the test tube. A semi-transparent screen was mounted between the light source and the test tube to help homogenise the light from the light source.

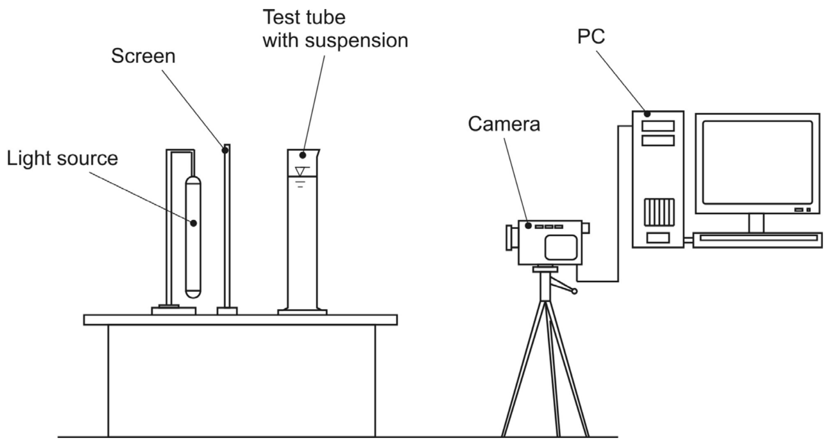

Fig. 1. *Experimental setup for determination of interdependence between the age of the suspension and the settling velocity*

Images of the suspension were then acquired using a Sony Hi8 TR820E camera with a resolution of 480×640 pixels at a frame rate of 25/s. The suspension was filmed for 30 minutes (a sequence) and was then returned to the reservoir. After the alternating interval of 6 or 18 hours the suspension was shaken, so that no sediments remained on the bottom of the reservoir, and was then poured again into the test tube. The whole procedure took 8 days, with two sequences of images taken 6 hours apart each day at the same time. The images were digitized on a PC using the Ulead Video Studio 5 DV software package.

The suspension concentration in the upper parts of the test tube decreases with time because of the continuous particle sedimentation on the bottom of the test tube. It is supposed that the greyscale level of the suspension images increases accordingly with time. For this purpose, four windows were chosen on each image, as shown in Fig. 2. Each window consisted of 2×2 pixels on the digitized images; vertical distance between the two windows was 86 pixels (1 pixel ≡ 0.78 mm). The windows were always at the same fixed position on each image. For every image in the sequence, the average greyscale intensity $A(K,t)$ was calculated for each window in order to smooth any temporarily fluctuations of the concentration [18]:

$$A(K,n) = \frac{1}{l}\frac{1}{m}\sum_{l}\sum_{m} E(l,m), \tag{2}$$

where K denotes the successive window number in each image of the sequence, and n denotes the successive acquired image. $E(l, m)$ denotes the greyscale intensity of each pixel in a particular window and ranges from 0 (black) to 255 (white), corresponding to an 8-bit resolution of the camera. l and m are the coordinates of the pixels inside the window.

At the beginning of each sequence the test tube was photographed empty and the average greyscale intensity A was calculated in each window. This greyscale intensity value was then used as a reference value for each window to cope with any vertical non-homogeneities of the lighting.

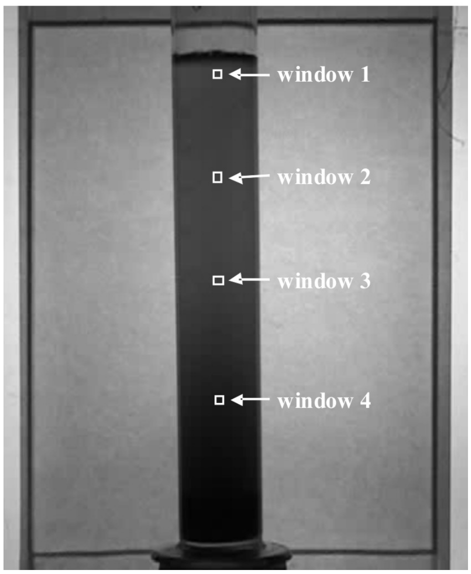

Fig. 2. *Position of windows for determination of greyscale intensity*

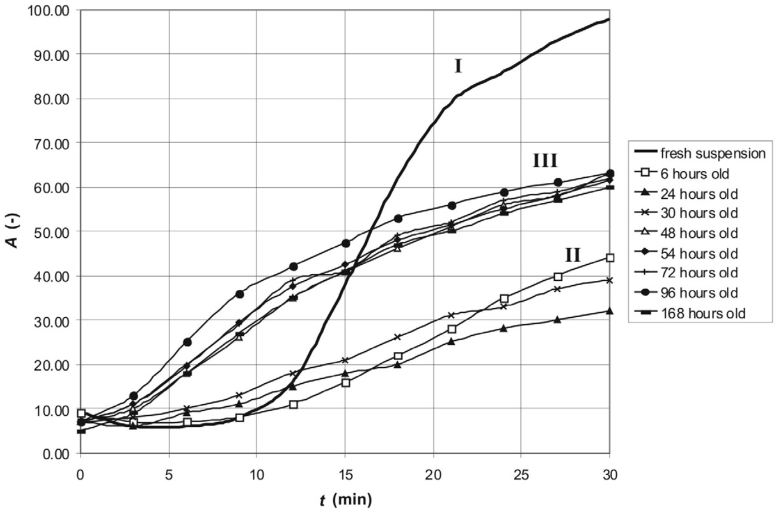

Fig. 3. *Greyscale intensity values in window 3 for different suspension ages*

Fig. 3 graphically shows the results of greyscale intensity calculations in window 3 in Fig. 2 for different suspension ages. It is evident that the settling velocity of the suspension of a particular age can be classified in one of the three groups I, II or III, indicated in Fig. 3. Group I is represented by the settling velocity of the fresh suspension which has the highest average value since it reaches the highest value of greyscale intensity in the first 30 minutes. The most significant changes in settling velocity occur in the first 6 hours (group II) where the average settling velocity is the lowest, and again in about 48 hours. The differences in settling velocity may be the consequence of flocculation [19], which the suspension undergoes during a certain time period, and the consequential hindered settling [17]. According to the diagram in Fig. 3, no significant alterations of the settling velocity were recorded between 48 and 168 hours (group III).

If the average settling velocity v_s of particles in suspension for each suspension age group is presented by the average gradients of greyscale intensity values $\partial A/\partial t$ in Fig. 3, then the following ratio between settling velocities can be obtained:

$$v_{s,I} : v_{s,II} : v_{s,III} = 1 : 0.28 : 0.63 \qquad (3)$$

Eq. 3 does not explicitly imply that the particles in suspension group II settle averagely 3.57-times slower than those in group I – that would mean that Eq. 1 is linear. Another fact that can be seen from Fig. 3 is that the physical nature of sedimentation can differ substantially between different age groups. In group I it appears that the decrease in concentration mainly occurs above a certain front, while below it the concentration does not change much; this is evident from the shape of the curve I in Fig. 3 between 0 and approx. 9 minutes, where the concentration (or greyscale intensity) stays almost unchanged – the front obviously has not yet reached the window 3. After that, when the front reaches and passes the window, the change in concentration takes place quite rapidly between 10 and 20 minutes (curve I, Fig. 3). On the other hand, the changes in concentration in groups II and III start almost immediately on the entire height of the test tube, but gradients appear to be much lower and they do not change as abruptly as in the case of the curve I.

1.2. Measurements of Integral Parameters in the Industrial Settling Tank

Measurements of integral parameters were carried out on a circular settling tank with continuous operation, which is achieved through constant circulation of the suspension flow. The layout of the tank is shown in Fig. 4 together with the suspension flow. The same type of particles (ground nut kernels) was used for the suspension as in the experiment described in section 1.1. The settling tank is fed with water suspension from the distribution ring on the top of the tank. The suspension than passes to the lower chamber of

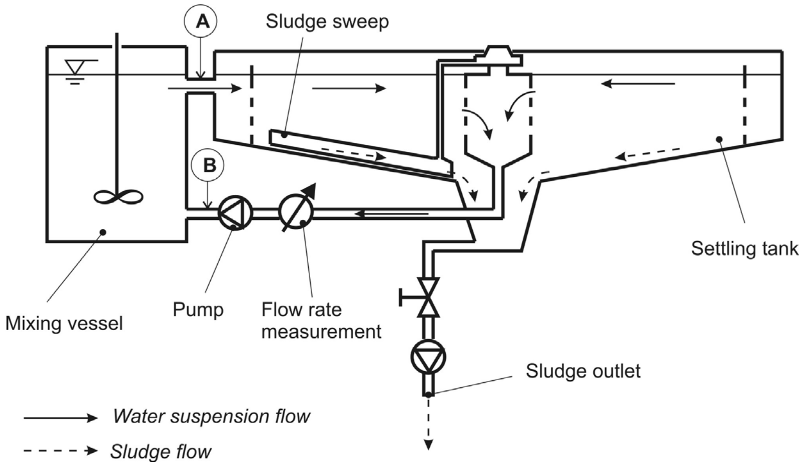

Fig. 4. *Schematic view of the settling tank and water suspension/sludge flow*

the tank divided into several radial vanes (omitted in Fig. 4 for clarity). These vanes enable a quicker transition from turbulent to laminar regime of the suspension flow in order to enhance the efficiency of the settling process.

Large ratio between the volume of the mixing vessel (i.e. reservoir) and the suspension flow in the system enabled the measurements to be carried out at almost steady state conditions.

The efficiency of the apparatus can be determined from the difference between the inlet- and outlet concentration of the suspension. The outflow of the sludge was disabled during the experiment – it remained in the settling tank. The inlet- and outlet concentrations were measured at regular intervals at points A and B, respectively. The flow of the suspension through the system was measured partially by the magnetic flow meter Fischer & Porter and partially by a standard orifice where the measurement of fluid flow relative uncertainty less than 1% was reached. The level difference between the mixing vessel and the settling tank was measured by a conventional U-tube.

Five measurement sets of inlet- and outlet suspension concentration as well as the difference between the suspension level in the settling tank and in the reservoir were carried out, each at a different volume flow rate of the suspension. The first measurement set started with the suspension that was prepared a day before and was thus 24 hours old. The time interval between two measurement sets was 24 hours, except between measurement sets 2 and 3 where the time interval amounted to 72 hours. The results are presented in Table 1.

2 PHENOMENOLOGICAL MODEL OF SEDIMENTATION EFFICIENCY

The experimental results from the previous section were used to form a multiregression phenomenological model of the concentration difference (i.e. difference between inlet- and outlet concentrations of the suspension), which in this case denotes a quantitative measure of the sedimentation efficiency. This parameter thus represents the dependent variable of the model, while the independent variables of the model are inlet concentration, suspension level difference and volume flow rate. According to Table 1, all the independent variables affect the dependent variable monotonously. Therefore, a power law was chosen to model the dependence of concentration difference on other process parameters [20]:

$$\Delta C = k \cdot C_i^{\alpha} \cdot \Pi_{\dot{V}}^{\beta} \cdot \Pi_H^{\gamma}, \tag{4}$$

where k denotes the constant of the model, which should also include the influence of the suspension age (Section 2.1). α, β and γ are powers of the independent variables. ΔC equals C_i - C_o, where C_i and C_o denote inlet- and outlet concentration, respectively. The volumetric flow rate and the level difference are presented with dimensionless parameters $\Pi_{\dot{V}}$ and Π_H, respectively, in order to avoid physical confusion with units.

Table 1. *Measurements of integral parameters - results*

Measurement set No.	Outlet concentration (vol. %)	Inlet concentration (vol. %)	Level difference (mm)	Volume flow (l/s)
1	2.5	4.6	220	4.67
	2.3	3.5	220	4.67
	2	2.7	220	4.67
	1.7	2.1	220	4.67
	1.5	1.8	220	4.67
	1.3	1.5	220	4.67
	0.9	1.2	220	4.67
	0.7	1	220	4.67
	0.45	0.9	220	4.67
2	3.7	4.97	155	4.86
	2	2.9	155	4.86
	1.8	2	155	4.86
	1.7	2	155	4.86
	1.2	1.5	155	4.86
	1.1	1.3	155	4.86
	0.8	1	155	4.86
3	3.2	4.97	30	4.29
	1.7	2.5	30	4.29
	1.4	1.8	30	4.29
	1.2	1.5	30	4.29
	0.8	1.1	30	4.29
	0.7	1	30	4.29
	0.55	0.7	30	4.29
4	4	4.97	155	5.02
	1.7	2	155	5.02
	1.35	1.6	155	5.02
	1.3	1.4	155	5.02
	0.95	1.2	155	5.02
	0.65	0.85	155	5.02
5	4.8	4.97	135	5.68
	2.8	2.9	135	5.68
	2.4	2.7	135	5.68
	2.5	2.55	135	5.68

The following relations couple those variables with their dimensionless expressions:

$$\Pi_{\dot{V}} = \frac{\dot{V}}{\dot{V}'}, \quad \dot{V}' = 1 \text{ l/s}, \tag{5}$$

$$\Pi_H = \frac{\Delta H}{\Delta H'}, \quad \Delta H' = 1 \text{ mm}. \tag{6}$$

A set of non-linear equations is obtained by inserting the results from Table 1 into Eq. (4) with four unknowns: k, α, β and γ. Calculating the logarithms of these non-linear equations yields a set of equations which are linear for the unknowns and therefore, easier to solve. The set of equations (Eq. 4) is overdetermined, since the number of equations is greater than the number of unknowns. It was solved numerically with the Matlab program package.

According to the results presented in Section 2.1 there was no suspension at the time of the integral parameter measurements to be classified in the age group I. Suspension in the measurement set 2 is classified in the age group II, whereas all other measurement sets comprised suspensions from the age group III.

The phenomenological model for measurement sets 2 to 5 with the same age group of suspensions has, according to Eq. (4), the following expression:

$$\Delta C = 71105 \cdot C_{\mathrm{i}}^{1.123} \cdot \Pi_{\dot{\mathrm{V}}}^{-9.966} \cdot \Pi_{\mathrm{H}}^{0.573}. \tag{7}$$

From the power values in Eq. (7) it can be concluded that the increase in inlet concentration C_i raises the concentration difference ΔC and thus enhances the sedimentation efficiency. On the other hand, higher values of the volume flow rate $\dot{V}$ lessen the sedimentation efficiency, i.e. the values of ΔC decrease accordingly. The increase in flow rate means higher Re number values that could in turn enhance turbulence [21] and adversely affect the sedimentation, while the increase in inlet concentration often leads to hindered settling [17]. On the other hand, higher suspension level difference ΔH between the settling tank and the reservoir means higher concentration difference ΔC or higher sedimentation efficiency. Fig. 5 shows the agreement between the measured and calculated values of ΔC. The agreement between both sets of values is good, with the regression coefficient R^2 = 0.94. This implies that the model in Eq. (7) sufficiently describes the influence of process parameters on the outlet concentration in the case of the suspension that is older than 48 hours.

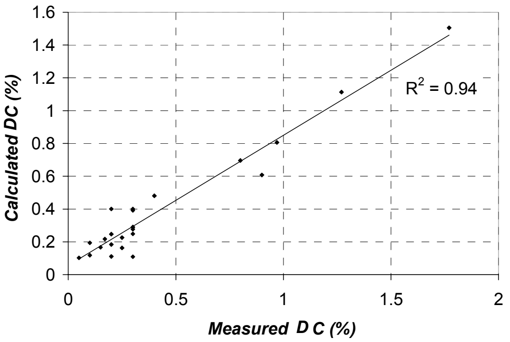

Fig. 5. *Agreement between measured and calculated values for ΔC (Eq. 7) in measurement sets 2 to 5*

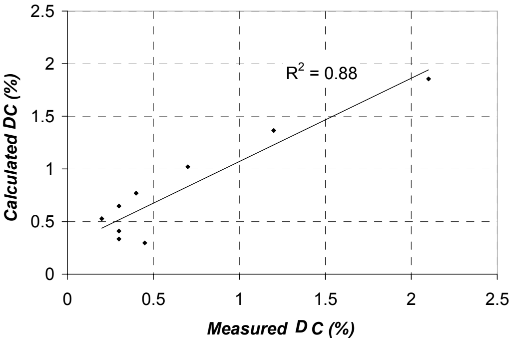

Fig. 6. *Agreement between measured and calculated values for ΔC (Eq. 7) in measurement set1*

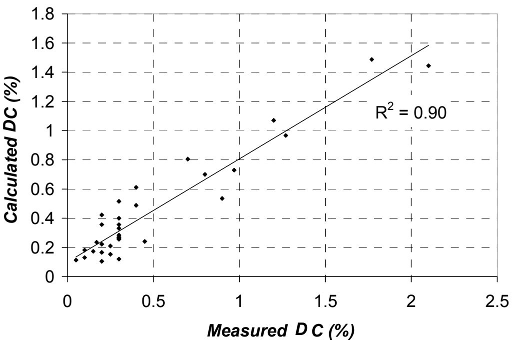

Fig. 7. *Agreement between measured and calculated values for ΔC (Eq. 8) in all measurement sets*

Fig. 6 shows the result of the same model (Eq. 7) applied to measurement set 1 with a suspension that had a different settling velocity in comparison to the ones used in measurement sets 2 to 5. The agreement between the measured and calculated results is slightly worse (R^2 = 0.88, Fig. 6) than for measurement sets 2 to 5 (Fig. 5), but is nevertheless close to the latter. It can therefore, be concluded that although the age of the suspension has a significant impact on the sedimentation process in stationary conditions (Section 2.1), it does not substantially affect the sedimentation process in the dynamic conditions inside the industrial settling tank. Accordingly, the results from the measurement set 1 in Table 1 can be used together with the results of other measurement sets to get the common phenomenological model, shown in Eq. (8):

$$\Delta C = 20768 \cdot C_{\mathrm{i}}^{1.097} \cdot \Pi_{\dot{\mathrm{V}}}^{-8.690} \cdot \Pi_{\mathrm{H}}^{0.398} . \quad (8)$$

Fig. 7 indicates that the agreement between the measured and calculated values is still good with R^2 = 0.9. A comparison between Eqs. (7) and (8) reveals that the power values retained their signs. The magnitude of the power of Π_{H} in Eq. (8) changed the most (for about one third of its value in Eq. (7)), which means that the influence of suspension level difference on the outlet concentration is even less significant. The constant *k* also changed, which may still be the influence of different suspension age.

3 CONCLUSIONS

A phenomenological model of sedimentation in an industrial settling tank was developed by applying the multi-regression analysis of integral parameters of the process on a macro scale. Integral parameters such as inlet concentration, volume flow rate and suspension level difference were measured on a full scale settling tank. Additionally, a stationary sedimentation test was carried out in a test tube in order to determine the influence of the suspension age on settling velocity of particles.

The results of the phenomenological model showed that the inlet concentration and the volume flow rate of the suspension have the most significant influence on the sedimentation efficiency. On the other hand, the difference of the suspension level between the settling tank and the suspension reservoir does not significantly affect the sedimentation process.

The stationary sedimentation test proved that the settling velocity depends on the age of the suspension. However, the age of the suspension had little if no significant impact on the sedimentation process in the settling tank. Therefore, it can be concluded that it is the dynamic conditions in the settling tank such as flow rate and inherent flow structures that govern the process of sedimentation.

By knowing the key parameters that are important for a specific type of the settling tank, the results of the model can serve as a basis for further investigation of the sedimentation process. This will represent a transition from macro scale to micro scale in order to determine the influence of important integral parameters (determined by the phenomenological model) on flow structures in the settling tank.

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