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ON-LINE QUANTIFICATION OF SETTLING PROPERTIES WITH IN-SENSOR-EXPERIMENTS IN AN AUTOMATED SETTLOMETER

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ABSTRACT

An on-line settlometer has been developed. Batch settling experiments lasting 40 min are performed in a model clarifier incorporated in the sensor ("In-Sensor-Experiment"). The descent of the sludge blanket interface is monitored and the settling characteristics are deduced. The hardware consists of a 10 litre Pyrex decanter, a stirring/wall-scraping mechanism, an external light source and a moving light-intensity scanner. Either stirred or non-stirred settling curves can be recorded.

Processing of the raw data readily produces the zone or hindered settling velocity (V_s) and the (stirred) sludge volume ([S]SV). The latter can be combined with a sludge concentration measurement to determine SVI-values, and dSVIs if a dilution step is included.

Initial results are reported on a more elaborate interpretation of the data based on sedimentation models. The Takács *et al.* and Cho *et al.* models described the settling curves equally well. However, an identifiability analysis showed that not all parameters can be given unique values on the basis of the simple batch settling experiments applied in the work. More elaborate "In-Sensor-Experiments" are required to obtain complete identification.

Two years of practical experience with the device on pilot- and full-scale treatment plants revealed its robustness, low maintenance requirements and reproducible monitoring of settling curves. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Activated sludge; identification; mathematical modelling; sedimentation; sensors.

INTRODUCTION

Increasing attention is being drawn to final clarification as the unit operation in activated sludge wastewater treatment that is critical to overall treatment performance. The separation of the bio- solids from the purified water (clarification) and their thickening is to a large extent dependent on the amount and physical properties of the flocs. However, these properties are not constant in time and the understanding of the causes of their change is only fragmentary.

For instance, population dynamics induced by wastewater changes and plant operation have their influence on the floc structure. Population shifts occur rather slowly, i.e. within days. The mechanisms of change and the relation between floc structure and settling properties are hardly understood.

Recently, as monitoring frequency increased, Reid and Nason (1993) suggested a dependency of the settling characteristics on the pollutant concentration remaining in the mixed liquor entering the final clarifier. Moreover, some indications have been found that the flocculation process that precedes actual clarification/thickening is influenced by the change in wastewater composition (e.g. ionic strength) caused by rain events, thus affecting sludge sedimentation. As these wastewater composition related phenomena have typical time constants of hours, the effects on the settling properties will be observed considerably faster than the changes induced by population alterations.

Normally, sedimentation characteristics are determined manually using batch settling tests (Catunda and van Haandel, 1992). However, this is time-consuming and the measuring frequency is too low (typically once per day) to track the time-varying sludge properties. To this end it is advantageous to make use of an automated system for sludge settling analysis. The study that eventually led to the device presented in this paper was initiated with the aim of gaining more insights in the dynamics of the settling properties so as to increase understanding of cause-effect relationships. Parallel work is carried out using image analysis to reveal the relation between sludge floc structure and settling properties (Grijspeerdt and Verstraete, 1996). The ultimate aim is to apply the gained insights to improved control actions for the final clarifier.

One approach to increase the analysis frequency is to install a measuring system that tracks the sludge blanket or concentration profiles in the full-scale clarifier (Takács *et al.*, 1991; Aspegren *et al.*, 1993; Reid and Nason, 1993; Dupont and Dahl, 1995; Jeppsson and Diehl, 1995). From this it is theoretically possible to deduce sludge settling characteristics on-line in the form of a mathematical description. However, as far as known no such exercises have been reported. One reason may be that the information content of such data is insufficient for reliable model identification as the final clarifier may exhibit too little dynamics during normal operation.

An alternative approach was introduced for the characterization of biodegradation kinetics in activated sludge systems (Vanrolleghem and Van Daele, 1994; Vanrolleghem and Coen, 1994). The methodology consists of incorporating a down-scaled version of the device under study (in this case a final settler) in a measuring system and performing experiments in this model reactor. These so-called "In-Sensor-Experiments" can be designed at will and can therefore provide rich information for characterization of the studied process, in casu settling.

A number of automated systems for quantification of settling properties, implicitly applying this methodology, have been described in the literature and are commercially available. Different measuring principles are used in these so-called settlometers (Severin *et al.*, 1985).

In one type the descent of the sludge blanket interface in batch settling experiments is tracked using light transmission, measured either via a fixed array of LEDs on one side and photodiodes on the other (Reid and Nason, 1993), or via a moving LED/photodiode couple (Sekine *et al.*, 1989).

In the second type, the sludge concentration is measured. Dupont and Dahl (1995) use a turbidimetric sensor to monitor the changing sludge concentration at a fixed point in the settling column, while Grijspeerdt *et al.* (1995) measure the sludge concentration at different heights in a continuous flow clarifier using image analysis.

Only for the last system was an attempt made on-line to estimate parameters of a settling model from the raw data. In the other set-ups, the main aim was to estimate (stirred or diluted) sludge volume indices or zone settling velocities, which were eventually used off-line to obtain a mathematical model of the settling process.

In this contribution a settlometer is developed operating according to the first principle, i.e. the sludge blanket during a batch settling experiment is monitored. The sensing system is based on light transmission measurements using a moving scanning system. Next to the determination of the zone settling velocity and sludge volume, important efforts were made to perform on-line model identification.

The paper is organized as follows. First the hardware of the settlometer and its mode of operation is introduced. The manner in which the batch settling curve is recorded is described next. Third, the direct deduction of some parameters of the sludge related to its sedimentation is presented and illustrated. After a short description of the applied mathematical models of sedimentation and a study of the model parameters that can be estimated, some initial results and experiences are given.

WORKING PRINCIPLE OF THE SETTLOMETER

Determination of the sludge settling properties is performed in a very simple and natural way. The settling of a mixed liquor sample in a small decanter is registered as the time course of the sludge blanket level, i.e. the position of the interface between activated sludge and clarified supernatant. From this settling curve, the sedimentation properties are deduced.

The basic principle of the "In-Sensor-Experiments" is as follows. A transparent vessel is filled with the secondary clarifier influent mixed liquor. Background light is provided. After initial mixing, the sludge is allowed to settle. Meanwhile, a scanner moves downwards from an upper reference point. When it reaches the sludge blanket, it detects a decrease in light intensity. The distance covered by the scanner and the time elapsed since the start of the settling experiment yield a first data point of the settling curve. The scanner now moves back up to the reference point and comes down again, looking for the decrease in light intensity. This cycle is continuously repeated. After a predetermined time, the experiment is stopped and the decanter is emptied and optionally cleaned. A next In-Sensor-Experiment can be started.

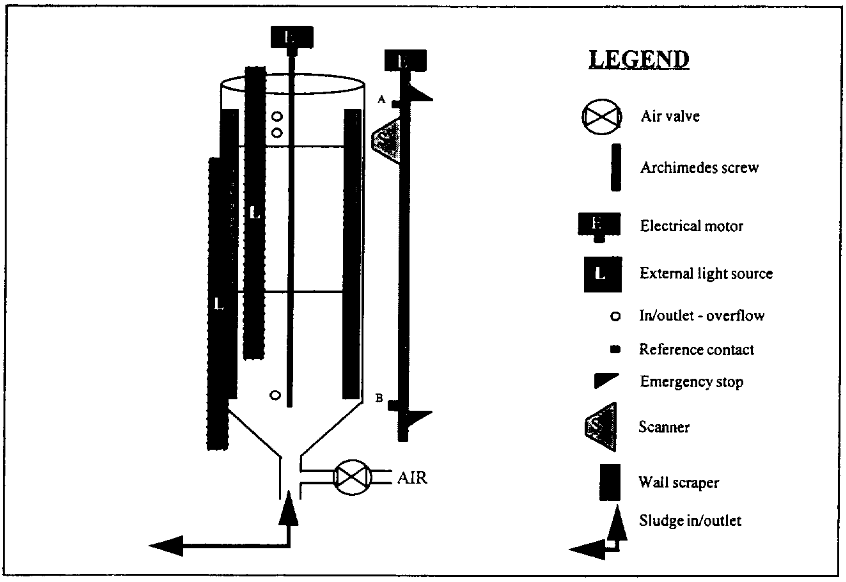

Figure 1. Schematic diagram of the settlometer.

BUILDING BLOCKS OF THE SETTLOMETER

A schematic diagram of the settlometer is presented in Fig. 1. The characteristics and purposes of the different building blocks will be described in the what follows.

The model clarifier

The settlometer built-in decanter is a Pyrex vessel. This material comes up to the requirements of transparency and is proof against scratches induced by particles in the sludge, the wall-cleaning mechanism or the movement of the scanner along the vessel. The vessel has a volumetric content of about 10 litres. It is cylindrical with a 14 cm diameter to avoid wall effects and prevent solids bridging. Its total height is 70 cm. The bottom is conical to avoid sludge retention in the vessel after emptying. Besides some in-/outlets in the wall, the decanter has a bottom centre hole through which loading and emptying takes place. The upper part is open to the air, but can be covered by a special lid.

The scanner

A low-cost Genius GS 4500, a common IBM-PC hand scanner, was chosen to track the light intensity along the decanter height. Since the scanner built-in LED-array's light emission intensity was found insufficient, two external light sources were provided as background lighting for the scanner device. They are long TL type lamps of 35 W each installed under 120° and 180° angles with respect to the scanner position. The scanner is attached to an Archimedes screw linear moving mechanism, parallel to the decanter. The screw is driven by an electrical motor with gearbox (150 rpm), resulting in a scanner moving speed of 30 cm/min. The scanner travelling range is limited by two reference switches (A and B in Fig. 1) and two emergency stop switches. The data collected using a dedicated program consist of 420 light intensities per scanned line and the number of lines travelled down from the reference switch. Linearity of the distance measurement was found excellent ($R^2 = 0.9995$) and the relative error on travelled distances was approx. 0.1% and normally distributed.

The GS 4500 scanner can only detect four grey levels. However, extensive tests with many different sludge sources showed that this suffices to distinguish clarified liquor from the sludge blanket. In practice, however, a lot of noise is registered if one considers separate photodiodes. The noise can be reduced by considering that each scanned line consists of the grey levels of 420 photodiodes that are collected. One data point is taken as the mean of two scanned lines. These primary data are processed for a final smoothing using a moving window regression with a window size of three data points.

Reliability and endurance of the scanner system were proven since the first hand scanner installed is still in use after nearly two years operation. No mechanical nor electrical problems were encountered.

The 1 rpm stirrer/wall wiper

Gentle mechanical mixing is advocated to prevent bridging, reduce the preferred liquid flow up the settler wall and improve flocculation. In this way the influence of the initial sludge concentration on the sludge volume index is greatly reduced (White, 1975). Breaking up of channels, increased packing density and improvement of consistency of test results have been mentioned as well (Vesilind and Jones, 1990).

As with other settlometers using light transmission as detection principle, cleaning of the transparent wall is essential to the reliable operation of the sensor. While Reid and Nason (1993) claim weekly manual wiping to remove the formed biofilm is sufficient, long-term tests showed that more regular cleaning is recommended. Sekine *et al.* (1989) installed a cleaning brush that is lowered after withdrawal of the sludge from the decanter. Here, the wall-cleaning mechanism is combined with the stirring mechanism and instead of brushes, rubber wipers are used.

The stirrer/wall wiper device is driven by an electrical motor with gearbox, resulting in a rotational speed of 1 rpm. Thanks to the narrowness of the wall wipers, their passage has limited effect on the detection of the sludge blanket by the light scanner. The two full-length wall wipers are attached to opposite sides of the rotating axis. They are equipped with springs to press their rubber strips against the wall for homogeneous cleaning. In case non-stirred settling curves are recorded, the wall cleaning mechanism is only active during the filling, mixing, withdrawal and cleaning phases. However, this was found sufficient.

The mixing mechanism

Since settling starts already while filling the decanter with sludge and since it may be desired to perform a further sedimentation experiment with the same sludge sample, a mechanism for sample homogenization must be provided. The mixing, however, should not influence the floc structure and, hence, the sedimentation characteristics. Therefore, large friction forces have to be avoided. As proposed by Sekine *et al.* (1989) agitation air is injected. Mixing for 2 minutes was found not to affect settling properties. The moment the aeration is stopped, recording of the settling curve is started.

The cleaning/dilution mechanism

Although wall wiping is performed by the stirring mechanism, some extra cleaning can optionally be added. In the covering lid a nozzle is installed at the top of the decanter. A water or cleaning solution supply can be connected to it, together with an appropriate valve. An additional application is to use this device to make dilutions of the sample.

Sampling pump

A Watson-Marlow pump, type 603 U, is used for sludge filling and emptying of the decanter vessel. The flow rate can be set sufficiently high to prevent sludge settling phenomena in the connecting tubes. Although vacuum suction of sludge has been proposed to circumvent sludge damaging by pumping (Severin *et al.*, 1985), results using different sludges taken from different sources have shown that peristaltic pumping is gentle enough not to affect sludge settling properties.

RECORDING OF THE SETTLING CURVE

Sludge blanket detection

Above it was discussed that 420 grey levels are obtained per scanned line and that the mean of two lines is used per data point retrieved. A 3-point moving window regression is the last step in the data preconditioning step.

The sludge blanket detection procedure will be explained on the basis of Fig. 2. Along its way down from the upper reference point, (filtered) light intensity values are collected by the scanner. One observes that the light intensity is high (a max. value of 420 diodes x 4 (max. grey level) = 1680 can be obtained, see Fig. 2) in the clarified zone (up to 80 scanned lines from the top) and then suddenly drops to a low intensity as the sludge blanket is reached. This light intensity profile along the decanter is now scrutinized to determine the sludge blanket height.

During the initial development, blanket detection was only based on a fixed threshold value. The point where the light intensity dropped below the threshold value was taken as the sludge blanket position. Since this value is dependent on the type of sludge, the system was soon modified. During initialization of the sensor, i.e. before the first settling curve is recorded, a calibration scan is performed. This determines the light intensity of the mixed liquor. This value is regarded as a reference for the treatment plant the settlometer is installed at and is subsequently used as a basis for calculation of the threshold value. In this way sludge independency is obtained.

An evaluation of the slope of the light intensity curve completes the detection procedure. The point where this slope is steepest (point 'a' in Fig. 2) is the first candidate for the sludge blanket height. However, it is only accepted if the point which is 25 lines down this candidate has a light intensity below the threshold value. This inflection point approach has more intuitive fundamentals and provides very stable sludge blanket determinations with little noise.

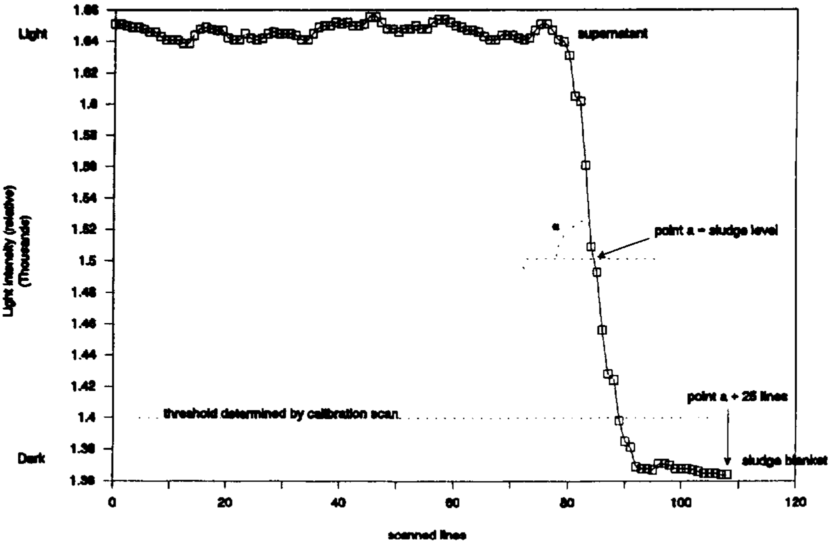

Figure 2. Detection principle of the settlometer. The inflection point 'a' in the light intensity curve is defined as the sludge blanket height.

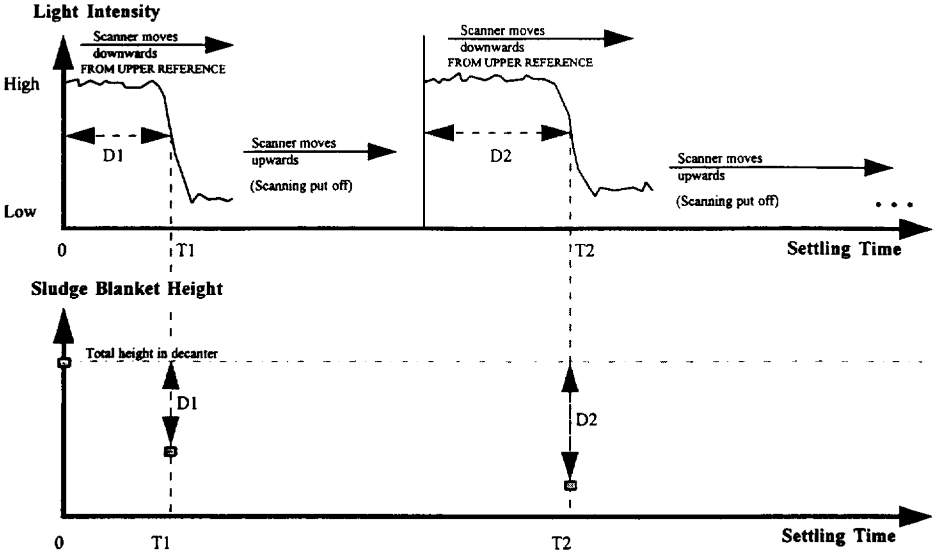

Figure 3. Principle of sludge settling curve recording.

Recording the settling curve

In Fig. 3, the construction of a settling curve from a sequence of recorded light intensity curves is illustrated. On the upper left the light intensity curve of the first scan started at T=0 is given. The position D1 of the sludge blanket (deduced from the number of scanned lines, cfr. Fig. 2) is detected after T1 minutes of settling. These two values determine the first point in the sedimentation curve (lower graph). Once the blanket is detected, scanning is switched off and the scanner is moved to the upper reference point again. This takes the same time as when it came down since the Archimedes screw is rotating at fixed pitch. When the reference point is reached, a new cycle is started (yielding position D2 and settling time T2).

Moving the scanner back to the upper reference point involves some loss of time and, thus, a lower number of data for the sedimentation curve are collected. Yet, with this approach the measurement of distance is much more accurate. Indeed, if the new position of the sludge blanket were to be determined beginning from the preceding one, errors would accumulate. Moreover, so far, the number of data in the settling curves sufficed for the intended settling characterization (see below).

The repeatability of the device is illustrated in Fig. 4. Four times a single sample of sludge was rehomogenized after recording of the settling curve. One observes the good agreement between consecutive experiments. Moreover, these data indicate that the homogenization using air does not affect the settling characteristics of the sludge.

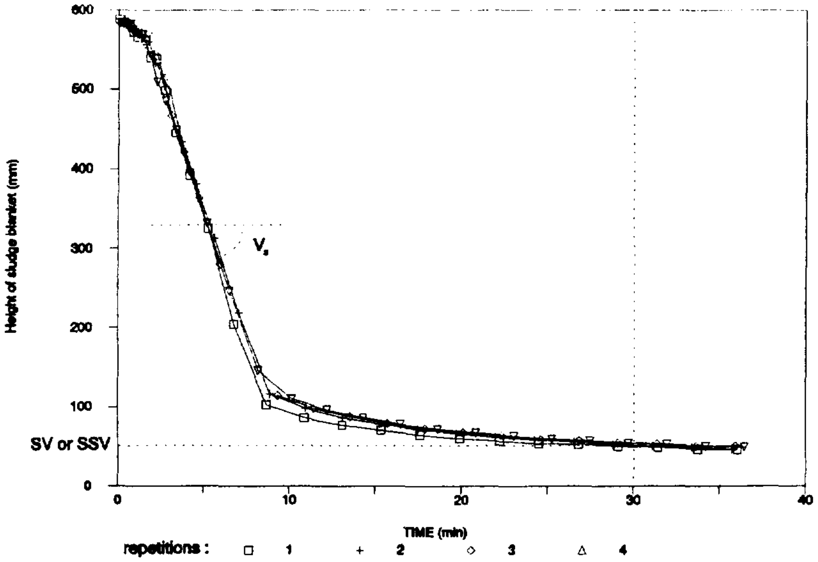

Figure 4. Reproducibility test of the settlometer: 4 rehomogenizations with one sludge sample.

SETTLING PARAMETERS DEDUCED DIRECTLY FROM SETTLING CURVES

The zone settling velocity, V_S (Fig. 4), is defined as the maximal down-slope of the curve, thus the highest velocity of the sludge blanket along its descent. This maximal slope is found at the inflection point of the graph. The slopes are readily available from a moving window parabolic regression on the settling curve data.

The sludge volume (SV) or stirred sludge volume (SSV) is the volume fraction occupied by thickened sludge after 30 minutes settling. It is obtained by interpolation between sludge blanket detections before and after 30 minutes duration of the settling experiment (Fig. 4).

Another settling related parameter can be obtained directly from the raw data. In this case the settling curve itself is not considered, but attention is focused on the light intensity curves obtained during each separate scan (cfr. Fig. 2). The parameter deduced after each scan is the sharpness of the sludge blanket interface, as indicated by the maximal slope in the light intensity curve (at point 'a', see Fig. 2).

It is believed, although no detailed study has as yet been conducted, that this sharpness is related to the distribution in settling velocities possibly induced by the particle size distribution (Takács *et al*, 1991; Otterpohl and Freund, 1992). Indeed, one can imagine that some of the flocs lag a little behind the bulk of the sludge so that a sludge concentration gradient forms near the blanket interface, which is detected as a light intensity gradient. In Fig. 5 the evolution of the interface sharpness is given as settling proceeds. It is remarkable to observe and it is consistent with the above hypothesis that the sharpness is smallest in the initial phases of the settling and becomes constant during the compression phase. In the latter phase it can be hypothesized that the slower particles catch up with the rest of the sludge blanket. These findings clearly warrant some further study.

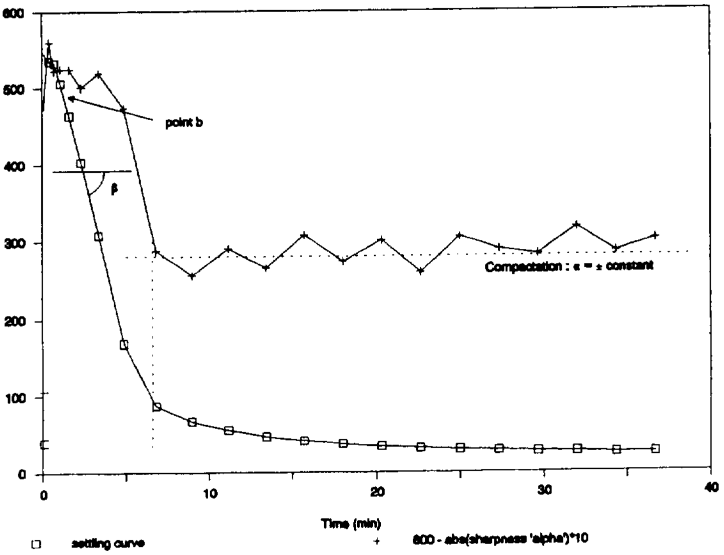

Figure 5. Evolution of the sharpness of sludge blanket interface (crosses) as settling proceeds (crosses).

MODEL-BASED INTERPRETATION OF SETTLING CURVES

Mathematical framework

The more distant aim of the current investigations is to use the data obtained from the settlometer in a control loop. Hence, we tried to extract as much information as possible from a settling curve in real-time. It is evident from the settling curves that, with the parameters described so far (V_S, (S)SV and "sharpness"), only a limited fraction of the information contained in the recorded settling curves is summarized.

The intention is to develop a control strategy based on a mechanistic mathematical description of the settler. In view of this we tried to obtain the settling velocity model from on-line settlometer data. The settling velocity model describes the dependence of the gravity settling velocity on the sludge concentration X, i.e. $V_S = f(X)$, and is the core of any solid flux based mathematical description of a clarifier, be it in a one-, two- or even three-dimensional form.

The traditional approach is to collect zone settling velocities V_S for different initial sludge concentrations and fit the model to these $[X,V_S]$ data (Catunda and van Haandel, 1992). Although these data can be obtained from a number of settling experiments with different dilutions (note that this can be automated in the developed settlometer), it is felt that this would take a prohibitive amount of time to be useful in a control context.

An alternative method was indicated by Kynch (1952) when he showed that settling rates for all concentrations could be derived from a single settling test. This allows one to calculate $[X,V_S]$ data from a settling curve and subsequently identify the velocity model.

The approach taken here is to eliminate the intermediate stage during which the $[X,V_S]$ data are calculated. Instead an estimate is made of the parameters of the settling velocity model directly from a settling curve. To this end, the differences are minimized between the data and the predictions of blanket descent made by the settling velocity model embedded in the partial differential equation (PDE) describing the mass balance in a settler.

Before going into some details on settling velocity models, a few remarks have to be made with respect to the solution of the PDE model. This involves a numerical approximation that leads to an important number of calculations, especially for 2D-models (Krebs, 1995), albeit that they are undoubtedly more accurate than one-dimensional descriptions. However, the non-linear parameter estimation needed to identify the settling velocity model requires many evaluations of the model with different parameter sets, and this would take a prohibitively long computation time were 2D-models to be applied. The one-dimensional description of a settler is given as (Jeppsson and Diehl, 1995):

$$\frac{\partial X(z,t)}{\partial t} + \frac{\partial F(X(z,t),z)}{\partial z} = s(t)\,\delta(z) \tag{1}$$

where $X(z,t)$ is the sludge concentration at depth z and time t, and F is an extended flux function including the modelling of outlets and the settling velocity model. On the right-hand side one finds the input to the settler described as a time-varying sludge concentration entering at a feed point (δ is the Dirac impulse function).

Traditionally, the numerical solution of this PDE-model is performed by a discretization along the space coordinate. The resulting discretized model is termed a layer model (Vitasovic, 1986). In most simulation programs a ten-layer approximation is used. A recent study clearly showed that this is too crude an approximation and that at least 50 layers are needed (Jeppsson and Diehl, 1995). Our studies to find the optimal trade-off between prediction accuracy and computational burden also led to a 50 layer model.

Several settling velocity models have been proposed, most notably the power and exponential (or Vesilind) models:

$$\textit{Power:}\quad V_s = kX^{-n} \qquad \textit{Exponential:}\quad V_s = V_0 e^{-nX} \tag{2}$$

However, the power model gives unreasonably high settling velocities at low concentrations, while the Vesilind model does not allow for an analytical solution of the limiting flux (Marsili-Libelli, 1993).

Takács *et al.* (1991) modified the Vesilind model to also simulate the settling velocity of dilute suspensions as observed during clarification. Grijspeerdt *et al.* (1995) evaluated different settler models and found the Takács model to be most appropriate to describe sludge concentration profiles in model settlers.

Another new settling velocity model was recently deduced by Cho *et al.* (1993) from the Carman-Kozeny equation for filtration. In contrast to most others, this model has a mechanistic basis and was claimed by its authors to have a better fitting ability than other models tested. As a result of its structure, it allows an analytical solution to be obtained for the limiting flux and gives reasonable settling velocities at low solids concentrations.

The fact that only batch settling is considered means that the outlet and inlet modelling can be omitted from the flux model F. However, batch experiments also induce a transient phenomenon before actual zone settling starts. This transient involves flocculation of the suspension and dissipation of the mixing energy. The settling models described so far do not consider such phenomena and, as a result, had to be modified for this application. A term [1-exp(-t/τ)] was found adequate in taking this transient into account. The Takács and Cho models modified for batch settling are:

$$V_s = \max\left(0, \min\left[V_{00}, V_0\left(e^{-r_h(X-X_{\min})} - e^{-r_p(X-X_{\min})}\right)\left(1-e^{-t/\tau}\right)\right]\right) \tag{3}$$

$$V = k\frac{(1-n_1X)^n}{X}e^{-n_2X}\left(1-e^{-t/\tau}\right) \tag{4}$$

Owing to space limitations, we refer for nomenclature to the respective papers. One should note that the power *n* in the Cho model is not set to 4 as in the paper by Cho *et al.* (1993) since it was desired to empirically assess its value.

Solving the model results in a time-varying sludge concentration for the 50 layers in the settler model. As the available data consist of sludge blanket levels, the sludge blanket must be deduced from the simulated concentration profile. The position of the sludge blanket was arbitrarily defined as the first layer with a solids concentration of at least 3 g/l (Vitasovic, 1986). Here, interpolation between the two layers with concentrations below and above this value enabled smoothing of the simulated sludge blanket evolution.

Identifiability of settling velocity model parameters

With these remarks the mathematical model used to predict batch settling curves is completed. With this model, it is now tried to estimate the different parameters in the settling velocity models. The set of parameters for the Takács model is $[V_{00}, V_0, r_h, r_p, X_{min}, τ]$, while for the Cho model the set is $[k, n_1, n_2, n, τ]$.

Before efforts are put into the estimation of this large number of parameters it is important to address the question whether the experimental data will allow unique values to be given to these parameters. If the identifiability is studied from a theoretical point of view under the assumption of perfect data, the structural identifiability is evaluated (Dochain *et al.*, 1995). If on the other hand the reliability of parameter estimates is evaluated for actual data obtained from particular experimental designs, conclusions with respect to the practical identifiability can be obtained (Vanrolleghem *et al.*, 1995). Here, a practical identifiability study is performed, i.e. it is evaluated whether the settling curves obtained with the settlometer performing batch experiments with sludge taken from the aeration tank yield enough information to give unique values for all parameters in the settling models.

For the Takács model, it became apparent that the parameters V_{00}, X_{min} and r_p cannot be identified from such experiments. It is believed that these are only identifiable when settling experiments are performed with low initial sludge concentrations. This is rather obvious since a sensitivity analysis of the model clearly shows that the settling curve is only sensitive to these parameters for low X. The model therefore reduces to a Vesilind model multiplied with the term describing the transient.

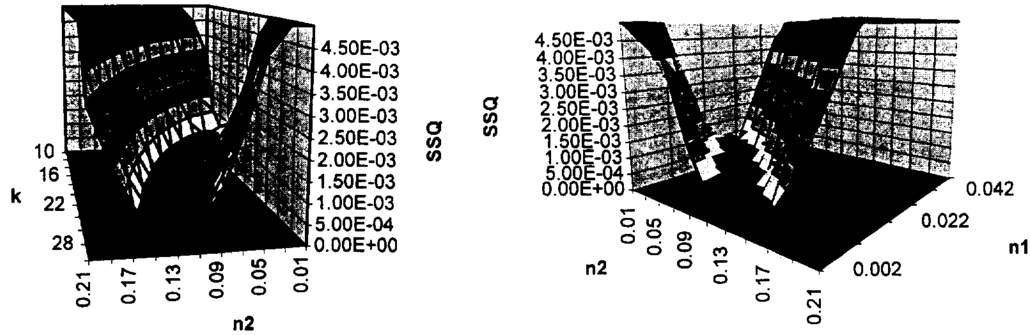

Figure 6. Sum of squared errors as function of two parameters of the Cho model. Best fit for n2 and k (left); Correlation between n1 and n2 (right).

In case of the Cho model, a detailed analysis was made for a typical data set. After fitting the model, parameters were considered two by two. For each couple of parameters, 121 different values taken from a 11x11 grid around the estimates were used to simulate the sedimentation profile. The sum of squared errors was determined. For each couple of parameters a three-dimensional graph resulted that could be interpreted in view of parameter identifiability (Fig. 6). For instance, one observes a clear minimum in the sum of squared errors for $n_2 = 0.09$ l/g and k = 21 m/h in Fig. 6 (left).

A first general result of the evaluation was that a distinct minimum could always be found for *n* values near four. This is in agreement with (but no proof for) the statement of Cho *et al.* (1993) that the model with power four is superior to the Steiner model in which the power is three. It is concluded to be safe to set *n* to a fixed value of four.

Second, a strong correlation was found between n_1 and n_2 (Fig. 6, right), i.e. for all combinations of n_1,n_2 defined by the line [$n_2 = 0.16 - 5\ n_1$] similar fits are obtained to the recorded settling curve. Cho *et al.* (1993) circumvent this identifiability problem by setting one or both to zero. In this way they also achieve a reduction in the complexity of the model structure as the power or the exponential term vanish. Following the preference given by Cho *et al.* (1993) to set n_1 to zero, a modified Vesilind model (division by X and multiplication with the transient term) is obtained.

As a conclusion of this practical identifiability study, it can be stated that the parameter sets identifiable from batch settling tests with typical aeration tank sludge samples are restricted for the Takács model to [V_0,r_h,τ] and for the Cho model to [k,n_2,τ]. A typical fit of both models to a settling curve is depicted in Fig. 7. One observes that the model structures are adequate for description of the batch settling behaviour. Concerning the necessary calculations, experience has taught that the 1D-models combined with an efficient fitting algorithm (Brent, 1973) can be identified within the allocated time (approx. 45 minutes) on an Intel-Pentium PC.

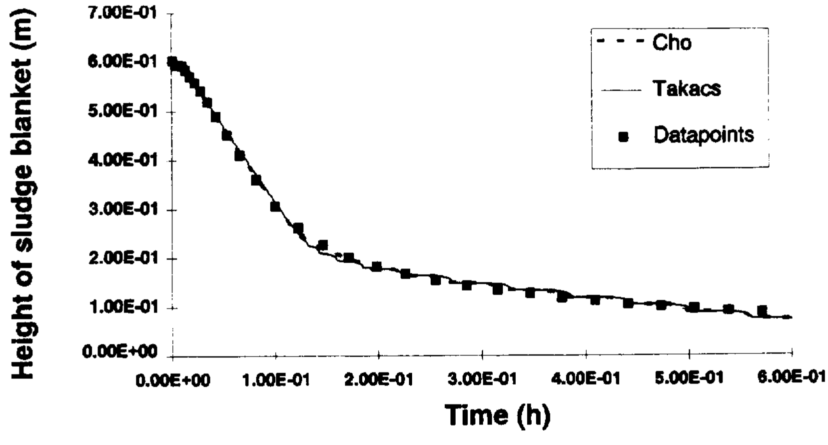

Figure 7. Comparison of model identification results for the Cho and Takács settling models.

FULL-SCALE EVALUATION OF THE SETTLOMETER

A prototype settlometer was tested for reliability at the WWTP of the Maria Middelares hospital in Gent (Belgium). Sampling of the sludge was done at the outlet of the aeration tank. The experiment continued uninterrupted for five days. Seventy seven sludge samples were taken in this period. Figure 8 shows the sequence of 77 stirred (bottom) and 77 non-stirred settling curves collected. The figure is constructed by placing subsequent settling curves next to each other along the "Sample no." axis. For clarity, the non-stirred settling curve of sample S31 is indicated. The aberrant curve shapes at higher sample numbers (54, 68, 72 and 75) are due to a flotation layer in the model decanter.

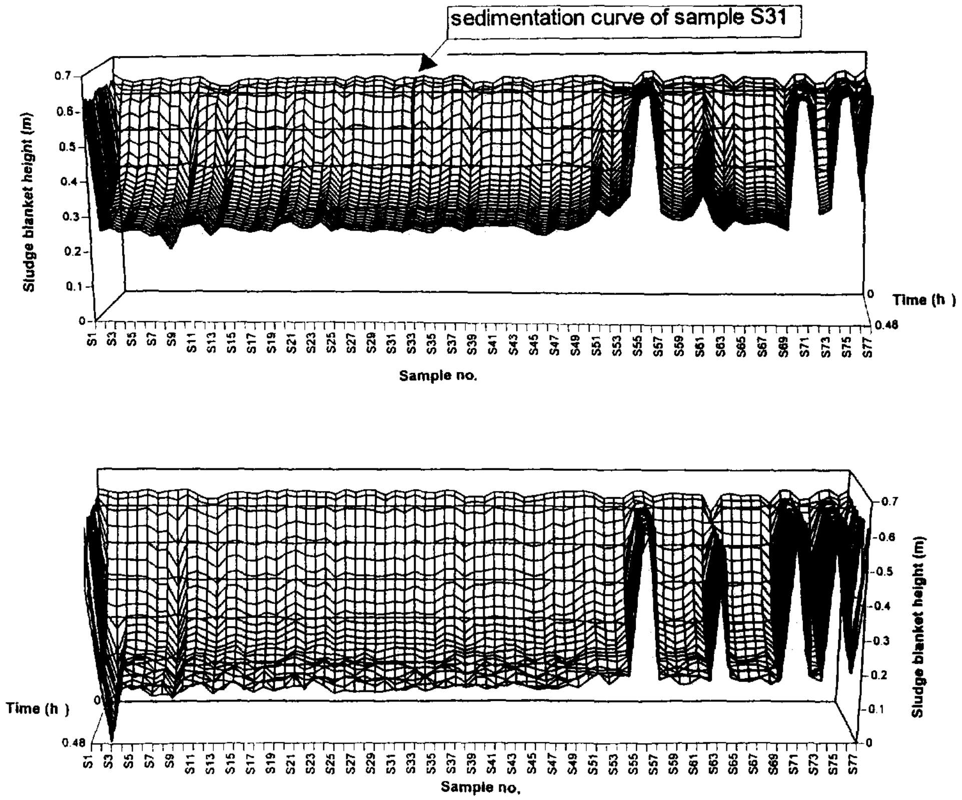

Figure 8. Time evolution of non-stirred (top) and stirred (bottom) settling curves collected on-line for 5 days at the Maria Middelares wastewater treatment plant.

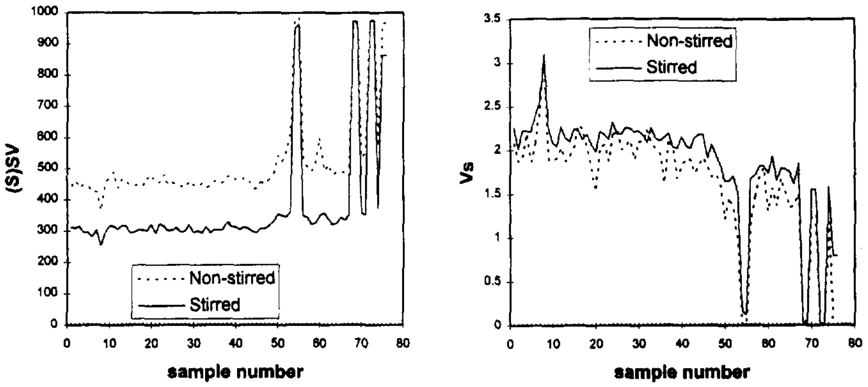

Figure 9. Time evolution of (S)SV (left) and Vs (right) for the data-set of Fig. 8.

Settling characteristics directly deduced from the settling curves

As explained above, the maximal slope V_S and the sludge volume (S)SV are calculated directly from the settling curve. Fig. 9 summarizes the results for the collected data set.

The large peaks again correspond with the flotation induced deviations from normal behaviour. Flotation layers can be formed because of hydrophobicity of the sludge flocs. Owing to this property gas bubbles may adhere to the sludge and induce flotation. As a result of the short retention time in the settlometer it is rather unlikely that the gas originates from denitrification, rather the air used for mixing may be blamed.

The data confirm that gentle stirring improves settling as exemplified by increased zone settling velocities and reduced sludge volumes. Moreover, the claim that addition of a slow stirrer improves reproducibility (Vesilind and Jones, 1990) is supported by the reduced variability of the V_s results (Fig. 9 right).

Finally, from the V_s data it can be observed that there is a tendency of the sludge settleability to deteriorate from sample no. 40 onwards.

Model-based interpretation of settling curves

Non-linear parameter estimation was performed on the collected (stirred and non-stirred) settling curves. To increase the rate of convergence and to minimize the risk of local minima in which the algorithm may "get stuck" during the fitting process, the set of parameter estimates for a previous settling curve was used as the initial set for the next parameter estimation. Moreover, each estimation was restarted once from the best estimates to improve reliability of the estimation results.

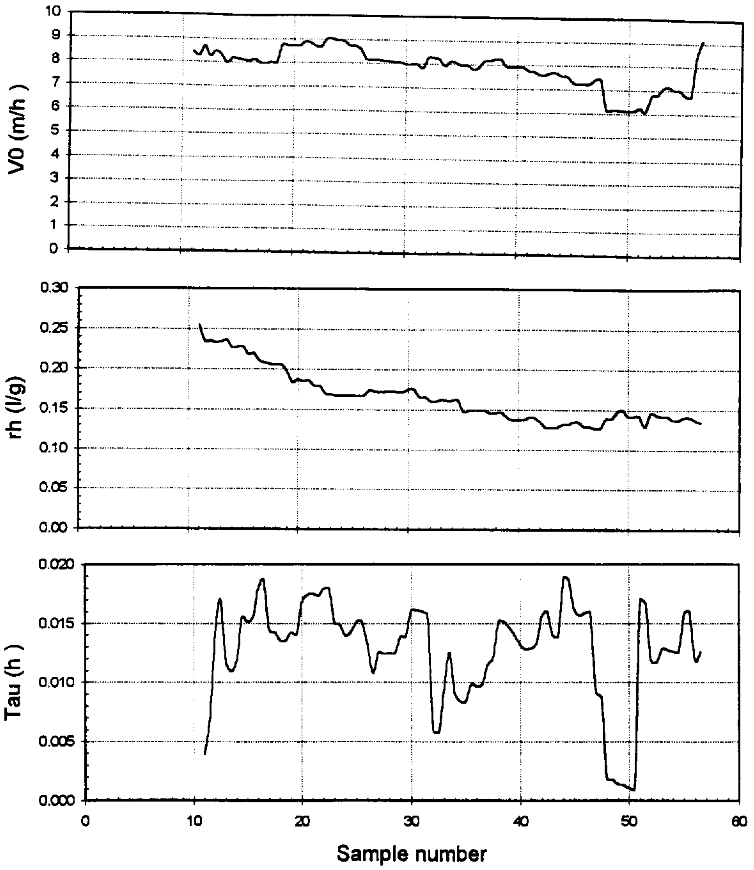

Figure 10. Evolution of the modified Takács settling velocity model parameters (V_0, r_h and τ) during full-scale settlometer trials at Maria Middelares WWTP.

A first result of the model identification studies confirmed the previously mentioned finding that the fitting performances of the modified Takács and Cho settling models were very similar (results not shown). Both models adequately described settling curves. Note that only the reduced parameter sets were used so that only three degrees of freedom were left for fitting.

Figure 10 summarizes the estimation results of the modified Takács based batch settling model. One observes a reasonably constant V_0 which reflects the relative similarity between settling curves (see Fig. 8). The slight decrease in V_0 from sample no. 40 on corresponds to the previous findings in the V_s results (Fig. 9). Contrastingly, the r_h results indicate a higher sludge concentration dependence of the settling velocity in the beginning of the experiment. However, again the smooth behaviour of the parameter estimates gives some confidence in the fitting procedure. Finally, for the τ-values a rather large variation is observed corresponding with different lengths of the transients.

The difference between τ-values obtained for stirred and non-stirred settling, i.e. approx. 0.06 h for non-stirred (results not shown) vs. 0.015 h for stirred experiments (Fig. 10), is as expected. By stirring, flocculation is promoted so that zone settling is initiated sooner. It can be concluded that the settlometer with the model-based interpretation can give an indication on the flocculation rate of a suspension. Again, this result warrants some further study.

CONCLUSIONS

A device was developed in which In-Sensor-Experiments are performed to characterize the settling properties of activated sludge. The settlometer consists of a model decanter in which batch settling tests are performed. A low-cost moving scanner was found adequate to track the descent of the sludge blanket. Stirred and non-stirred settling curves can be recorded.

Two levels of data interpretation were developed. Zone settling velocities and (stirred) sludge volumes can directly be deduced from the raw data. The light intensity curves recorded by the scanner also provide an indication of the sharpness of the sludge blanket interface.

A more elaborate interpretation is based on mathematical models that describe the settling dynamics in the batch test. A 50-layer discretization was found an adequate approximation of the PDE model. Two settling velocity models were evaluated. It was found necessary to add a term that takes the initial flocculation into account. An identifiability analysis revealed that not all parameters can be given unique values. A restricted set of 3 parameters could be estimated on the basis of the batch settling curves.

The settlometer was tested at full-scale, revealing its robustness and low maintenance demands. The recorded data allowed reproducible assessment of sludge settling properties.

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