New measurement techniques for secondary settlers: a review

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Abstract In activated sludge wastewater treatment research, most of the attention has been devoted to the biodegradation process. However, in terms of effluent quality, the final settling and clarification processes are at least as important because any particle carried over the overflow weir brings with it not only COD, but also nitrogen and phosphorus. In recent years we see indeed increased attention on this separation step, and alternatives such as membrane separation are increasingly introduced. Still, a large installed base of settlers exists, whose operation could/should be optimised. The measurement techniques presented in this contribution each focus on one of the key processes in the secondary settler: hydrodynamics, particle aggregation and breakage, hindered settling and compression. For each technique, the measuring principle is explained and a typical data set shown.

Keywords Clarifiers; flocculation; mathematical modelling; sensors; particle sizing; wastewater treatment

Introduction

In sewage treatment the wastewater is transformed in clean water and solid matter. In order to get the clean water the solids are most often separated from it by gravity in a secondary settler, although recently membrane separation is getting increased attention. Past research has mostly concentrated on the biological kinetics and stoichiometry and the corresponding bioreactor. Yet, the settler is crucial for the overall performance; improper operation results in a washout of solids, increasing the concentration of effluent particulate pollutants and involuntarily wasting mixed liquor. Violation of effluent permits and deterioration of the receiving waters is then the unavoidable result, with long-term release of nitrogen, phosphorus and COD as the solids degrade.

The clarification process is driven by gravitational forces that act on the flocs present in the mixed liquor coming out of the preceding bioreactor. As long as the sludge concentration is sufficiently high, hindered settling prevails. Under such conditions bulk density and floc morphology are more important for process efficiency than floc size. However, above the sludge blanket the concentration is considerably lower and the regime of discrete settling prevails. Here, hardly any hydrodynamic interaction between (discrete) particles exists and their settling is largely determined by floc properties such as density, size, permeability, etc. Of course, floc aggregation and disaggregation occur in the settler. This is influenced both by the floc properties and by the hydrodynamics of the system.

From the above, it must be clear that to improve the operation of secondary settlers, a better understanding and control of settling properties, hydrodynamics, biomass concentrations and particle size distributions are advantageous. Preferably, data should be collected at high frequency (in view of the fast dynamics that are sometimes involved), with a high spatial resolution (in view of the local effects on settling) and, of course, with

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high accuracy. Another item on the measurement wish-list is that the measurement of these properties should be done in a way that is as close as possible to reality, i.e. preferably they should be non-invasive and be performed in situ.

This paper focuses on a few recent developments that allow obtaining high quality data by which the behaviour of a secondary settler can be analyzed in a comprehensive way and modifications to its operation can be prepared and monitored subsequently. Firstly, an Acoustic Doppler Current Profiler for the characterization of the hydrodynamics is presented. Secondly, hindered settling is studied with a settlometer that automatically performs batch settling tests for a range of sludge concentrations. Thirdly, in situ particle sizing using a laser backscattering method that still operates at high solids concentrations is illustrated. Finally, a non-invasive radiotracer method is presented that allows not only studying hindered settling in great detail, but also compression phenomena.

Non-invasive flow field profilers

Non-ideal hydraulics in settlers can be detrimental for the solids removal performance. Hence, improved operation and design retrofitting might be desired and is supported by computational fluid dynamics (Krebs *et al.*, 1995; Brouckaert and Buckley, 1999). In this respect, flow velocity profiling is an essential ingredient of such studies for both flow field visualization and model calibration.

In literature, attempts have been reported to measure the flow field in settlers by using drogues (Anderson, 1945; Bretscher *et al.*, 1992; Ueberl and Hager, 1997), mechanical (Fulford, 1995) and ultrasonic flow meters (Larsen, 1977, Fulford, 1995). Unfortunately, practical problems are encountered such as the difficulties to measure low velocities and the limitation that one can measure only in one dimension. The major drawback for these methods, however, is the invasiveness of the mentioned flow meters, i.e. the local flow field is altered.

Electromagnetic velocity meters work according to Faraday's law, i.e. any change in a magnetic environment will cause a voltage to be induced in the conductor. For velocity measurements the magnet is stationary and the liquid, being the conductor, moves… This movement causes a voltage, which is measured over electrodes, and is proportional to the liquid velocity. Krebs *et al.* (1998) evaluated the device against laser Doppler velocimetry in a lab-scale settling tank. In their experiments the absolute deviation from the laser Doppler velocimetry measurements was below ± 1.6 mm/s. It was shown that velocity values were reliable down to a velocity of about 1 cm/s. The measurement accuracy typically is about 1% of the measured velocity. Although the sensors record velocities in one dimension, they can be combined to measure two- or three-dimensional velocities.

Laser Doppler Velocimetry (LDV) is a very popular technique to measure flows in reactors. The basic idea of LDV is that the velocity of a particle leads to a frequency change of scattered light due to the Doppler effect. Hence, the particle velocity can be deduced from this light frequency shift. The main advantage of LDV is its non-invasive character. It provides instantaneous and local velocities. It even allows the characterization of turbulence (Lyn & Rodi, 1990). One of the major drawbacks of the technique is intrinsic to the measurement principle itself: the fluid velocity is assumed to equal the particle velocity. Particles are supposed to accurately follow the flow, which is very dependent on the particles' drag. Also, the cost of the high quality components is a drawback. Its application is further limited to suspensions with solids concentrations below 4 g TSS/l (STOWa, 2002).

As the name already indicates, acoustic Doppler velocity meters also use the principle of the Doppler effect. These probes emit acoustic waves from a transmitter and analyse the reflected waves. Their main advantage is the large measurement depth. However, as for the LDV, the particles' velocity is measured and not the liquid velocity. This has major consequences for velocity measurements in settling tanks. Indeed, the settling process implies large particles that may experience considerable drag, resulting in particle velocities deviating from the liquid's velocity. This is clearly demonstrated in Figure 1 (left) showing velocity measurements in a secondary settling tank.

The measurements at the bottom part of the settling tank were accurate because fluid velocities are high at these locations and complete flow entrainment of the particles occurs. Near the surface, however, fluid velocities are too low to completely entrain the particles and, as a result, they settle. This explains the vertical velocities found in the upper part of the settling tank. In this region the probe's ability to measure the fluid velocity is definitely restricted. However, one should not forget though that the measurement of the particles' velocities is of clear interest also when studying settling tank behaviour.

Acoustic velocity meters can be subdivided in two major categories, i.e. the point-velocity meters and the current profilers.

As an example of a point-velocity meter, the Acoustic Doppler Velocity meter (ADV) measures a 3D velocity in a small volume by employing one transmitter and three transducers placed under a certain angle (Figure 2). ADVs typically measure velocities between -10 and $+10$ m/s, and have an accuracy of about 0.5% of the measured velocity.

In ocean and estuary research, non-invasive acoustic Doppler current profilers (ADCP) have been widely used to obtain the flow field of a large volume (Lohrman *et al.*, 1990; Stacey *et al.*, 1999a,b). A typical ADCP (Figure 1, right) transmits and receives signals via three transducers arrayed in the so-called Janus configuration; they are positioned around a horizontal circle every 120 degrees, and are directed outwards at a certain angle to the vertical. The device listens to and processes the echoes coming with different time delays from successive volumes along the beam to determine how much the signal has shifted. From this shift the 3D-velocity vector is calculated. In the neighbourhood of the device itself measurements are impossible. The size of this neighbourhood depends on the so-called *blanking period*, i.e. the time needed to convert the equipment head from a transducer to a receiver. Within this time frame no measurements can be performed. Also at the bottom of the tank a loss of measurement capability occurs due to reflections

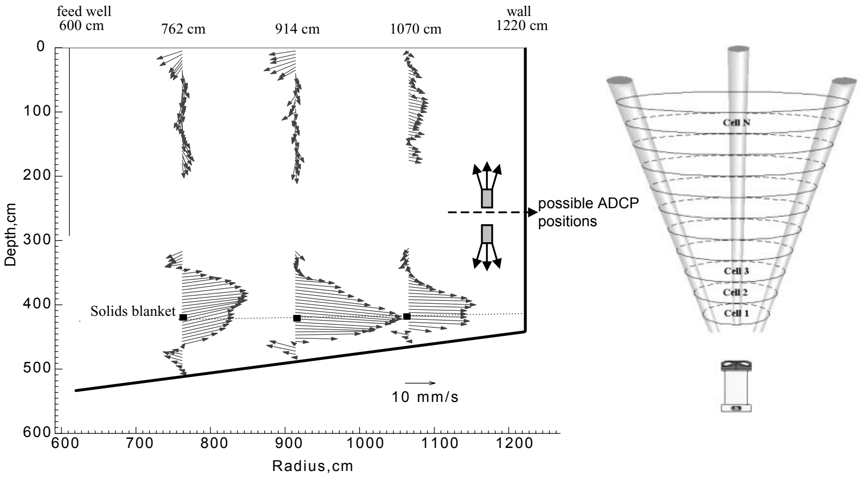

Figure 1 Velocity profiles obtained at the Central Davis settler (left) with an ADCP current profiler (right) (De Clercq *et al.*, 2002)

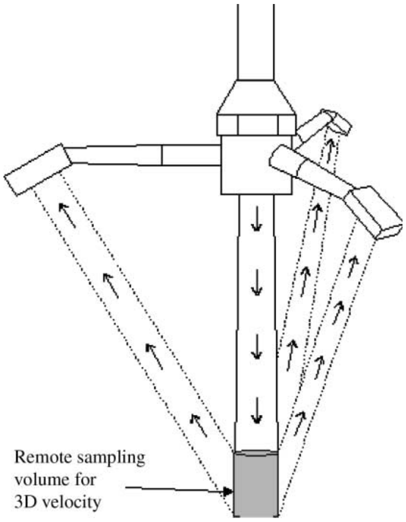

Figure 2 Layout and measurement principle of the ADV (Sontek/YSI Inc.)

of the emitted waves on the wall. Similar to the ADV, these sensors measure between −10 m/s and +10 m/s. Unfortunately, ADCPs are a little less accurate than ADVs, i.e. ±1% of the measured velocity. However, they measure a complete velocity profile.

An example of an ADCP velocity profile is given in Figure 1 (left). For three radial distances in the settler of Central Davis County Sewer District (Salt Lake City, Utah), two vertical velocity profiles are given, corresponding with the downward and upward deployment of the sensor in the settler. The figure shows the presence of a strong density current, typical to secondary settlers. At every radial distance, a radial-outward density current develops in the vicinity of the sludge blanket that is indicated with the squares (Lakehal *et al.*, 1999; Armbruster *et al.*, 2001). A reverse top current is also induced. The upward looking ADCP does not record this since the particles move independently of the liquid. Immediately above the density current the vertical velocities are still (mostly) downwards. Again, this is due to settling: the sludge concentration is fairly low and does not restrict settling.

It must be clear that the amount of information collected at once from such an ADCP device is very high and can support the detailed study of flow velocity and turbulence profiles in secondary settlers.

Characterization of settling

At the end of the 1980s and early 1990s a number of settlometers were developed for continuous monitoring of settling properties by performing automated batch settling tests (Severin *et al.*, 1985; Sekine *et al.*, 1989; Reid and Nason, 1993; Vanrolleghem *et al.*, 1996). As an example, the settlometer developed by Vanrolleghem *et al.*, (1996) is built around a small settling column that is designed in such a way that wall effects are avoided and that solids bridging is prevented. It has a capacity of 10 litres, a diameter of 14 cm and a height of 70 cm. With an external light source and a moving light-intensity scanner, the sludge blanket height is continuously determined as the vertical location where the highest light intensity gradient occurs.

These devices allow high frequency monitoring of the settling properties by taking sludge samples about every hour (De Clercq *et al.*, 2003). They have been used to pinpoint recurring operational settling problems (Vanderhasselt *et al.*, 1999a) or to identify possible improvements to the operation of secondary settlers, e.g. through better controlled polymer addition (Vanderhasselt *et al.*, 1999b).

Settlometers directly produce data on sludge volume or in some cases sludge volume index. More intrinsic settling property information as, for instance, expressed in settling velocity functions that can then be related to solid flux information, appears very valuable. Vanderhasselt and Vanrolleghem (2000) tried to extract information on the sludge concentration dependency of the settling velocity, but found that this is difficult to obtain from a single sludge settling curve obtained at a particular sludge concentration (typically the one prevailing in the aerator or in the sludge recycle line).

Hence, the settlometer described by Vanrolleghem *et al.* (1996) was extended with an automatic dilution system that mixes return activated sludge with clarified effluent. The dilutions were set at 0%, 30%, 60%, 70% and 80% fraction of effluent in the settling column. An experiment was set up in which, in total, 417 batch settling curves were recorded by the settlometer. Figure 3 shows the recording on a particular day. The effect of dilution can be clearly seen and the often-reported induction period (Vanderhasselt & Vanrolleghem, 2000) was obviously smaller at higher dilution. The results also show that the settling properties (and solids concentration obtained from a built-in turbidimeter) did not change significantly during the whole day. Indeed, the different curves at the same dilution coincide. The zone settling velocity was determined for every curve, allowing to monitor the solid flux properties of the activated sludge under study at an unprecedented frequency, i.e. a round of dilutions is performed every 3 hours.

In situ particle sizing

It is obvious that the Particle Size Distribution (PSD) is a key variable for the separation performance of single particles in the upper zones of the settler. Information about the PSD can be used to build so-called population balance models that describe the change of the PSD due to flocculation and break-up (Nopens *et al.*, 2005). Such models can be applied for system optimization and evaluation of the effect of different process and operating conditions.

To investigate the PSD of the sludge, several sizing techniques are available. In literature, methods as image analysis (Spicer and Pratsinis, 1996), Coulter counter (Li and Ganczarczyk, 1991) and laser diffraction (Biggs, 2000; Govoreanu *et al.*, 2004) are

Time	Dilution	Concentration (mg/l), legend on the graph
0:40	60	1613
1:20	30	2909
2:10	0	4031
3:40	70	1247
4:20	60	1613
5:10	30	2909
6:40	80	831
7:30	70	1228
8:10	60	1688
9:00	30	2909
9:40	0	4094
10:20	80	819
11:10	70	1228
12:50	30	2822
13:30	0	4156
14:10	80	791
15:00	70	1167
15:50	60	1531
16:40	30	2702
17:20	0	4094
18:50	70	1228
19:40	60	1663
20:30	30	2866
21:10	0	4031
21:50	80	831
23:30	60	1663

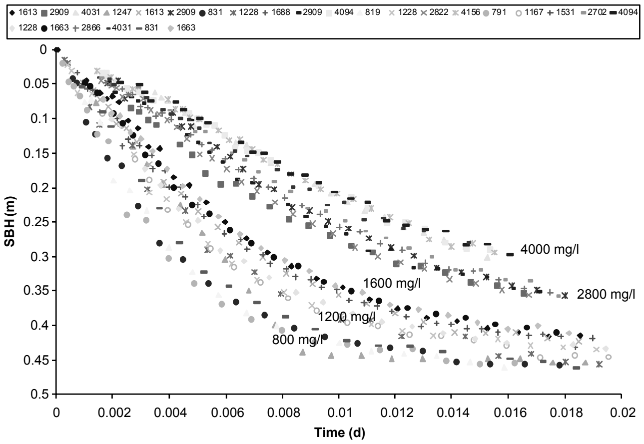

Figure 3 Settlometer data collected during one day (right) using the dilution sequence (left) expressed as percentage of effluent water in settling column

widely applied. Unfortunately, in general, they can only be applied in a lab environment and not in situ. As a consequence, in situ particle sizing techniques are rather rare. Firstly, spectroscopy of an acoustic wave reflected on the particles can reveal information on the PSD (Reichel and Nachtnebel, 1994). However, this technique is still in its infancy. Secondly, the focused beam reflectance method (FBRM) can be applied in situ, even to highly concentrated particle dispersions.

The probe used by De Clercq *et al.* (2004) was the Lasentec FBRM M500 (Mettler-Toledo/Lasentec, Redmond, Washington, USA). It consists of a laser that rotates at a fixed speed, i.e. 2 m/s (Figure 4). As particles pass by the focal plane, the focused beam intersects the edge of a particle and begins to backscatter the laser light. The backscatter continues until the beam reaches the particle's opposite edge. The time period of reflection is multiplied by the scan speed and the result is a distance, i.e. the *chord length*; flocs were sized in the 1 to 1000 μm range over 90 logarithmic channels.

The municipal wastewater treatment plant under study was located at Oxley Creek, near Brisbane (Australia). The examined circular settler had a central feed, a peripheral overflow weir, a central conical sludge hopper and blade scraper (Figure 5). It had a maximum depth of 5.4 m and a surface area of 308 m^2. The inlet flow rate was characterized by a diurnal pattern and, during the measurement campaign, the inlet solids concentration ranged between 1800 and 2200 mg/l. PSD measurements were performed at afternoon inlet flow rates ($0.147 \pm 0.012\ m^3/s$), which were the most stable that could be obtained. Inside the flocculator five PSDs were recorded at increasing depths. Measurements outside the well and at different depths were performed as well. The necessary measurement duration was determined by the total number of chord counts (400,000 to 4,000,000) in order to obtain a statistically sound and representative PSD. Hence, all locations were sampled over a 10-minute interval, except for the four upper locations (above the sludge blanket) outside the flocculator where sampling lasted for 30 minutes due to the lower solids concentrations.

Figure 5 shows the PSD inside and outside the flocculator. At high sludge concentration all PSDs are very similar, hence they are grouped and are given by a single representative PSD in Figure 5. Due to this apparent invariable PSD inside the flocculator, the role of this structure needs to be questioned. Presumably, most of the flocs are already formed inside the distribution pit, pipe, momentum diffuser and in the flocculator section close to the diffuser. Compared to the PSDs at high concentration it is clear that at low concentration (upper location and just outside the well) the number distributions are shifted to the lower chord length range. A strong peak at small chord lengths exists, indicating that large flocs were separated by gravity. Due to the low local shear/velocity large particles are able to settle. Instead, small ones remain in suspension due to Brownian motion. Finally, note that the sludge concentration is reflected in the count frequency too (compare the range of the Y-axes in Figure 5).

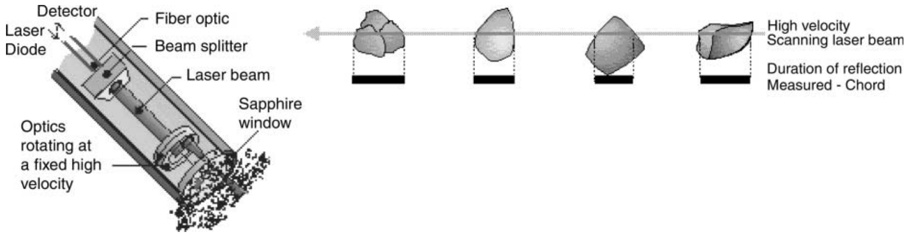

Figure 4 Principle of FBRM; probe layout (left) and definition of chord length (right) (Lasentec)

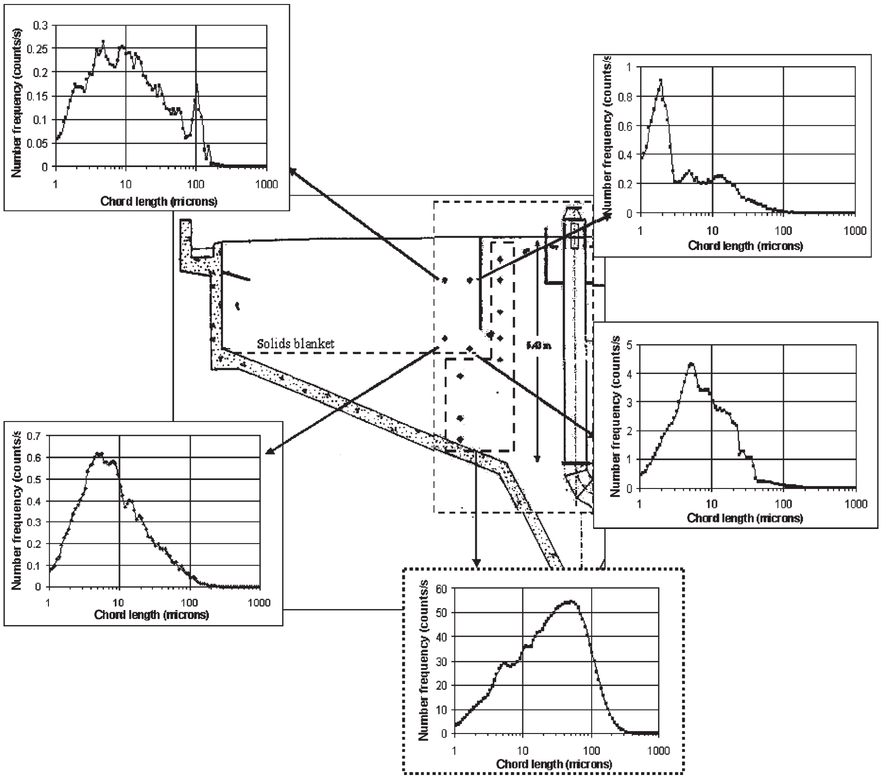

Figure 5 Measured PSDs at pseudo-constant inflow rates. The diamond symbols indicate the sampling locations in the settling tank. The dashed line delineates the region with identical PSDs

In this work, the FBRM has proved its *in situ* applicability to settler PSD-monitoring and the PSD can be measured in a wide range of solids concentrations, in contrast to most alternative particle sizers.

Non-invasive sludge concentration profiling

The last measuring technique presented in this paper is at this stage not applicable to full-scale treatment facilities, but the authors feel it is a breakthrough for the detailed study of both hindered and compression settling. With the presented technique, the evolution of the sludge concentration profile during batch settling can be monitored at an unprecedented level of spatial and temporal resolution.

Non-invasive techniques to measure concentration profiles, such as gamma-ray (Scott, 1968; Bergström, 1992; Dreher, 1997) and X-ray scanning (Been and Sills, 1981; Shih *et al.*, 1986; Wells, 1990; Tiller *et al.*, 1991) and CATScan (Chu *et al.*, 2003) have been applied to batch settling of suspensions other than activated sludge. However, these suspensions all have a higher solids concentration and solids density than activated sludge which, given the accuracy of the measurement, i.e. 0.5 (Bergström, 1992), 0.25 (Been and Sills, 1981) and 0.1 vol% (Chu *et al.*, 2003), is too low for application due to activated sludge (solids concentration of only 0.1–0.4 vol%).

Optical devices, ultrasound and dielectric spectrometry have been used for the measurement of solids concentrations in wastewater treatment (Vanrolleghem and Lee, 2003). However, such sensors cannot be used for monitoring the solids concentration profile during batch settling since they are commonly positioned inside the settler, disturbing the settling process. Since the reported techniques cannot be used, the idea of measuring a characteristic of a substance, which adsorbs to the solids in a non-invasive way, arose. Solids tracers have already been used to determine the sludge residence time distribution: $MnCl_2$ (Lumley and Balmèr, 1990), pyrene (Grijspeerdt and Verstraete, 1995), radioactive Au-198 and La-140 (Audic *et al.*, 1993; IAEA, 2001). Radioactive tracers have the advantage over Mn and pyrene that they can be measured on-line, rather than off-line after sampling.

An alternative radiotracer, Tc-99m, is the most commonly used radioisotope in nuclear medicine. This popularity in medicine is due to its good half-life (long enough to perform a study and short enough to limit the radioactive dose received by patients), the monochromatic gamma-ray energy it emits, and its existence in oxidation states from $+1$ to $+7$. Hence, since the activated sludge solids are negatively charged, a cationic Tc-99m complex could be used to trace them. One such positively charged complex is Tc-99m Sestamibi (Methoxy IsoButyl Isonitril), which could be produced and detected at the Department of Nuclear Medicine of the Ghent University Hospital, where a Mo-99/Tc-99m generator and different gamma cameras are available.

De Clercq *et al.* (2005) proved that Tc-99m Sestamibi adsorbs well onto activated sludge, and, very importantly, did not alter the settling properties. It can, therefore, be used to monitor sludge concentration profiles during batch settling.

The experimental set-up at the Ghent University Hospital is shown in Figure 6 (left). The 1.6 m Plexiglas settling column has an inner diameter of 386 mm, large enough to avoid wall effects. The gamma camera detects the 140 keV photons emitted from Tc-99m during a chosen time interval and produces a 2-dimensional projection of the radioactivity of the emitting object, i.e. an image. Images are produced every 30 or 60 seconds, which results in radiotracer profiles over time. The images have a resolution of 256 by 256 pixels, each pixel sizing 2.33 by 2.33 mm. As the solids concentration profile is considered homogeneous in a horizontal plane, the 2-dimensional data of each image is transformed into a 1-dimensional vertical profile by summing the values per pixel in every plane. The data are subsequently corrected for radioactive decay (Tc-99m's half-life is approximately 6 hours).

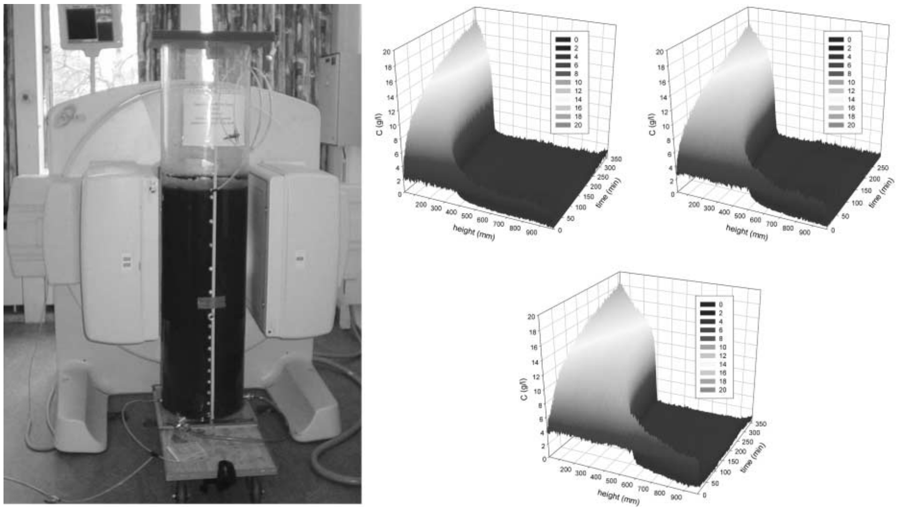

Figure 6 Left: Scanner around settler set-up at Ghent University Hospital. Right: Solids concentration profile during batch settling of Destelbergen sludge (top left: C = 2.40 g/l; top right: C = 3.23 g/l; bottom: C = 4.30 g/l)

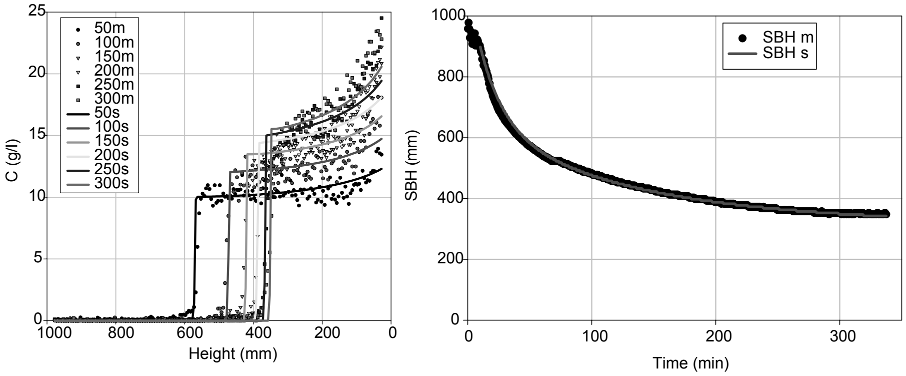

Figure 7 Measured and simulated concentration profiles at 50 minute intervals (left; legend: numbers are in minutes, s: simulated; m: measured) and resulting evolution of sludge blanket height

Solids concentration profiles obtained with different initial concentrations of sludge collected at the BNR treatment plant of Destelbergen (Belgium) are shown in Figure 6 (right). The high-resolution profile gives a nice representation of the settling process and can be used for a better understanding and modelling of the process. The coefficient of variation of the obtained solids concentration, calculated from the ratio of the standard deviation σ of the measured counts and the measured solids concentration, is about 15–20%. In comparison, the reported accuracy of 0.1 vol% of the CATScan measurements (Chu *et al.*, 2003) corresponds to a coefficient of variation of 50%.

All profiles show the same trend: initially, the solids concentration is uniform but subsequent profiles show the accumulation of sludge at the base as a result of settling, as well as a decrease of the sludge blanket height (Figure 7). The concentrations at the base are continuously increasing and higher concentrations move towards the sludge blanket height. The existence of compression is evidenced by the form of the iso-concentration lines observed (results not shown). When only hindered settling is occurring, the iso-concentration lines are straight lines, while they become curved when compression occurs (Bürger *et al.*, 2004). Modelling of these data needs to elucidate compression further (initial results are presented in Figure 7).

Conclusions

In this contribution a number of new measurement techniques characterized by their non-invasiveness have been presented. They yield high quality data that focus on different aspects of the physical processes taking place in secondary settlers, i.e. hydrodynamics, hindered settling, compression settling and flocculation/deflocculation. Typical experimental data sets have been presented that show the potential of these measurement techniques to support the analysis of operational and design problems of secondary settlers. In this way they can contribute to the development and implementation of new operating schemes and design options.

Acknowledgements

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