A novel methodology for the calibration of discrete settling behaviour of activated sludge

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Abstract: A new measurement device was developed which allows collecting detailed data of changes in Particle Size Distributions (PSD) during discrete settling. The results show that the discrete settling behaviour of activated sludge can be described by dividing the sludge in roughly 5 classes. Moreover, by measuring the evolution in PSD along different depths in the settling device, the discrete settling velocities of the different classes can be quantified. This information can now be used in a coupled flocculation-CFD model in order to model the impact of different conditions on the effluent concentration.

Key words: settling velocity; particle size analysis; SST

Introduction

The operation and control of SSTs is still an important performance-limiting factor in conventional wastewater treatment plants. The efficiency of the latter depends on the flocculation of the microorganisms in large, dense flocs that settle fast, thus separating the sludge from the treated water. Therefore, the settling behaviour of the sludge is a crucial factor in understanding the performance of the solid-liquid separation.

Classical settling models relate the sludge settling velocity to the local sludge concentration. However, this relation will only be valid if the concentration of the flocs exceeds a certain threshold where the inter-particle forces become sufficiently strong to drag each particle along at the same velocity irrespective of size or density (i.e. hindered settling). At lower concentrations (below a treshold concentration X_{lim} = 600-700 mg/l (Mancell-Egala et al., 2012)), as can be found in the region above the sludge blanket in an SST, the particles are too far apart to sense each other and the settling velocity will depend on the size and density of each individual floc and not on their concentration (i.e. discrete settling according to Stokes' law). Each particle will thus settle at its own characteristic velocity (Ekama et al., 1997). This top region of an SST is of particular interest since particles that settle poorly here, will never make it into the sludge blanket and be carried over the weir deteriorating the effluent quality. Therefore, in order to accurately describe the settling behaviour in this region, detailed information on the dynamics of the Particle Size Distribution (PSD) is required.

Recently, attempts have been made to describe this discrete settling behaviour by coupling of a CFD model with a flocculation model (Griborio and McCorquodale (2006), Torfs et al. (2013)). The flocculation model (Parker et al., 1972) divides the sludge particles in 2 classes: flocs and primaries and it includes both aggregation and breakage of particles. Through the coupling of these models specific regions in the SST where flocculation is taking place can be determined (Figure 1). This approach allows simulating the quantitative effect of varying conditions on the effluent concentration (Table 1) from which appropriate operational and control strategies can be developed.

However, for this type of coupled models to be used in practical applications they need validation. This means that for each particle class a discrete settling velocity has to be determined. Therefore, this work aims to develop a new measuring technique through which high quality data of the discrete settling process can be collected.

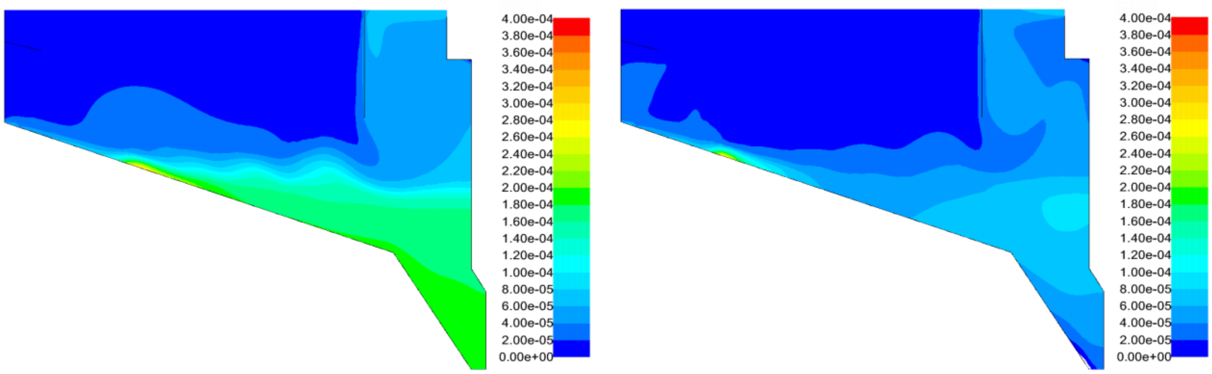


Figure 1: Concentration profiles of primary particles in the secondary clarifier without flocculation and discrete settling (left) and with flocculation and discrete settling included (right). (Torfs et al., 2013)

Table 1: ESS concentrations with and without discrete settling. (Torfs et al. 2013)

Simulation	ESS (total) mg/l	ESS (primaries) mg/l	ESS (flocs) mg/l
No discrete settling	8.86	2.97	5.89
With discrete settling	7.27	2.79	4.48

Material and Methods

A new measurement device was developed to determine discrete settling velocities of different size ranges of activated sludge useful as inputs of a coupled CFD-flocculation model. The device consisted of a settling column of approximately 9 liters with an inner diameter of 150 mm and sampling points at different heights along the column. A total of sixteen sampling holes were located at four different heights. At each height 4 holes were spread equally over the diameter of the settling column. The dimensions and a schematic representation of the settling column are shown in Figure 2. This set-up allows taking frequent samples at different heights in the settling column during a batch settling experiment. By switching the sampling locations at one depth between the 4 sampling holes along the diameter, subsequent samples can be taken independently of hydraulic disturbances that might have been caused by previous sampling.

With respect to the choice of sampling technique, care was taken to ensure that the measurements are not biased by wall effects or sample disturbances. Finding the optimal sampling technique is not straightforward. Larger diameters will have less chance of causing interaction of the particles with the wall of the sampling channel but will create larger sample volumes and thus more disturbance in the column. Sampling at a larger distance from the wall entails less risks of wall effects but forces the sample to cross a longer trajectory through the sampling tube which can again disturb the sample. Therefore, a number of sampling strategies (differing in diameter of the sampling tube and the distance of the sampling point from the inner wall of the column) were tested and compared to a reference sample. The reference sample was collected with a pipette of approx. 2 mm in diameter at the same height as the first sampling holes by submerging the pipette from the top of the column. By comparing the different sampling techniques to the reference sample, it was found that the length of the sampling tube should be kept as short as possible and that a diameter of 1 mm is sufficient to obtain a very good correspondence to the reference sample.

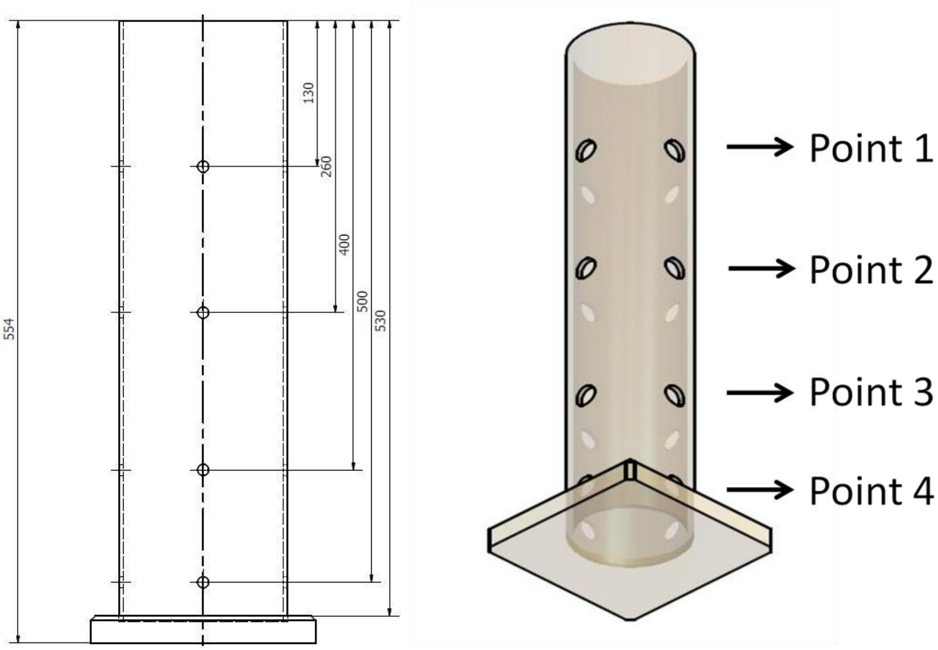


Figure 2. Schematic representation of the settling column

To investigate the changes in PSD during settling, all samples were analysed with the Eye-Tech particle size analyser (Ankersmid, The Netherlands). This device incorporates two different methods for particle size analysis: (1) a video channel which uses image analysis and (2) a laser channel which uses a measurement of Laser Obscuration Time (LOT). In this study, all samples were analysed through the video channel since this allows studying particles in 2-D incorporating information on both size and shape of the particles.

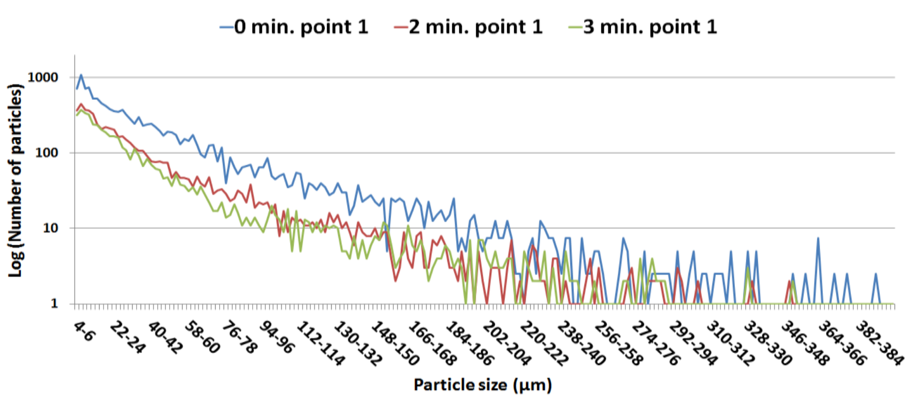
The settling column tests were performed on activated sludge collected from the WWTP of Roeselare (Belgium). This WWTP has a biological capacity of 65,760 inhabitant equivalents (IE). To investigate the discrete settling behaviour, a sludge sample from the aeration tank was diluted to approximately 1 g/l and allowed to settle in the column. The experiments were performed at a concentration of 1g/l to ensure that the initial settling behaviour is in the hindered settling regime. In this way both transition from hindered settling to discrete settling and the consequent evolution in discrete settling can be studied.

Results and discussion

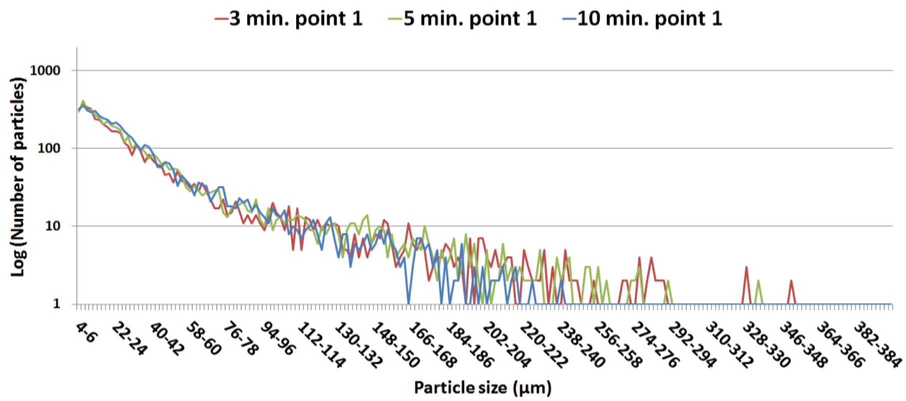
Batch settling experiments were performed in the settling column on two different measurement days. On each measurement day, several experiments were conducted during which frequent samples were collected in time and the dynamic evolution of the particle size distribution was measured with the Eye-Tech analyser. The resulting PSDs are shown as absolute number of particles vs. particle size (µm). Presenting the results as number distributions was preferred over volume distributions since the latter are very sensitive to small variations in large particles (the occurrence of only 1 or 2 large particles can cause a severe shift in volume distribution) but much less sensitive to changes in small particles. Hence, to investigate discrete settling behaviour, the absolute number distribution provides more relevant information than the volume distribution.

Figures 3-6 show a detailed evolution of the changes in particle size distribution at the top of the column (sampling point 1) during 2 hours of settling. It should be noted that particles larger than 400 µm were not sampled with the current device even though they were visually detected in the settling column. The reason for this lies in the small diameter of the sampling tube and the fact that these larger particles (even though they represent a significant volume) are only present in very low numbers. A possible improvement for this would be to increase the diameter of the sampling tube. However, this would still not ensure accurate detection of the larger particles since the volume for analysis in the Eye-Tech device is only 3 ml making it very likely that no particles larger than 400 µm will be present in an analysed sample. Nevertheless, from visual observations it could be concluded that these large particles settle very fast and will be removed from the system at a very early stage in the experiment. In a coupled flocculation-CFD model, they can thus be classified as a single class of particles with a very high discrete settling velocity (approx. 30cm/min).

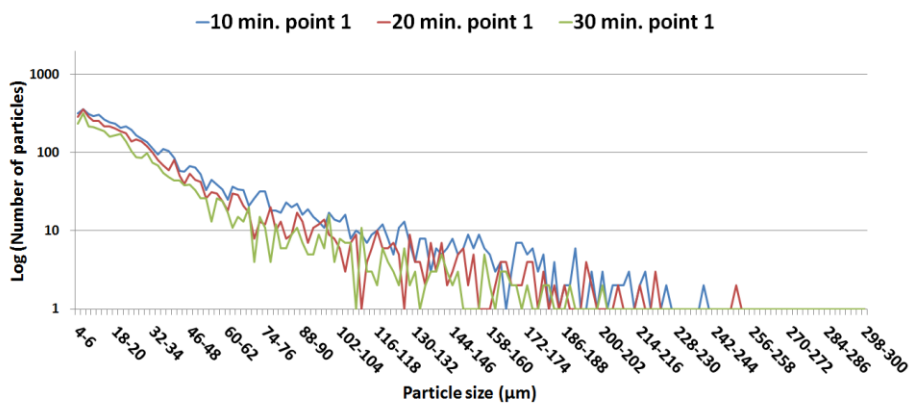
From figure 3 it can be seen that during the first 2 minutes of settling, the number of particles in all particle classes decreases simultaneously indicating that the settling process is dominated by the hindered settling regime. After this initial period of hindered settling, discrete settling starts with the preferential settling of particles larger than 400 µm between 2 and 5 min. after the start of the experiment. Since these very large particles are not sampled, their discrete settling behaviour is not captured in the PSD results but was detected visually. From 5 min. onwards, the measured PSDs clearly show sequential settling of particle according to their size. After 10 minutes of settling particles larger than 250 µm are no longer found in the sample (Figure 4). This class of particles was thus removed from the top of the settling column between 5 and 10 min after the start of the experiment. Particles in the range of 200-250 µm and particles in the range of 100-200 µm are resp. removed after 20-30 minutes and 1-2 hours of settling (Figure 5 and 6). Particles smaller than 100 µm do not show any significant decrease in numbers even after 2 hours of settling (Figure 6).



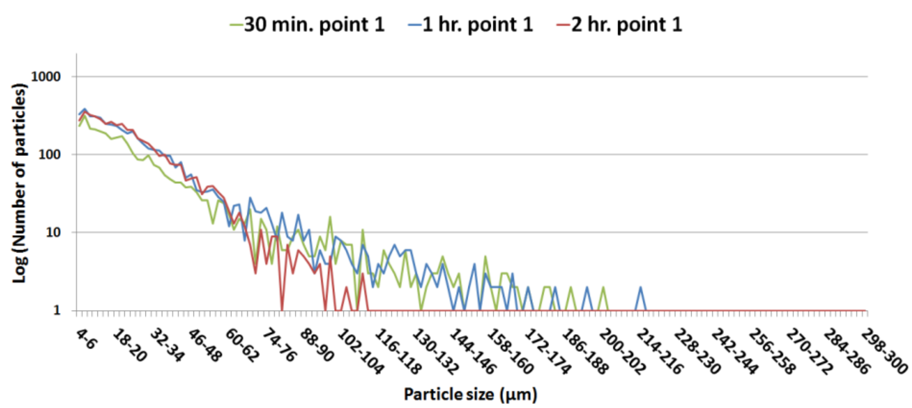
Figuur 3: Evolution in absolute number distribution at sampling point 1 during the first 3 minutes of settling.



Figuur 4: Evolution in absolute number distribution at sampling point 1 between 3 and 10 minutes of settling.



Figuur 5: Evolution in absolute number distribution at sampling point 1 between 10 and 30 minutes of settling.

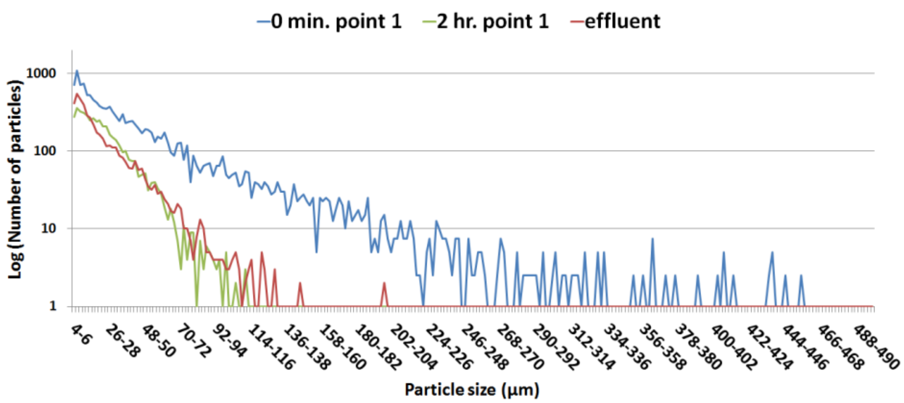


Figuur 6: Evolution in absolute number distribution at sampling point 1 between 30 minutes and 2 hours of settling.

These results indicate that the discrete settling behaviour of an activated sludge sample can be described by dividing the sludge in 5 classes going from large flocs (>400 µm) with a high settling velocity to very small particles <100 µm that do not show any tendency to settle in the discrete settling regime. In between these two extremes, 3 more classes can be defined (250-400 µm, 200-250 µm and 100-200 µm) with decreasing settling velocities.

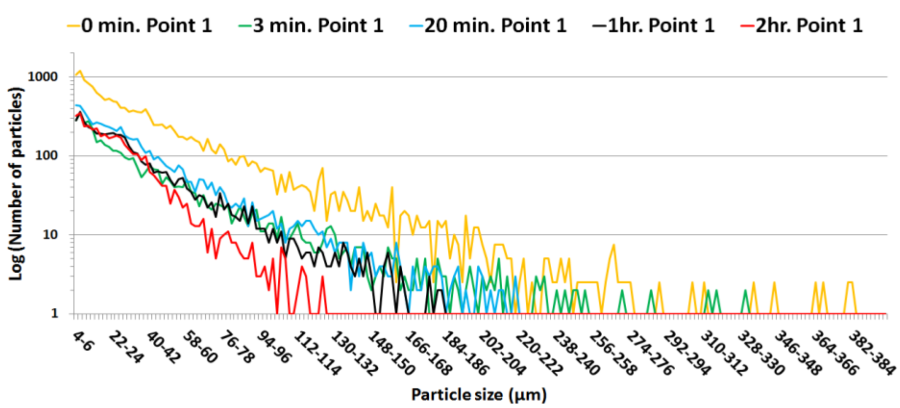
To investigate the quality of the settling process during settling in the batch column, the supernatant PSD after 2 hours of settling was compared to the PSD in the effluent of the WWTP (Figure 7). The number distribution after 2 hours of settling shows very good correspondence to the number distribution in the effluent sample for particles smaller than 100 µm. This confirms that particles smaller than 100 µm can be considered as a class of non-settling particles, even in a full-scale settler. Removal of particles smaller than 100 µm should thus be accomplished through flocculation of these particles in the flocculation well or by capturing them in the sludge blanket during the hindered settling regime.

The effluent sample, however, still shows the presence of particles between 100 and 150 µm whereas after 2 hours of settling in the settling column all particles in this range were removed. Online measurements of the incoming flow rates during sampling show that the average hydraulic residence time in the SST is only 1.5 hours. This explains the observed difference in PSD between the effluent sample and the sample after 2 hours of settling in the column.



Figuur 7: Comparison between the absolute number distributions after 2 hours of settling in a settling column and in an effluent sample of the WWTP of Roeselare.

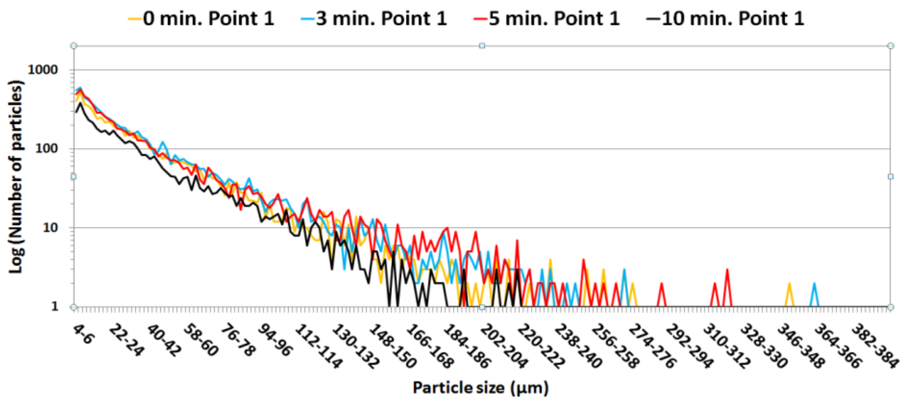
The batch settling experiment was repeated on a second measurement day and the results are shown in Figure 6. Similar trends as for the first measuring day can be observed: hindered settling prevails during the first few minutes of settling followed by sequential settling of particles of different sizes during the remainder of the experiment. Particles smaller than 100 µm show very poor settling properties although some reduction in particles between 50 and 100 µm can be observed after 2 hours. However, in a real settler much less time is available for settling.



Figuur 8: Evolution in absolute number distribution at sampling point 1 during 2 hours of settling (on measurement day 2).

Finally, the settling column test was repeated at a lower initial concentration (by diluting the mixed liquor sample to approx. 500mg/l). With this set-up, the initial concentration is too low for hindered settling and the settling should immediately start in the discrete regime. The resulting

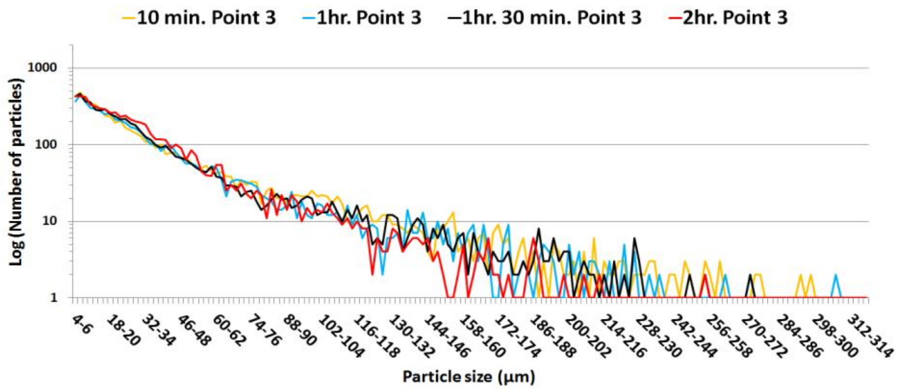
PSD distributions (Figure 7) show no simultaneous settling of all size ranges thus confirming that no hindered settling is taking place. During the first 5 minutes of settling no significant changes in PSD are measured, however, discrete settling of particles >400 µm could be observed visually during this time. Between 5 and 10 minutes after the start of the experiment, discrete settling of particles between 220 and 400 µm can be observed (Figure 7). The remainder of the experiment shows similar trends as the experiments at higher initial concentrations.



Figuur 9: Evolution in absolute number distribution at sampling point 1 during the first 10 minutes of settling at an initial concentration of 500 mg/l.

The results above (measured at the first sampling point) allow distinguishing different classes of particles depending on their settling velocity. However, in order to quantify these discrete settling velocities, the time it takes for particles of a certain class to travel the distance along the column needs to be measured. This can be accomplished by comparing the changes in PSD at different heights throughout the column. Information from the lowest sampling point cannot be used since this sampling point is located in the sludge blanket. Therefore, the changes in PSD at sampling point 3 (located 27 cm below sampling point 1) during 2 hours of settling are investigated (Figure 10) and compared to the results at sampling point 1 (Figure 8).

Similar as to what was observed at the top of the settling column, also in the lower regions of the column a first period of hindered settling can be observed. However, at this height, it takes approx. 5 minutes for the smaller particle classes to reach a stable distribution (results not shown). Approx. 5 minutes after the start of the experiment, the settling behaviour shifts to the discrete regime. As can be seen from Figure 10, it takes a long time for particles <400 µm to reach this height from the top of the column. Only after 1.5-2h of settling a significant decrease in particles between 220 and 400 µm can be observed indicating that it takes 1h20-1h40 for the particles in this size class to travel the 27 cm distance between point 1 and point 3 thus travelling at a velocity of approx. 0.3 cm/min. Note that this is extremely slow. The differences in settling velocities between particles larger than 400 µm (30 cm/min) and particles smaller than 400 µm (0.3 cm/min) are too large to be explained based only on differences in size. According to Stokes' law a particle of 1 mm that travels at a velocity of 30cm/ min has a density of 1.02 kg/m^3. However a particle of 250 micron that travels at a velocity of 0.3 cm/min has a density that is only a fraction higher than that of water. Therefore, in order to come to an even better understanding of the discrete settling behaviour, the experiments could be extended by including dynamic density measurements in combination with particle size analysis. In order to quantify the settling velocities of the smaller size classes, the experiment should be conducted for longer settling times and more frequent data should be collected at later times during the settling process.



Figuur 10: Evolution in absolute number distribution at sampling point 3 between 10 minutes and 2 hours of settling (on measurement day 2).

Conclusions and perspectives

Although the coupling of a flocculation model to a CFD model allows to model the discrete settling process in the top region of an SST, the practical application of these models is hampered by a lack of knowledge about settling velocities. Therefore, a new measurement device was constructed which allows to measure the changes in PSD during discrete settling in a batch settling column. The results indicate that the discrete settling behaviour of an activated sludge sample can be described by dividing the sludge in roughly 5 classes: a class of large flocs (>400 µm) that settle rapidly and will be preferentially removed during the first few minutes of settling, 3 intermediate classes (250-400 µm, 200-250 µm and 100-200 µm) with settling velocities that are decreasing with size and a very slow settling class consisting of particles <100 µm.

Moreover, measuring the evolution in PSD at different depths throughout the column allows quantifying the discrete settling velocities for the different classes. Particles in the two largest size classes (>400 µm and 250-400 µm) settle at a velocity of resp. 30 cm/min and 0.3 cm/min. The large difference between these settling velocities indicates that particles in these two classes do not only differ in size but also in density. This kind of detailed information on dynamic PSD can significantly aid in understanding (and modelling) the complex settling and flocculation behaviour of sludge particles at low concentrations which will consequently lead to improved predictions of the effluent concentrations. We therefore believe that this simple test method can bring a lot of new insights with respect to activated sludge settling.

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