Settling characterisation using on-line sensors at a full-scale wastewater treatment plant

Alexis Vanderhasselt[1], Henrik Aspegren[2], Peter Vanrolleghem[3] and Willy Verstraete[1]*
[1] *Laboratory of Microbial Ecology and Technology, University Gent, Coupure Links 653, B-9000 Gent, Belgium*
[2] *Malmö Water and Sewage works, S-20580 Malmö, Sweden*
[3] *BIOMATH Department, University Gent, Coupure Links 653, B-9000 Gent, Belgium*

Abstract

An on-line settlometer is presented which automatically records sludge settling curves. From these curves the sensor deduces the initial hindered zone settling velocity (Vs). In order to evaluate the information gathered by the sensor, the instrument was used at an information-rich full-scale wastewater treatment plant (Klagshamn, Sweden). This plant is operated as a single sludge post-denitrification activated sludge system with an external carbon source. With the sensor a diurnal pattern of Vs could be detected. This pattern was mainly caused by the diurnal change of the sludge concentration. Using the Vesilind equation it was possible to standardise Vs to the sludge concentration (Vs'). The variation in the standardised Vs' was less compared to the experimental Vs. Still, it was possible to detect a sudden drop in Vs' on nearly daily basis. At two of these instances rising sludge was even detected in the settlometer during the 35 min lasting sedimentation period. The fact that this could be observed is remarkable as the water temperature was only 7.5°C, the bulk liquid entering the settlometer was aerobic and only a very low amount of carbon sources was found in the effluent. Hypotheses are put forward that could give an explanation for the occurrence of rising sludge under these circumstances. In the observed post-denitrification plant a positive correlation could be found between the airflow to the reaeration tank and the sedimentation velocity.

Introduction

In the global activated sludge process final clarification is a very important unit process (Albertson, 1992). The separation of the sludge from the purified water and its thickening is dependent on the amount and physical properties of the flocs and the hydraulic conditions in the clarifier. The hydraulic loading of the settler can change rather rapidly. On the occurrence of a rain event, the hydraulic loading can easily become five times as high as during dry weather conditions. Apart from this, changes in the physical properties of the sludge are also possible. For instance, bacterial population dynamics induced by changes in operational conditions can have a strong influence on the sludge settling properties. These shifts occur rather slowly and have time constants in the order of days or even weeks. Reid and Nason (1993) suggested a dependency of the settling characteristics on the pollutant concentration remaining in the mixed liquid entering the final clarifier. Also changes in conductivity can influence the floc formation (Zita and Hermansson, 1994). The wastewater composition can change within a matter of hours, so their effect on the sludge settling can be much faster as in the case with population shifts.

Sedimentation characteristics are normally determined manually using batch settling tests (Catunda and Van Haandel, 1992). These measurements are usually performed only once a day. This frequency is obviously too low to enable the operator to detect short-time changes in the sludge settleability. Furthermore, laboratory experiments such as the SVI (sludge volume index) have often been criticised (Dick and Vesilind, 1969) and the settling conditions can be quite different from the ones encountered in full-scale settlers: in small settling columns bridging can become important and settling properties are often evaluated at reduced sludge concentrations.

* To whom all correspondence should be addressed.
☎+32(0) 9 264 59 76; fax +32(0) 9 264 62 48; e-mail willy.verstraete@rug.ac.be
Received 4 January 1999; accepted in revised form 14 June 1999.

Methods

At the University of Gent (Belgium) a settlometer was developed in which sludge settling characteristics are determined in a very simple and natural way (Fig. 1) (Vanrolleghem et al., 1996). The core of this apparatus is formed by a 10 ℓ down-scaled Pyrex decanter equipped with a stirrer (1 r/min). This model decanter is operated in a batch mode: the decanter is filled with sludge, the sludge is mixed with air and then the sludge is allowed to settle.

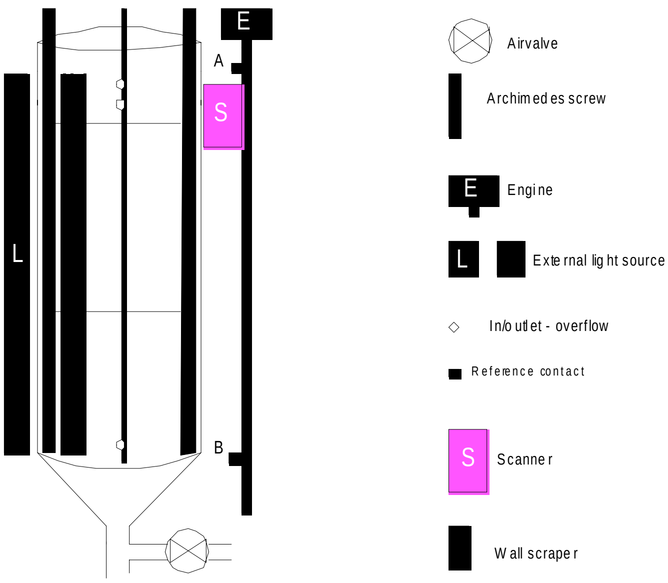

Figure 1
Schematic diagram of the settlometer

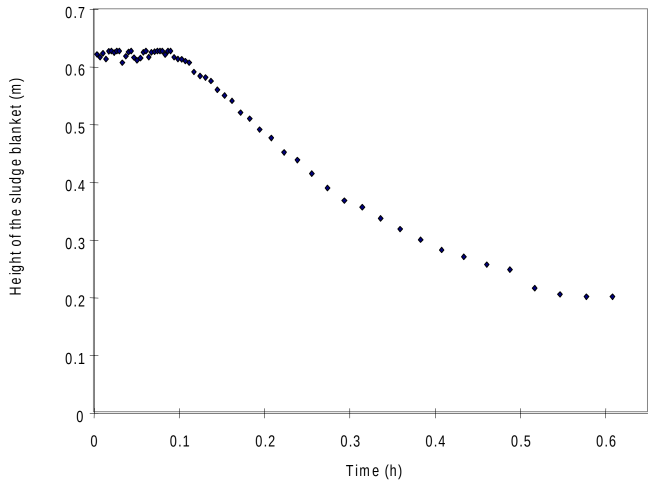

Figure 2
Typical sedimentation curve recorded during the observation at Klagshamn

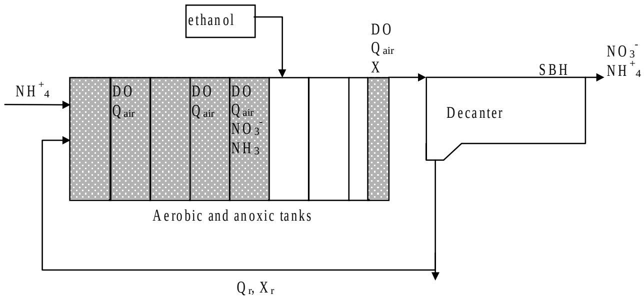

Figure 3
Schematic representation of the Klagshamn wastewater treatment plant. ▢ aerobic zone, ▢ anoxic zone. The most important parameters that are measured on-line are depicted at their measurement place: NH_4^+= ammonium nitrogen (mg/ℓ), DO = dissolved oxygen (mg/ℓ), Q_{air}= air supply to aerobic vessel (m^3/h), NO_3- = nitrate nitrogen (mg/ℓ), X = sludge concentration (kg/m^3), Q= effluent flow (m^3/h), Q_r= recycle flow (m^3/h), X_r = recycle sludge concentration (kg/m^3), SBH = sludge blanket height (m)

TABLE 1
KEY PARAMETERS OF THE KLAGSHAMN PLANT DURING THE OBSERVATION PERIOD

Designed capacity	90 000 persons
Pre-settling tanks	Clarification area: 4*250 m^2, depth: 2.2 m
Activated sludge tanks	2 parallel flow trains each with 8 cells of 275 m^3
Final settler	Clarification area: 8*170 m^2, depth: 3.6 m
Influent flow	580 m^3/h (ranging from 400 till 800 m^3/h)
Sludge return flow	900 m^3/h (fixed)
Ethanol dosage	58 kg COD/h (fixed)
Diluted sludge volume index	205 mℓ/g
Sludge concentration in aeration tank	3.3 g/ℓ

TABLE 2
VARIATION OF SOME IMPORTANT PROCESS VARIABLES: 25 RESPECTIVELY 75 PERCENTILES

Parameter	25 percentile	75 percentile
Conductivity after pre-settling	2.17 mS/cm	246 mS/cm
Influent flow line 2	254 m^3/h	316 m^3/h
NH_4-N after pre-settling	25 mg/ℓ	32 mg/ℓ
NO_3^--N before denitrification	29 mg/ℓ	43 mg/ℓ
Temperature	7.3°C	7.6 °C
Sludge concentration in cell 8	3.2 g/ℓ	3.4 g/ℓ
DO zone 8	1.8 mg/ℓ	2.4 mg/ℓ
Air supply to 8	136 m^3/h	199 m^3/h
NO_3^--N in effluent	7 mg/ℓ	10 mg/ℓ

During the settling test the height of the sludge water interface is monitored by a moving scanner. Background light is provided in an opposite direction to the scanner. The scanner moves downward from the 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 subsequently moves back up to the reference point and comes down again, measuring again the decrease in light intensity. This cycle is repeated until the difference between the beginning of the experiment and the actual time exceeds 35 min. This procedure results in a sedimentation curve (Fig. 2). From this curve, Vs is obtained as the maximum downward slope.

When a new sensor is developed it is important to look to what extent this sensor provides new relevant data. Furthermore it is important to check whether it is possible to link the new observed phenomena to variations in process parameters registered by other on-line sensors. In other words, it must be verified if new cause-effect relationships can be detected. With this purpose in mind, the settlometer was placed at the Klagshamn plant (Malmö Water, Sweden). This full-scale wastewater treatment plant is well suited for this task as it is rich in on-line information (Fig. 3). The plant has, among others, on-line measurements for influent flow, sludge recycle flow, sludge concentration both in the aeration tank and in the return sludge, oxygen concentration, airflow to the basins, temperature, conductivity, NH_4^+-N in both the influent and effluent, NO_x^--N before the denitrification and in the effluent, and measurement of the sludge blanket height in the secondary clarifiers. The key parameters of this plant are summarised in Table 1. In order to give the reader an idea of the range over which the parameters varied during the observation period Table 2 gives the most relevant process variables with their 25 and 75 percentile.

For the further understanding of this paper, it is good to pay special attention to the reaeration tank. In this tank the nitrogen gas produced during denitrification is stripped off and the mixed liquor is returned to aerobic conditions. A more detailed description of this plant can be found in Nyberg et al. (1996).

The settlometer sampled mixed liquor just before the overflow weir in front of the secondary clarifier. At this specific place a sludge concentration probe was present. In the sampling routine, enough time between two samples was provided in order to make sure that the tube between the sampling point and the settlometer was emptied.

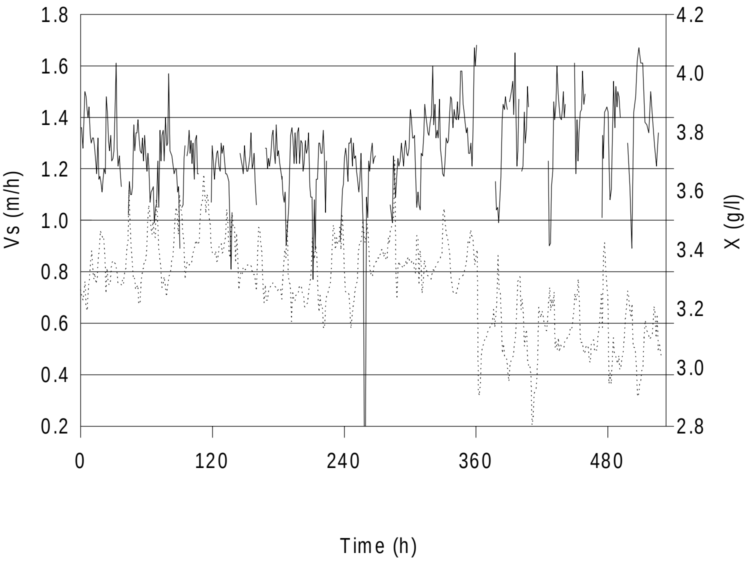

Figure 4
——Vs (m/h) and -------X (g/ℓ) as function of time (h)

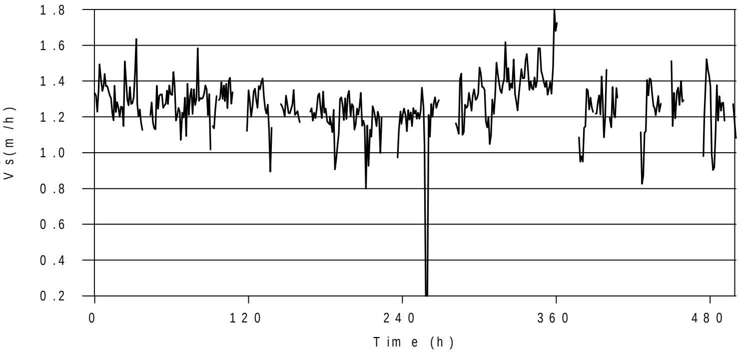

Figure 5
Vs' (m/h) as function of time (h)

Results

During the 23 days observation period, 395 sedimentation curves were recorded. This period was characterised by stable operating conditions and by the absence of rain. As a consequence the sludge blanket remained below the detection level (0.5 m) of the sludge blanket height meter during the whole period. The sludge sedimentation curves were recorded with the stirrer of the settlometer activated. Without stirring, the sludge blanket descended only 5 cm during a 35 min. sedimentation period. With the stirrer on, the sludge front descended around 40 cm. Experience with this device has learned that such a large difference between stirred and non-stirred settling curves is mainly observed with filamentous sludges.

At times 260 h and 261 h no sedimentation was observed at all, and hence, the settling velocity was zero. In Fig. 4 the evolution of Vs and the sludge concentration is given as a function of time. Variations in Vs run up to 30% of the average value and follow a regular diurnal pattern. Rises in Vs are clearly accompanied with decreases in X and vice versa. The influence of the sludge concentration on the settling velocity is well-known and is explicitly recognised in mathematical sedimentation models in which sludge concentration and Vs are negatively correlated (Cho et al., 1993). Changes in X result in changes in Vs while the sludge settling properties as such are not affected. The regular pattern in the sludge concentration is caused by the diurnal variation in the influent flow rate in combination with the constant recirculation flow. This cycle is found in the evolution of Vs.

Consequently, in order to be able to observe the evolution of the settling of the sludge as such, it is necessary to remove the effect of the sludge concentration on the settling velocity. The effect of the sludge concentration on the settling properties is generally described by Eq. (1). Removal of the effect of X therefore requires the knowledge of the Vesilind parameter (n). At time 245 h, off-line sedimentation tests were performed with different initial sludge concentrations. This was done using a 2 m tall column with equal diameter and type of stirrer as found in the settlometer. Samples with different initial sludge concentrations were obtained by diluting the sludge (obtained at the settlometer sampling point) with effluent uniformly ranging from 2.7 to 1.3 g/ℓ. The initial sedimentation velocities were evaluated as a function of the sludge concentration. The Vesilind parameters were determined which resulted in a value of -0.61 m^3/kg for n and a value of 7.5 m/h for k with a correlation coefficient of 0.991. These parameters make it possible to convert the observed Vs to a sedimentation velocity value standardised to the sludge concentration (Vs'). For the standardisation of Vs a sludge concentration of 3.3 g/ℓ was used as this was the average of the sludge concentration during the observation period. In this standardisation scheme, the Vesilind parameter (n = - 0.61) together with the measured X and Vs are brought in Eq. (1). In this way an expression is obtained for k. This expression together with the fixed n yields Eq. (2).

$$Vs = k*e^{X*n} \text{ (Vesilind, 1968)} \quad (1)$$

$$Vs' = Vs*e^{-0.61*(3,3-x)} \quad (2)$$

An analogous procedure with a fixed k yielded an equivalent standardised value. The standardised values are shown in Fig. 5. If the sedimentation properties would have been constant (k and n constant), Vs' should have been constant throughout the observation period. The variations in Vs' are lower compared to the variations observed in Vs (Fig. 4). Still a regular, nearly daily, drop in Vs' could be detected. At most of those instances gas bubbles could be observed at the surface of the sludge flocs. The occasions on which a drop in Vs' was accompanied with the observation of gas bubbles are marked with * on Fig. 5. The absence of sedimentation at 260 and 261 h and the occurrence of rising sludge at 137 and 212 h fit within this recurrent pattern. The detection of rising sludge was concluded from sedimentation curves originating from situation where, after an initial decrease of the sludge blanket (allowing the calculation of Vs), a sudden rise was detected (Fig. 6). In the beginning only a small number of particles rose to the top, but after some time more and more sludge particles accumulated at the top of the settlometer resulting in the detection of a sludge blanket at the top. At the other instances marked in Fig. 5 the bubbles only caused a decrease in sedimentation velocity without causing the sludge to rise.

The formation of nitrogen gas bubbles and the detection of rising sludge in the settlometer is rather remarkable. Henze et al. (1993) stated that in order to obtain rising sludge through endo-

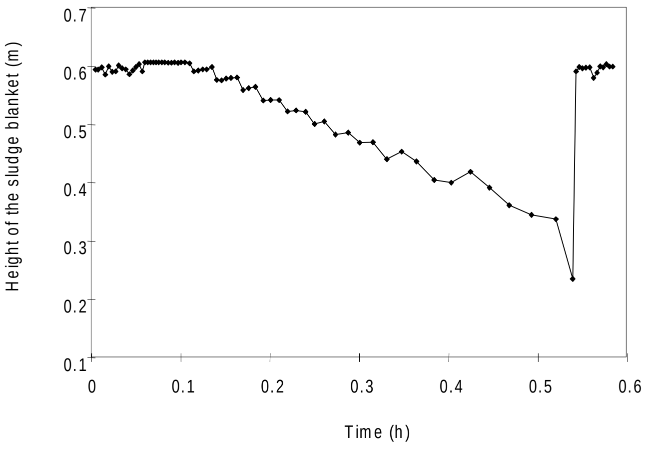

Figure 6
Settling curve of rising sludge at t=137 h

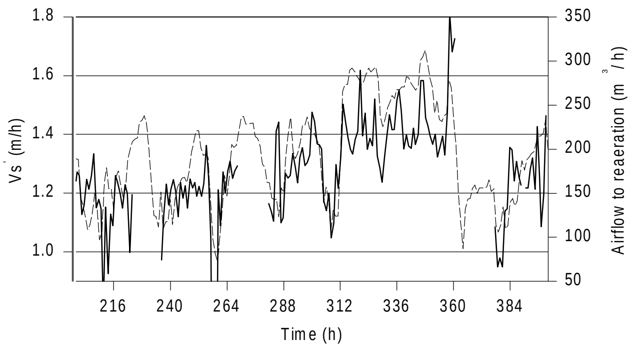

Figure 7
Evolution of Vs' (m/h; ——) and the airflow to the reaeration (m^3/h; ------) as function of time

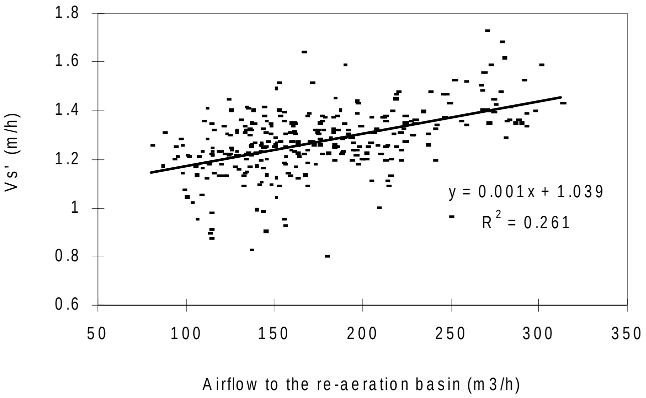

Figure 8
Phase plot of Vs' (m/h) and airflow to the reaeration basin (m^3/h)

genous denitrification, residence times of more than one hour are needed at temperatures of 15 to 20°C. The sedimentation period in the settlometer is limited to 35 min. Furthermore, the water temperature was only 7.5°C on average, which should slow down the denitrification considerably (EPA, 1993). The mixed liquor entering the settlometer had a dissolved oxygen (DO) concentration of around 2.5 mg/ℓ. Hence it can be stated that the reaeration tank is successful in restoring aerobic conditions in the mixed liquor. Horan (1991) stated that the hydraulic residence time in the reaeration tank should be more than 5 to 10 min. As the hydraulic residence time in the actual compartment was more that 10 min., this operational condition is fulfilled. Off-line analysis of the effluent showed a BOD_7 less than 5 mg/ℓ. One argument that is in favour of rising sludge is the fact that more than 6 mg NO_3^--N is present which means that there is enough nitrate present for the formation of nitrogen bubbles (Henze et al., 1993). Also, the hydrostatic pressure in the settlometer is less than the one at the bottom of the full-scale clarifier. This lowers the amount of nitrogen (N_2) that has to be produced before nitrogen bubbles are generated. On the other hand, it must be stressed that in all experiments the hydrostatic pressure in the settlometer was constant, while rising sludge was only observed at very specific instances. In conclusion, it can be stated that the observations made are connected with the system dynamics. In the full-scale clarifier no major onsets of rising sludge could be detected. Nevertheless, in the full-scale effluent, some sludge particles could be observed.

In order to investigate the effect of the reaeration intensity on the sedimentation properties, an experiment was performed on the full-scale plant. The airflow (Q_{air}) was increased during a short experiment to favour the stripping of nitrogen gas and increase the DO concentration in the reaeration zone. Between time 288 h and time 310 h the aeration setpoint was increased from 2 to 2.5 mg/ℓ. Hereafter, between time 310 h and time 358 h the air supply to the reaeration tank was fixed at a high level (260 m^3/h), resulting in oxygen concentrations around 4 mg/ℓ. The evolution of Vs' during this period is given in Fig. 7.

During the period with increased aeration the mean sedimentation velocity was at a higher level and the daily negative peak in Vs' was smaller. (Furthermore, the increase in the airflow was accompanied with an increase in the settling velocity). Due to a technical failure it was unfortunately not possible to monitor the sludge settling characteristics at the moment the aeration intensity was put back to the normal level. When the settlometer was operational again, the sludge sedimentation was again similar to the one observed before the increase in airflow. Consequently, it can be stated that an increase of the aeration intensity in the reaeration cell had a significant and positive effect on the sedimentation characteristics of the sludge.

In order to obtain a better picture of the effect of Q_{air} on Vs' for the whole observation period both variables were put into a phase plot (Fig. 8). High aeration intensities are associated with high Vs' values: a linear relationship between the two can be found with a regression coefficient of 0.26. ANOVA analysis showed that this regression is statistically significant. The low regression coefficient points out that only 26% of the variance of the measurement points is explained by the regression. This was somewhat expected as sludge sedimentation is influenced by many other parameters.

This analysis was repeated with the experimentally observed Vs. An analogous regression was found but now the regression coefficient was only 0.16 which points out that the correction of Vs for X was useful.

Vs' was also plotted against other parameters. Only for the DO concentration in the reaeration zone a statistically significant relationship could be detected. This relationship is of course only a reconfirmation of the correlation with Q_{air}. The other parameters did not vary enough to have a detectable influence on Vs'.

Discussion

The fact that the evolution of Vs follows the evolution in the sludge concentration indicates that the data gathered by the settlometer are meaningful. During the evaluation of the settling properties, it is necessary to remove the effect of the sludge concentration on Vs. This was done by creating a settling velocity standardised for sludge concentration (Vs’) and using this as a tool to reduce the effect of X on the settling velocity. In literature a technique is described which allows the extraction of two parameters from a single batch sedimentation curve (Fitch, 1983). However, this technique requires plotting the height of the compression zone. These data were not available during the observations and would have required a density scanning device (Fitch, 1983). Moreover, the settling curves recorded by the settlometer are discrete and from time to time noisy (e.g. Fig. 6) where Fitch’s approach assumes continuous data with limited noise. Therefore the technique used in the present paper can be seen as a reasonable alternative.

The standardisation technique used in this paper requires that the parameter n of the Vesilind equation is constant. In the present study, the sedimentation properties changed and consequently it cannot be guaranteed that this condition is fulfilled. Therefore Vs’ should be seen as a tool to detect changes in the settling properties.

In situations where the settling properties are constant, n is constant and consequently the resulting Vs’ will be constant. In the present study this was not the case, so it can be stated that real changes in the settling properties were detected.

The settling properties appeared to change on a daily basis. The detection of nitrogen bubbles and the occurrence of rising sludge are explained as being related to denitrification. For the appearance of rising sludge in the short batch settling experiment, different complementary hypotheses can be put forward:

- The reaeration compartment succeeds in making the bulk liquid aerobic but in the sludge flocs anoxic zones remain (Focht and Verstraete, 1977).
- The nitrogen gas is only stripped partially from the sludge flocs. Rising sludge and periods of slow settling sludge occurred at moments when the airflow to the reaeration compartment was low. The formation of nitrogen gas is limited by the added amount of carbon source. During the study the amount of carbon added was constant in time. Hence, at low aeration, the stripping intensity is lower while the nitrogen formation is constant as the latter is limited by the carbon.
- Part of the ethanol is stored in the cells and makes it possible to denitrify faster compared to the strictly endogenic conditions assumed in the calculations of Henze et al. (1993).

The fact that no major onsets of rising sludge were observed in the full-scale plant can be explained by:

- The low loading of the clarifier.
- Rising sludge was only observed in the settlometer for a short period, only one batch sample at a time. This was maybe too short in order to significantly affect the settler.
- At these times when rising sludge was observed, the actual recycle rate was very high (200%).
- The higher hydrostatic pressure at the bottom of the full-scale clarifier compared to the settlometer.

Use of the settlometer at this full-scale wastewater treatment plant revealed its ability to detect short-term variations in settling properties. Further, the usefulness of a reaeration zone is obvious. At the studied wastewater treatment plant, the mixed liquor entering the clarifier is during a short time interval on a nearly daily basis closer to gas saturation than during the rest of the day. The aeration intensity in the reaeration tank seems to have positive effects on the settling properties of the sludge beyond the prevention of rising sludge. Therefore, in systems where the clarifier is critically loaded it may be interesting to increase the aeration intensity in the reaeration zone. For the aeration requirements of a average plant, this would only mean an increase of a few per cent. Furthermore, by doing so a faster shift from anoxic to aerobic conditions would be achieved. This should be beneficial to the control of sludge bulking as it can improve the settling characteristics by means of population shifts (Wanner, 1994).

Conclusion

During a four-week period a new on-line settlometer observed the sludge settling properties at a full-scale activated sludge plant. The data gathered by the sensor are meaningful: the major trends in the settling velocity could be explained by variations in the sludge concentration. After reducing the influence of the sludge concentration the corrected settlometer data revealed that the intrinsic settling capacity of the sludge at the observed plant is affected by the reaeration intensity. When the airflow to the reaeration tank was low the standardised zone settling velocity decreased. These short-term variations would not have been detected without the use of an on-line sensor. Hypotheses were formulated for the observed phenomena which appear related to denitrification. It was further stated that an increase of the aeration intensity in the reaeration zone could be beneficial to the settling properties of the sludge.

Acknowledgments

This research was funded by a scholarship from the Flemish Institute for the Improvement of Scientific-Technological Research in the Industry (IWT). Financial support was also obtained from COST-action 682. Financial support for this work was partially provided by the Belgian National Fund for Scientific Research (F.W.O. Vlaanderen). The authors would further like to thank all the people of Malmö Water and Sewage Works who made the experiments possible.

References

ALBERTSON OE (1992) Clarifier design. In: Randall CW, Barnard JL and Stensel HD (eds.) *Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal*. Technomic Publishing, Lancaster. 185-254.

CATUNDA PFC and VAN HAANDEL AC (1992) Activated sludge settling. Part I: Experimental determination of activated sludge settleability. *Water SA* **18** 165-172.

CHO SH, COLIN F, SARDIN M and PROST C (1993) Settling velocity of activated sludge. *Water Res.* **27** 1237-1242.

DICK RI and VESILIND PA (1969) The sludge volume index - What is it? *J. Water Pollut. Contr. Fed.* **41** 1285-1291.

EPA (1993) *EPA-Manual Nitrogen Control*. Washington, Office of Wastewater Enforcement and Compliance. 311 pp.

FOCHT DD and VERSTRAETE W (1977) Biochemical ecology of nitrification and denitrification. *Adv. Microb. Ecol.* **1** 135-214.

FITCH B (1983) Kynch theory and compression zones. *Am. Inst. Chem. Eng. J.* **29**(6) 940-947.

HENZE M, DUPONT R, GRAU P and DE LA SOTA A (1993) Rising sludge in secondary settlers due to denitrification. *Water Res.* **27** 231-236.

HORAN NJ (1991) *Biological Wastewater Treatment Systems: Theory and Operation*. Wiley and Sons Ltd, West Sussex. 310 pp.

NYBERG U, ANDERSSON B and ASPEGREN H (1996) Experiences with on-line measurements at a wastewater treatment plant for extended nitrogen removal. *Water Sci. Technol.* **33**(1) 175-182.

REID JMC and NASON RB (1993) Automatic monitoring of activated sludge settling characteristics and plant control applications. *J. Inst. Water Environ. Mananage*. **7** 636-645.

VANROLLEGHEM PA, VAN DER SCHUEREN D, KRIKILION G, GRIJSPEERDT K, WILLEMS P and VERSTRAETE W (1996) On-line quantification of settling properties with In-Sensor-Experiments in an automated settlometer. *Water Sci. Technol.* ***33****(1) 37-51.*

VESILIND PA (1968) Theoretical considerations: Design of prototype thickeners from batch settling tests. *Water and Sewage Works.* 115-302.

WANNER J (1994) *Activated Sludge Bulking and Foaming Control*. Technomic Publishing, Basel. 327 pp.

ZITA A and HERMANSSON M (1994) Effects of ionic strength on bacterial adhesion and stability of flocs in wastewater activated sludge system. *Appl. Environ. Microbiol.* (Sept.) 3041-3048.