# scale waste water treatment plant

Alexis Vanderhasselt*, Henrik Aspegren°, Peter Vanrolleghem** & Willy Verstraete*

** Laboratory of Microbial Ecology, University Gent, Coupure Links 653, B-9000 Gent, Belgium*
*° Malmö Water and Sewage works, , S-20580 Malmö, Sweden*
*** BIOMATH Department, University Gent, Coupure Links 653, B-9000 Gent, Belgium*

## ABSTRACT

An on-line settlometer has been presented which automatically records sludge settling curves. From this curve the sensor deduces the initial hindered settling velocity (Vs). In order to evaluate the information gathered by the sensor, the instrument was used at an information rich full scale waste water treatment plant (Klagshamn, Sweden). This plant consists of a primary sedimentation tank followed by a single sludge post denitrification activated sludge system operated with an external carbon source. With the sensor a diurnal pattern could be detected in Vs. This pattern was mainly caused by the diurnal change in the sludge concentration. Using the Vesilind equation it was possible to standardise Vs for the sludge concentration. The variation in the standardised Vs' was less than for the experimental Vs. Still it was possible to detect a decrease in Vs' on nearly daily basis. At two of these instances rising sludge was detected in the settlometer during the 35 minutes 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 oxic 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. In the observed post-denitrification plant a positive correlation could be found between the airflow to the re-aeration tank and the sedimentation velocity.

## KEYWORDS

Activated sludge, Clarifier, On-line Monitoring, Settling, Waste Water Treatment

## INTRODUCTION

Within the 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, 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. Recently, 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 & Hermansson, 1994). The wastewater composition can change within a matter of hours, so their effect on the sludge settling can be much faster than in the case of population shifts.

Sedimentation characteristics are normally determined manually using batch settling tests (Catunda & 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 in-lab experiments as the SVI have often been criticised (Dick & Vesilind, 1969) and the settling conditions can be important and settling properties are often evaluated at reduced sludge concentrations.

## METHODS

At the University of Gent (Belgium) a settlometer (now commercially available from AppliTek, Belgium) was developed in which sludge settling characteristics are determined in a very simple way (Fig. 1) (Vanrolleghem *et al*., 1996). The core of this apparatus is formed by a 10 l downscaled Pyrex decanter equipped with a stirrer (1 rpm). Grijspeerdt *et al*. (1996) have demonstrated that the evolution of the sludge blanket height in this decanter is representative for the one in a full scale circular settler when the flow to and from the downscaled version were proportionally reduced to his surface. Within the sensor this 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.

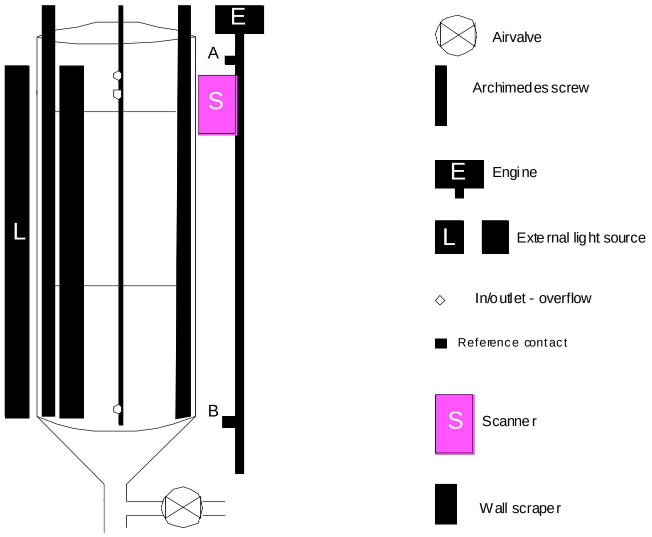

*Fig. 1. Schematic diagram of the settlometer*

During the settling test the height of the sludge water interface is monitored by a moving scanner. Opposite to the scanner background light is provided. 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 now moves back up to the reference point and comes down again, looking for the decrease in light intensity. This cycle is repeated until the difference between the beginning of the experiment and the actual time exceeds an operator predetermined value (typically 35 minutes). This procedure results in a sedimentation curve (Fig. 2). From this curve the zone settling velocity (Vs) is obtained as the maximum downward slope.

When a new sensor is developed it is important to look to what extent this sensor gives 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. Or, in other words, can new cause-effect relationships be detected. With this purpose the settlometer was placed at the Klagshamn plant (Malmö Water, Sweden). This full scale waste water 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 influent, $NH_4$-N in effluent, $NO_x$-N before the denitrification, $NO_x$-N in effluent and measurement of the sludge blanket height in the secondary clarifiers. The key parameters of this plant are summarised in Table 1. For the further understanding of the paper it is good to pay special attention to the re-aeration tank.

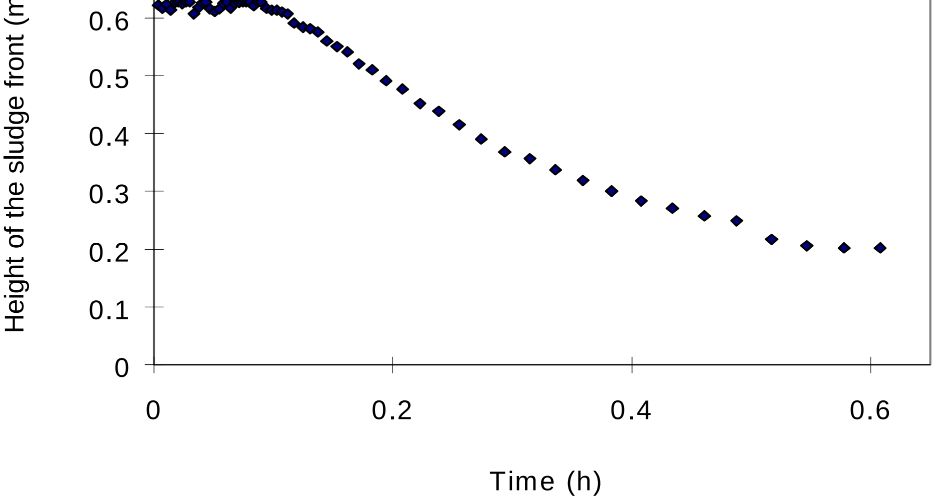

*Fig. 2. Typical sedimentation curve recorded during the observation at Klagshamn*

In this tank the nitrogen gas produced during the denitrification is stripped off and the mixed liquor is brought again under oxic conditions. A more detailed description of this plant can be found in Nyberg *et al*. (1996). The settlometer sampled mixed liquor right before the overflow weir in front of the secondary clarifier. At this specific place a sludge concentration probe was present. By sampling there the settling properties of the sludge that goes to the clarifier are monitored. In the sampling routine enough time was provided in order to make sure that the tube between the sample point and the settlometer was emptied between two samples.

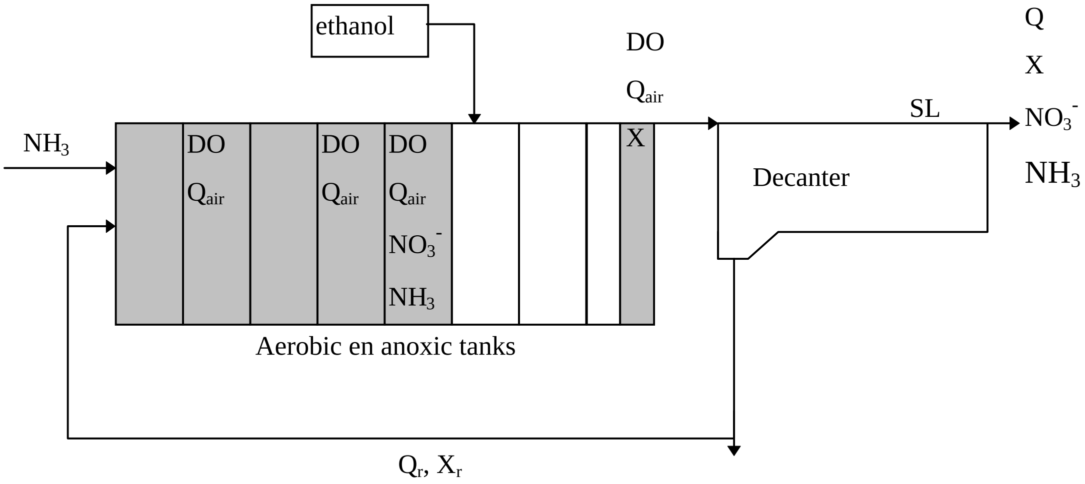

*Figure 3. Schematic representation of the Klagshamn waste water treatment plant. ▨aerobic zone, ☐anoxic zone. The most important parameters that are measured on-line are depicted at their measurement place: $NH_3$= ammonical nitrogen (mg/L), DO= dissolved oxygen (mg/L), $Q_{air}$= air supply to aerobic vessel ($m^3/h$), $NO_3^-$= nitrate nitrogen (mg/L), X= sludge concentration (g/L), Q= influentflow ($m^3/h$), $Q_r$= recirculation flow ($m^3/h$), $X_r$= recycle sludge concentration (g/L), SL= height of the sludge level (m)*

TABLE 1. Key parameters of the Klagsham 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 |

During the observation period of 23 days, 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 level remained under 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 on. Without activation of the stirrer the sludge blanket descended only 5 cm during a 35 minute sedimentation period. With the stirrer on the sludge front descended around 40 cm. The experience learned that such big difference between stirred and non stirred settling curves is mainly observed with filamentous sludge's.

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 . At 260 h and 261 h no sedimentation was observed at all, and hence, the settling velocity was zero.

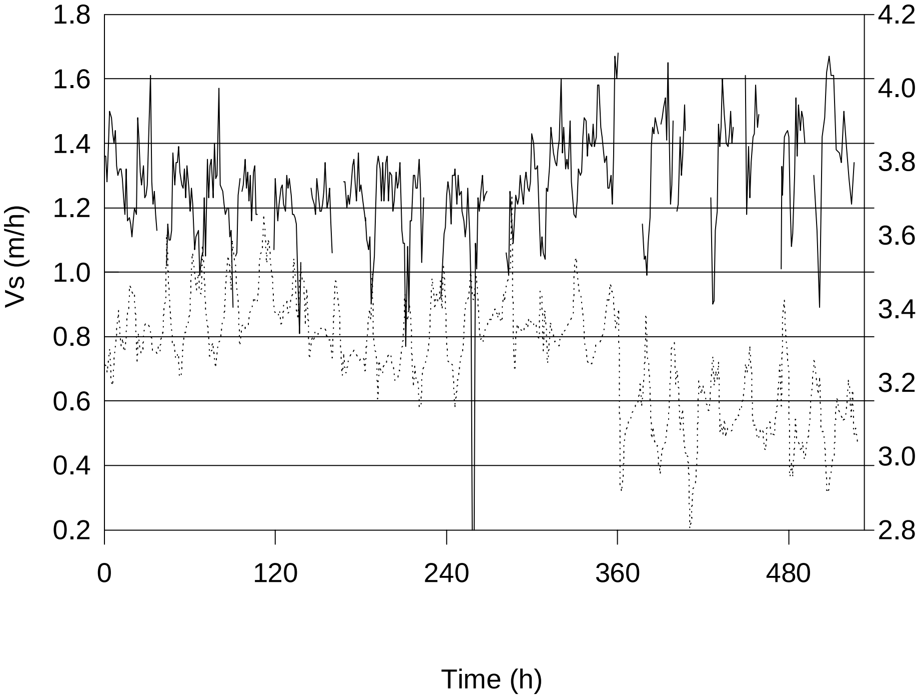

*Fig. 4. ——Vs (m/h) and ----X (g/L) in function of time (h)*

Rises in Vs are clearly accompanied with decreases in X and vise 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.

At time 245 h off-line sedimentation tests were performed with different initial sludge concentrations. This was done using a 2 meter 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 sample point) in five steps with effluent from 2.7 till 1.3 g/l. The initial sedimentation velocities were evaluated as a function of the sludge concentration. The parameters from the classical Vesilind settling velocity function (Eq. 1) were determined which resulted in a value of -0.61 $m^3/kg$ for n and a value of 7.5 m/h for $V_0$ with a correlation coefficient of 0.991. These parameters make it possible to convert the observed Vs to a sedimentation velocity value standardised for 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

X and Vs are filled in equation 1. In this way an expression is obtained for $V_0$. This expression together with the fixed n yields equation 2.

$$Vs = V_0 * e^{X*n} \text{ (Vesilind, 1968)} \qquad (1)$$

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

An analogous procedure with a fixed $V_0$ yielded an equivalent standardised value. The standardised values are shown into Fig. 5. Clearly the variations in Vs’ are lower compared to the variations observed in Vs (Fig.4). Still a regular (almost daily) peak reduction in Vs’ could be detected. 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.

At 137 h and 212 h rising sludge was detected in the settlometer. This was concluded from sedimentation curves in which after an initial decrease of the sludge blanket (allowing the calculation of Vs) a rise was detected (Fig. 6 ). In the beginning a small amount of particles rose to the top, 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. Gas bubbles could be detected at the sludge surface. Analogous bubbles appeared also at the surface of the sludge flocs on moments when the sludge sedimentation velocity was low. The occasions on which a reduction in Vs’ was accompanied with the observation of gas bubbles are marked with * on Fig. 5. At these moments the denitrification only caused a decrease in sedimentation velocity without causing the sludge rise. The detection of rising sludge in the settlometer and the formation of nitrogen gas bubbles is rather remarkable. Henze *et al.* (1993) stated that in order to obtain rising sludge through endogenous denitrification residence times of over an hour are needed at temperatures of 15-20 °C. The sedimentation period in the settlometer is limited to 35 minutes. Further, the water temperature was only 7,5 °C on average, which should slow down the denitrification considerably (EPA, 1993).

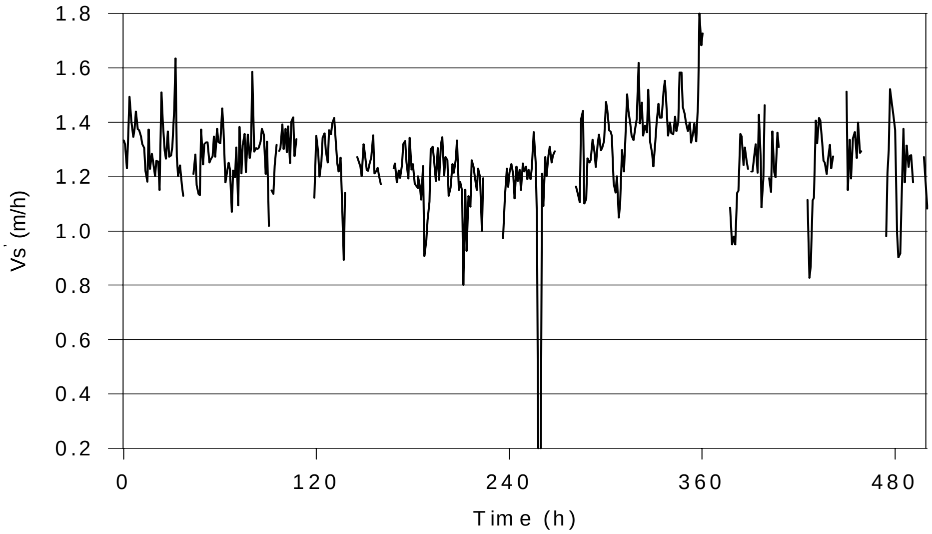

Fig. 5. *Vs' (m/h) as a function of time (h )*

The mixed liquor entering the settlometer had a dissolved oxygen concentration of around 2,5 mg/l so it can be stated that the re-aeration tank is successful in restoring oxic conditions in the mixed liquor. Horan (1991) stated that the hydraulic residence time in the re-aeration tank should be larger than 5 to 10 minutes. As the hydraulic residence time in the actual compartment was more that 10 minutes, 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 so 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 in the bottom of the full scale clarifier what lowers the amount of nitrogen ($N_2$) that has to be produced before

Still, sometimes sludge particles could be observed in the effluent.

In order to counteract the observed rising sludge it was decided to increase the airflow to the re-aeration compartment during a short experiment. This should favour the stripping of nitrogen gas and increase the dissolved oxygen concentration zone. Between 288 h and 310 h the aeration setpoint was increased from 2 to 2.5 mg/l. In the next two days (310-358h) the air supply to the re-aeration 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.

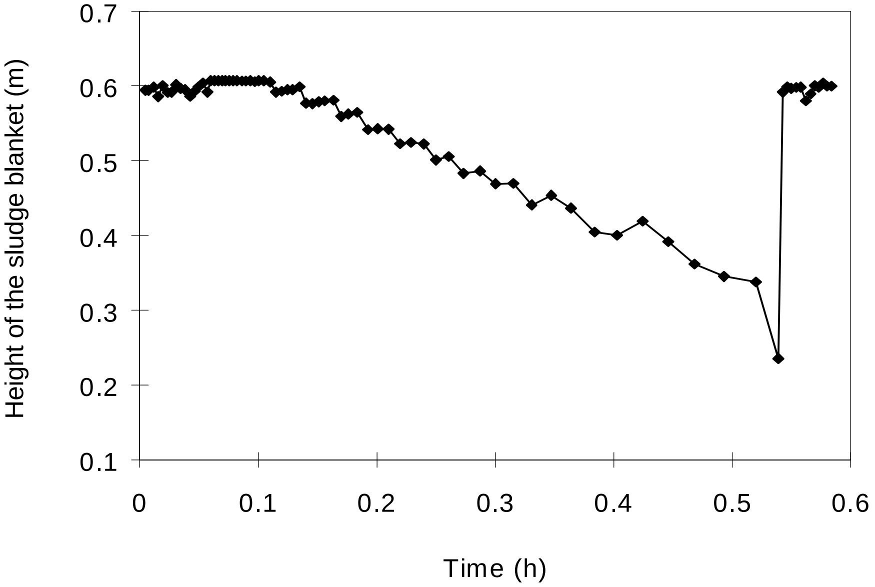

Fig. 6. *Settling curve of rising sludge at t=137 h*

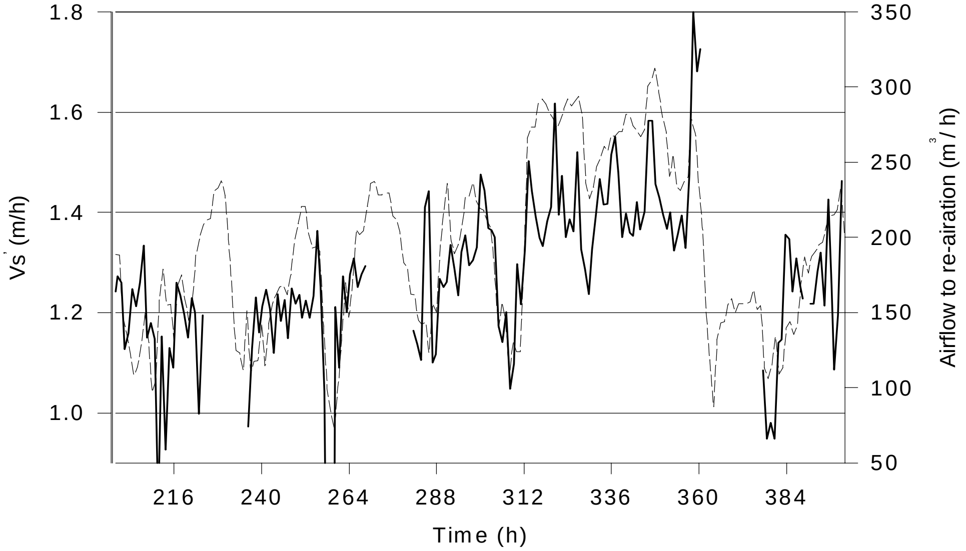

Fig. 7. *Evolution of Vs$^{'}$ (m/h)* —— *and the airflow to the re-aeration (m$^3$/h)* - - - - *as a function of time*

During the period with increased aeration the mean sedimentation velocity was at a higher level and the daily decrease 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 on the normal level. When the settlometer was airflow. So it is genuine to state that an increase of the aeration intensity in the re-aeration cell had a positive effect on the sedimentation characteristics of the sludge.

In order to obtain a clear picture of the effect of $Q_{air}$ on the 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 : between both a linear relationship 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.

Next, Vs' was also put into a phase plot with other parameters. Only for the dissolved oxygen concentration in the re-aeration 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 didn't vary enough to have a detectable influence on Vs'. In order to give the reader an idea of the range in which the parameters varied during the observation period in Table 2 the most relevant process variables are given with their 25 and 75 percentile.

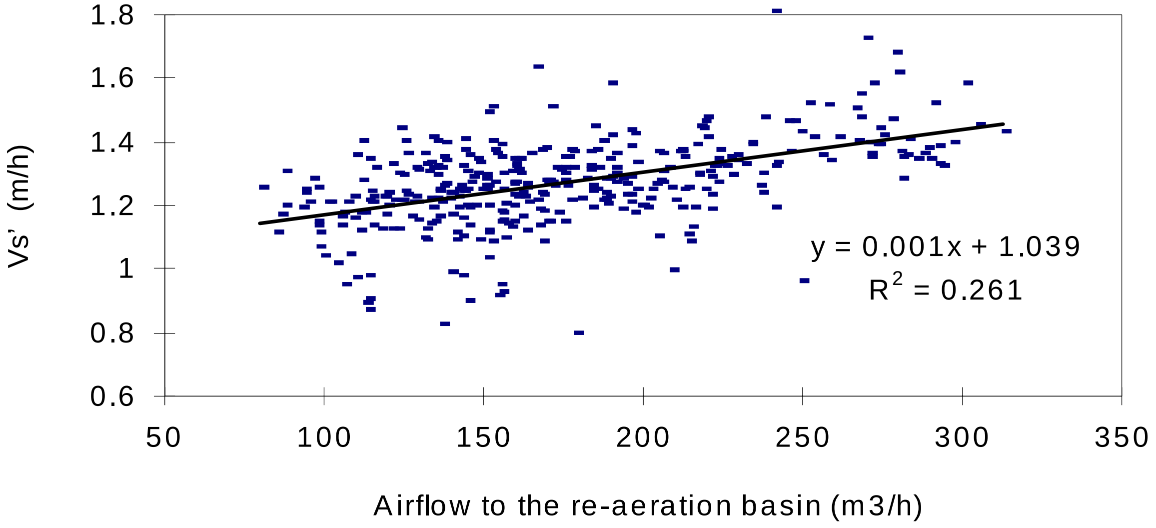

Fig. 8.Phase diagram of *Vs' (m/h) and the airflow to the re-aeration basin (m³/h)*

TABLE 2 Variation on the important process variables: 25 respectively 75 percentiles

| Parameter | 25 percentile | 75 percentile |
|---|---|---|
| Conductivity after pre settling | 2.17 mS/cm | 2,46 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 |

## DISCUSSION

gathered by the settlometer are meaningful. During most of the observed day a decrease of the settling properties of the sludge was noticed that could not be explained by changes in the sludge concentration. The detection of nitrogen bubbles and the occurrence of rising sludge allows to explain these lower velocities as being caused by denitrification.

For the appearance of rising sludge in the short settling period different complementary hypotheses can be put forward.

- The re-aeration compartment succeeds in making the bulk liquid oxic but in the sludge flocs anoxic zones remain. Focht & Verstraete (1977) mention that within sludge floc anoxic zones can be present while the bulk liquid is oxic.
- 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 re-aeration compartment was low. As the formation of nitrogen gas is limited by the added amount of carbon source its formation is constant in time.
- Part of the ethanol is stored in the cells and makes it possible to denitrify faster than under strictly endogenic conditions.

The fact that no major rising sludge was observed in the full scale plant can be explained by the relatively high recirculation ratio (150 %) which kept the sludge blanket and thus the sludge residence time in the settler low. Further it has to be stressed that the rising sludge was only detected for a very limited time interval (no more than two samples at a time). This was maybe too short in order to significantly affect the settler.

However, the fact that within the current re-aeration strategy (fixed set-point) the settling capacity of the sludge is reduced at certain moments, should not be ignored. From an operational point of view it would have been interesting to test this effect under severe circumstances as rain events. Fortunately for the existing system the airflow to the re-aeration basin will be high when the hydraulic loading of the plant is high due to the set-point control of the dissolved oxygen. An other solution may be to put the airflow to that vessel at a constant high status. This would mean that the average aeration intensity for this vessel would be increased with around 50 %. For the aeration requirements of the whole plant this would only mean a few percentages and reduce the need for an oxygen electrode and control loop. Further, by doing so a faster shift from anoxic to oxic conditions would be achieved. This should be beneficial to the control of sludge bulking as it can in the long run improve the settling characteristics by population shifts (Wanner, 1994).

## CONCLUSIONS

During a four weeks period a new on-line settlometer observed the 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 the variations in the sludge concentration. After reducing the influence of the sludge concentration the settlometer data revealed that the intrinsic settling capacity of the sludge at the observed plant is affected by the re-aeration intensity. When the airflow to the re-aeration tank was low the Vs' was reduced. 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 to be denitrification related.

## ACKNOWLEDGMENTS

This research has been 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 (N.F.W.O.) through research grant G.0102.970. The authors would further like to thank all the people of Malmö Water and Sewage works who made the experiments possible.

# REFERENCES

Albertson, O. E. (1992). Clarifier design. In: *Design and retrofit of wastewater treatment plants for biological nutrient removal*. Eds. Randall, C. W., Barnard, J. L. & Stensel, H. D. Technomic Publishing, Lancaster, 185-254.

Catunda P.F.C. and van Haandel A.C. (1992) Activated sludge settling. Part I: Experimental determination of activated sludge settleability. *Water SA*, **18**, 165-172.

Cho, S. H., Colin, F., Sardin, M. & Prost, C. (1993). Settling velocity of activated sludge. Water Research, **27**, 1237-1242.

Dick, R.I. & Vesilind, P.A. (1969). The sludeg voulme index- What is it ? *Journal Water Pollution and Control Federation*, **41**, 1285-1291.

EPA. (1993). *EPA-Manual Nitrogen Control*. Washington, office of wastewater enforcement and compliance, 311p.

Focht, D. D. & Verstraete, W. (1977). Biochemical ecology of nitrification and denitrification. *Advances in Microbial Ecology*, **1**, 135-214.

Grijspeerdt, K. Bogaert, H. & Verstraete, W. (1996). Design and verification of a model secondary clarifier for activated sludge. *Journal of Chemical Technology and Biotechnology*, **67**, 404-412.

Henze, M., Dupont, R., Grau, P. & De La Sota, A. (1993). Rising sludge in secondary settlers due to denitrification. *Water Research*, **27**, 231-236.

Horan, N.J. (1991). *Biological wastewater treatment systems : theory and operation*. Wiley & Sons Ltd, West Sussex, p310.

Nyberg, U., Andersson, B. & Aspegren, H. (1996). Experiences with on-line measurements at a wastewater treatment plant for extended nitrogen removal. *Water Science and Technology*, **33**(1), 175-182.

Reid, J. M. C. & Nason, R. B. (1993). Automatic monitoring of activated sludge settling characteristics and plant control applications. *Journal of the Institution of Water and En-vironmental Management*, **7**, 636-645.

Vanrolleghem P.A., 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 Science and Technology*, **33**(1), 37-51.

Vesilind, P. A. (1968). Theoretical considerations: Design of prototype thickeners from batch settling tests. *Water & Sewage Works*, 115-302.

Wanner, J. (1994). *Activated sludge bulking and foaming control*. Technomic Publishing, Basel, 327p.

Zita, A. & Hermansson, M. (1994). Effects of ionic strength on bacterial adhesion and stability of flocs in wastewater activated sludge system. *Applied and Environmental Microbiology*, **9**, 1994, 3041-3048.