ON-LINE CONTROL OF POLYMER ADDITION TO PREVENT MASSIVE SLUDGE WASHOUT

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ABSTRACT: An experimental method that quantifies the effect of polymer dosing on sludge settling characteristics is proposed. This method consists of recording batch settling curves at a grid of sludge and polymer concentrations. The effect of the polymer was found to depend on the mixing time between the dosing of the polymer and the start of the batch sedimentation. The recorded effects could be successfully implemented in a 1D dynamic settler model. From the literature it was concluded that keeping the sludge blanket below a certain critical height is an effective way of controlling the effluent suspended solids. From a model-based analysis this strategy appeared to be sound. Different control strategies using, respectively, the sludge blanket height [feedback (FB)], the hydraulic loading [feedforward (FF)], the solids loading (FF), or the sludge volume loading (FF) were tested for their ability to keep the sludge blanket below the critical height. The control strategy based on the hydraulic loading was the least efficient with respect to minimizing polymer dosage. The others appeared equally effective provided that they were properly tuned. Using the excess of the critical sludge blanket height as a measure of effectiveness, strategies based on more than one measured variable appeared to be less sensitive to suboptimal tuning.

INTRODUCTION

Dynamic control of activated sludge plants should try to minimize the concentration of suspended solids in the effluent X_{eff}. Control strategies aimed at minimizing effluent suspended solids can be developed based on different measured variables such as the effluent suspended solids concentration itself. Because feedback control strategies solely based on X_{eff} can only become active once there is an increase in X_{eff}, they will always lag one step behind the dynamics of the clarifier. For this reason, Müller and Krauth (1998) identified the effluent suspended solids concentration as an inadequate variable for control purposes. Alternatively, control strategies can be based on measurements of the solid flux to the settler (product of flow to the clarifier and sludge concentration), the sludge volume loading (product of flow to the clarifier and sludge volume, Nielsen et al. 1996), or keeping the sludge blanket below a certain critical height. The latter strategy was found to be sound by several authors (''Hydraulische'' 1981a; Deininger 1994; Nyberg et al. 1996; Müller and Krauth 1998). These investigators learned, from full-scale observations, that effluent suspended solids concentration only rose significantly when the sludge blanket exceeded a critical level. However, the location of this critical sludge blanket level seems to depend on the specific clarifier. Critical blanket levels ranged from 0.2 m (''Hydraulische'' 1981a) to 2 m below the water surface (Müller and Krauth 1998). In the review of literature, Ekama et al. (1997) concluded that, in general, a distance of 1–1.5 m from the water surface should be safe. Still, care should be taken because the effective safe level for a clarifier could be significantly different and would vary depending on the hydraulic conditions.

The number of manipulated variables that can be used as a control action is quite limited and can be identified into two categories. First, a number of control actions exist that affect the sludge flux from, or to, the clarifier. In this category fall: the sludge waste flow rate, the sludge recycle rate, the use of a step feed strategy, and limitation of the influent flow to the wastewater treatment plant. Limitations on the use of these strategies are outlined here. The sludge waste flow rate can only be manipulated between narrow boundaries, as its use will affect the biologic process performance. Its use is further limited because the effect on the settler is quite slow (Olsson 1977). The use of the recycle flow rate has some potential as a manipulated variable, except that contradictory opinions on how it should be varied can be found in literature. Andrews et al. (1976) reported that control of the recycle rate should be done in a manner proportional to the plant's influent flow rate. However, Albertson (1992) stated that the control of the recycle should never be proportional, and Tsai et al. (1996) recommended inverse proportional control. Furthermore, Olsson and Jeppsson (1994) indicate that the control effect of the recycle ratio on clarifier performance is minimal. The use of step feed is an interesting and useful alternative because it decreases the loading rate to the clarifier, but its use requires that the plant is designed for it. Also, the use of changes in step feed has a rather slow action, with a time constant of the same order as the retention time of the aeration basin, thus limiting its application as a fast control strategy. Finally, while limiting the plant's influent flow is the most stringent control action, it is only possible if appropriate capacity for hydraulic buffering is present, or if an occasional discharge of unpurified water is acceptable (Nyberg et al. 1996).

A second mode of control of settler performance is the dosage of additives such as organic polymers (Vanderhasselt and Verstraete 1999), which enhance the settling properties of the sludge. While the dosage of polymer does not affect the sludge flux to the settler, it changes the settling properties of the sludge entering the settler, thus increasing the effective capacity of the clarifier. Provided an appropriate additive is present, this mode of control is an interesting option because it typically provides a fast action and can be implemented at essentially any kind of wastewater treatment plant. A polymer was successfully used to prevent the washout of sludge during wet weather conditions (''Overbelasting'' 1981b). Other reports of

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successful use of polymer addition to tackle sludge settling problems can be found in Lumely et al. (1988) and Shao et al. (1997). Typically, polymer addition is operator controlled and polymer use is almost constant at the maximum rate required to maintain effective sedimentation.

For the present paper, an industrial wastewater treatment plant was studied where polymer (Zetag 88N) is currently added continuously at the overflow weir of the aeration tank, according to the operator's experience. On average, a polymer concentration of 13 ppm is used to prevent massive washout of sludge flocs. At this site, the possibilities for settler control strategies based on influent flow restriction, recycle flow rate, or step feed are limited.

This study investigates the potential of using automated control of polymer addition to reduce polymer use while maintaining effective clarifier performance. Several settler control strategies based on different measured variables and polymer dosing can be formulated. Testing all of these strategies in full-scale would be quite expensive, as it entails not only the placing of all the sensors involved, but also their implementation in a control loop and empirical tuning of the control laws. As the operation of the full-scale installation can never be brought into jeopardy, experimental degrees of freedom are rather limited. Further, it would be difficult to subject the different strategies to the same disturbances. Therefore, evaluation of the performance of these control strategies in a simulation environment was considered as a good alternative. In the simulation environment, all strategies were subjected to the same hydraulic and solids loading. For this, a 2,500-h full-scale data set of on-line effluent flow measurements and off-line sludge concentration measurements in the aeration basin were used. The recycle flow was kept constant during this period at 60 m^3/h. The influent flow rate to the (model) clarifier was calculated as the sum of the recycle and the effluent flow rate. This approach was chosen as it generates a sludge flux to the settler, which is the same for all strategies. Alternatively, one could simulate the whole treatment system and consequently generate a sludge flux from an aeration tank. However, such an approach does not guarantee that all strategies will be subjected to the same sludge fluxes, e.g., when a strategy results in a massive washout of sludge, then the sludge flux to the settler will be reduced in the time period following the washout.

The most accurate predictions of effluent suspended solids from clarifiers are made using 2D and 3D hydrodynamic models (Krebs 1995). However, due to their complexity and the large amount of data needed for their calibration, such models are not well suited for on-line control applications. 1D models have less predictive accuracy for suspended solids, but can adequately describe the evolution of the sludge blanket height (SBH). It was already mentioned that a massive escape of sludge occurred only when the sludge blanket rose above a critical level. Therefore, within this context, 1D modeling can be considered useful in the study of control actions aimed at preventing the massive washout of sludge.

METHODS

Model Structure

A 1D settler model was constructed in the simulation environment West++ (available from Hemmis, Kortrijk, Belgium) and consisted of 10 horizontal layers with the clarifier feed in layer 4 (counted from top). For the calculation of the settling fluxes, the traditional Vesilind (1968) model was selected. This model is used frequently in the literature (Ozinsky and Ekama, 1995; Jeppsson 1996) to compute the settling velocity *Vs*

$$Vs = ke^{-nX} \quad (1)$$

where k = Vesilind settling parameter (m/h); n = Vesilind settling parameter (m^3/kg); and X = sludge concentration (kg/m^3).

When changing the dosage of polymer dynamically, by a control loop, sludge treated with a particular polymer concentration, and hence, with different settling properties, is flowing into the clarifier. In the model the variation in settling properties was modeled as follows. To be effective, the polymer has to be situated in or on the sludge flocs. Therefore, active polymer is attached to the solids and follows its propagation. Consequently, the concentration of polymer in a certain layer is calculated by a mass balance of polymer based on the fluxes of polymer that are taken proportional to the sludge fluxes. The settling velocity of the solids and accompanying polymer is calculated for every layer based on the local polymer concentration and sludge concentration.

In general, it is not known how flocs treated with different amounts of polymer interact. In zone settling and compaction conditions, it is fair to say that different types of flocs will descend together. Some preliminary experiments were carried out (data not shown) that revealed that sludge treated at 5-ppm polymer concentration settled in the same way as a 50% mixture of sludge treated at 0 and 10 ppm. This finding justifies the way in which the effect of the polymer in the different layers is calculated.

As the polymer provides bridging between sludge flocs (Wen et al. 1997), it is possible that the addition of polymer would affect the amount of nonsettleable particles in the sludge. Therefore, the option was taken to include this effect of the polymer in the model, provided that a substantial effect of the polymer could be demonstrated.

In practice, a stirred sludge volume (SSV) measurement is only available every 45 min. Polymer dosing pumps are not manipulated continuously to avoid superfluous wear and tear. Hence, in the model the pump's flow rate adjustment is made with the same frequency as the SSV sampling (every 45 min). This frequency was used for all of the control laws tested. In this way, a more realistic behavior is modeled.

Experimental Setup

Traditionally, the Vesilind settling parameters are determined by measuring the settling velocity at different sludge concentrations. In this way the sludge fluxes can be calculated at different sludge concentrations. To evaluate the effect of the polymer, it was necessary to determine the settling velocity not only as function of the sludge concentration but also as function of the polymer concentration. It was decided to record the settling curves at six more or less equidistant sludge concentrations, ranging between a sludge concentration 20% lower than the settler influent to a concentration situated 20% higher than the sludge recycle concentration. Seven equidistant polymer concentrations were chosen, ranging between 0 and 18 ppm. Such high dosages were necessary to obtain polymer/sludge ratios equal to those found at the clarifier inlet in the high sludge concentration range of the experiments. The settling curves were recorded with the recently developed Settlometer [Vanrolleghem et al. (1996), provided by Applitek nv, Deinze, Belgium]. This device automatically provides the initial settling velocity *Vs* and the SSV as output of a batch settling experiment. Sludge is pumped into the settling column that has a height of 70 cm and a diameter of 14 cm, and is equipped with a stirrer (0.33 rpm). Before starting the batch sedimentation, a background scan is performed, taking a total of 2.5 min. During this period, sludge is homogenized by a limited injection of air, and concomitantly, polymer is dosed.

The whole experimental procedure was repeated twice: Once with polymer dosing 120 s before the end of the background scan, and once with the dosing 20 s before the end of the background scan. This was performed to check whether the mixing time would have a significant impact. In one procedure, a total of 42 sedimentation curves had to be recorded. As the experimental procedure required the presence of an operator, only 10 sedimentation curves could be recorded daily. Hence, the experiment was spread over several days. To limit the eventual effect of a change in the sludge properties during this period, the sequence of the different sludge-polymer objects was randomized. Every day, sludge was collected and aerated overnight before use the following day. In this way, sludge with stable sedimentation characteristics was obtained (Vanderhasselt and Verstraete 1999). The storage and settling experiments were performed at ambient temperature.

To evaluate the effect of the polymer on the nonsettleable fraction, sludge was collected at the end of the aeration basin and put into seven different 1-L graduated cylinders. Polymer aliquots were added to each cylinder, resulting in equidistant polymer concentrations ranging between 0 and 18 ppm. The suspensions were mixed and allowed to settle. After 1 h of sedimentation, a supernatant sample was taken and analyzed (*Standard* 1992).

RESULTS

Experimental Results

Effect of Polymer Dose, Total Suspended Solids (TSS), and Mixing Time on Vs and SSV

The results of the experimental procedure with 120 and 20 s of mixing time are summarized in Figs. 1 and 2, respectively. Clearly, the polymer is able to increase *Vs* and to reduce SSV. However, comparison of Figs. 1 and 2 shows that the polymer is more effective when the mixing time, between the addition of polymer and the start of the sedimentation period, is limited to 20 s. It was observed macroscopically, that an increased duration of excessive mechanical mixing reduced the flocculation effect brought on by the polymer. Hence, shear is put forward as the main cause for reduction of the beneficial effect of the polymer. It can be concluded from this that dosing of the polymer should be as close to the settler as possible. Biodegradation of the additive is certainly not occurring because additional experiments showed that the addition of polymer did not increase BOD (data not shown).

In the full-scale system used as the specific case for this study, the polymer is dosed at the outlet of the aeration tank. This point is separated from the clarifier inlet structure by approximately 1 min of turbulent flow (Reynolds number $2 \times 10^5 >> 3{,}000$) in a pipe. Therefore, moving the dosing point to the clarifier inlet structure is expected to improve the efficiency of the polymer. Although the effect of doing so was not studied here, all simulations were based on assuming the polymer addition on the settling behavior of the sludge was that observed for a dosage at 20 s preceding sedimentation. We have recommended that in the future the dosing point of the full-scale system should be moved closer to the clarifier inlet structure.

In view of the considerable effect of the mixing interval on the polymer's efficiency, one may be concerned about changes in the effect of the polymer while sludge resides in the settler. However, this should not be of concern because the mixing intensity in a clarifier is low and is substantially less than in the present settling column. Therefore, it was postulated that as a first approximation, the effect of the polymer could be considered constant throughout the settler.

Using nonlinear regression (SPSS 7.5, SPSS, Inc., Chicago, Ill.), relationships were sought between *Vs* and SSV, and the sludge *X* and polymer concentration *P*. With the data displayed in Fig. 2, the following regressions were obtained:

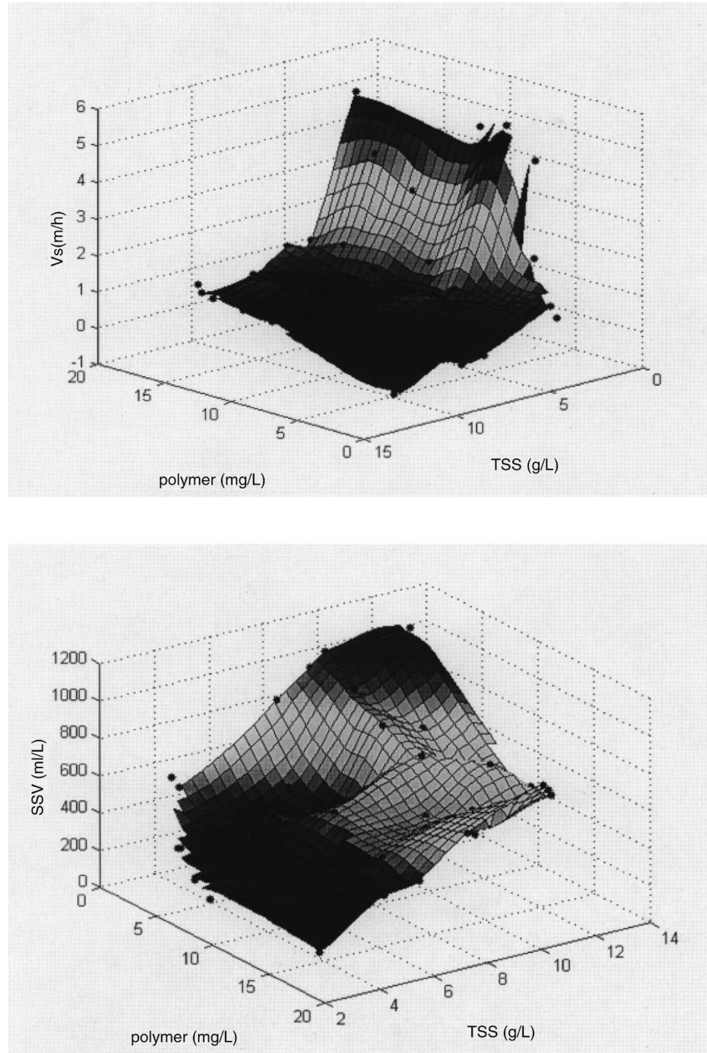


FIG. 1. Evolution of *Vs* (m/h) and SSV (mL/L) as Function of Sludge Concentration (g/L) and Polymer Concentration (mg/L) with 120 s of Mixing between Dosage of Polymer and Start of Sedimentation (Surface = Regression Result; Bullets = Data Points; Data Points below Surface Are Hidden by Surface)

$$Vs = 10.59 * e^{-X/(1.54*P+2.5)}, \quad (R^2 = 0.82) \tag{2}$$

$$\text{SSV} = 80.26 * X * e^{-0.08*P}, \quad (R^2 = 0.88) \tag{3}$$

Effect of Polymer Dose on Nonsettleable Fraction

With a polymer dosing ranging between 0 and 18 ppm, no significant effect of the polymer on the nonsettleable fraction could be detected (data not shown). Therefore, in the model, it was not necessary to incorporate an effect of the polymer on the nonsettleable fraction. Hence, the model used in the simulation study was restricted to the basic Vesilind model.

Simulation Results

Before evaluating the different control strategies, a reference simulation was performed in which it was investigated how the settler would perform when no polymer was dosed. The result of this reference simulation is depicted in Fig. 3. From this graph, it is clear that without polymer addition the clarifier performance is poor and subject to frequent events of massive sludge washout. Correlations of X_{eff} to Q_{infl} and clarifier loading, $Q\_infl * X\_inf$, indicated a poor correlation ($R^2 = 0.271$) between the influent flow rate to the clarifier and the effluent suspended solids concentration. Ekama et al. (1997) report

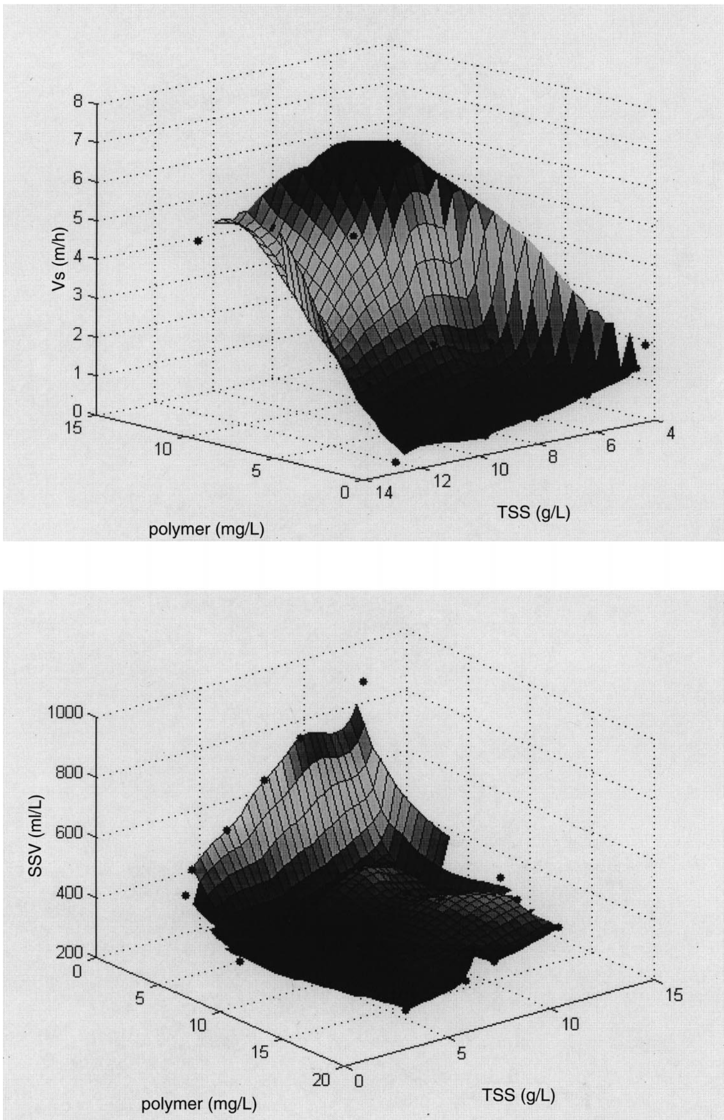


FIG. 2. Evolution of *Vs* (m/h) and SSV (mL/L) as Function of Sludge Concentration (g/L) and Polymer Concentration (mg/L) with 20 s of Mixing between Dosage of Polymer and Start of Sedimentation (Surface = Regression Result; Bullets = Data Points; Data Points below Surface Are Hidden by Surface)

many full-scale operational references showing no relationship between X_{eff} and Q_{infl}. Consequently, the influent flow rate to the clarifier appears to not be a suitable measured variable in a strategy aimed at maintaining low effluent suspended solids. On the other hand, the correlation between solids loading to the clarifier and X_{eff} was high (R^2 = 0.788). This points to the potential of using solids loading as a measured variable for polymer dosage control.

In Fig. 4, X_{eff} from Fig. 3 is plotted as a function of the SBH. The data clearly indicates that X_{eff} remains low as long as the blanket height is not more than 1.7 m thick. The simulation result statement is in agreement with the previously reported full-scale observations that the effluent suspended solids concentration would only deteriorate when the sludge blanket exceeded a certain height. For the control strategies described and tuned later in this study, a height of 1.5 m was taken as maximum allowable blanket height that still could guarantee an acceptable low X_{eff}. By taking 1.5 m instead of 1.7 m, additional safety was incorporated in the control law.

Different control strategies were formulated to maintain the SBH below the critical level. The SBH, the solids loading, or the sludge volume loading were considered as control variables. Control strategies based on a combination of the SBH and one of the other measured variables were also taken into consideration. The basic characteristics of all proposed control strategies are summarized in Table 1. Each control strategy was tuned using West++ by the Praxis optimization algorithm (Brent 1973) to achieve the lowest polymer cost while still

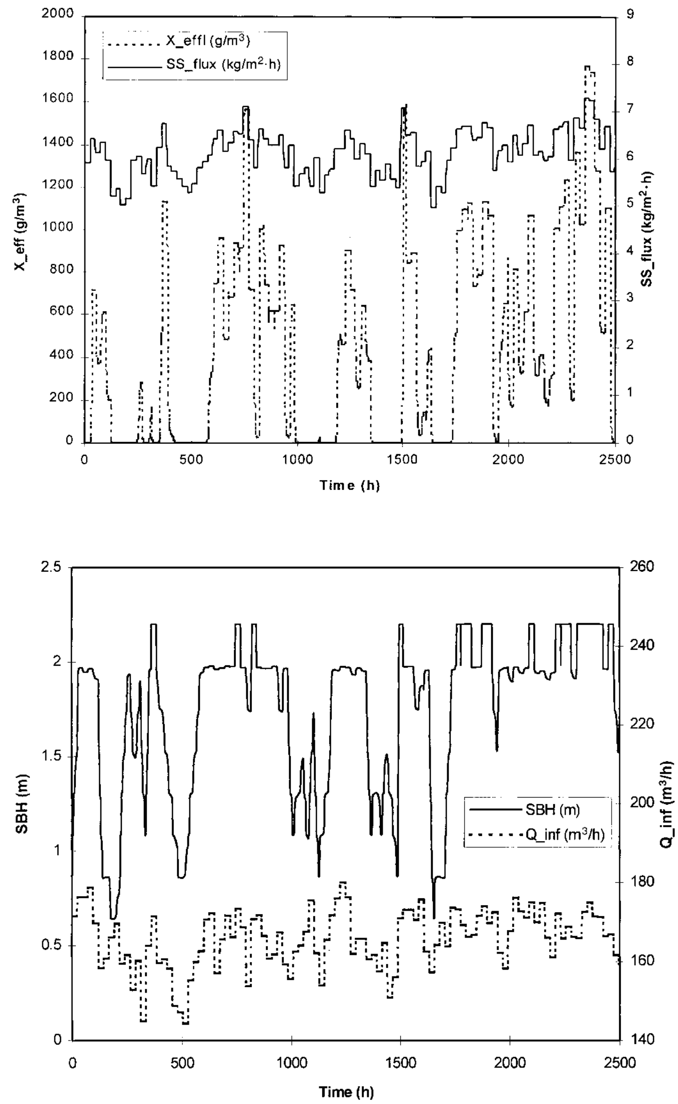


FIG. 3. Solids Loading of Clarifier (kg/m²h, Top), Effluent Suspended Solids Concentration (g/m³, top), SBH (m, Bottom), and Influent Flow Rate (m³/h, Bottom) as Function of Time for Reference Case (No Polymer Dosage; Simulation Results)

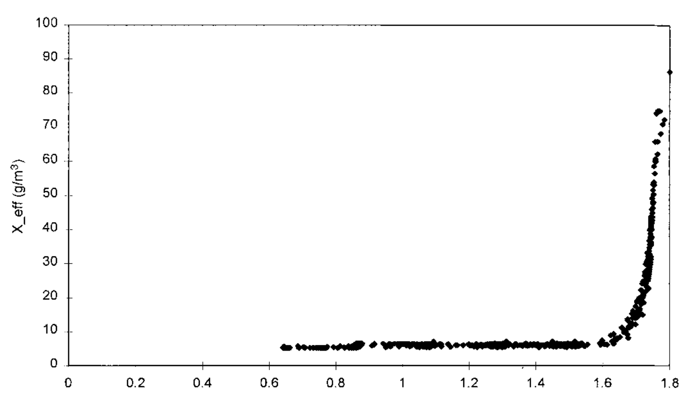


FIG. 4. Effluent Suspended Solids Concentration (g/m³) as Function of SBH (m) for Reference Case (Simulation Results)

TABLE 1. Evaluation of Different Control Strategies by Their Polymer Requirements

Type of control (1)	Control law (2)	Polymer requirement (0.1%) (m^3) (3)	Pure polymer requirement per month (L)[a] (4)
FB	$Q_{pol} = 4.1 * (SBH - 1.5)$	22.7	6.5
FF	$Q_{pol} = 10^{-3} * (Q\_infl - 140)$	64.5	18.6
FF	$Q_{pol} = 1.5 \times 10^{-7} * (X_{infl} * Q_{infl} - 800{,}000)$	24.3	7.0
FF/FB	$Q_{pol} = 10^{-7} * (X_{infl} * Q_{infl} - 775{,}000) + 10 * (SBH - 1.5)$	23.7	6.8
FF	$Q_{pol} = 2 \times 10^{-6} * (SSV_{infl} * Q_{infl} - 85{,}000)$	31.7	9.3
FF/FB	$Q_{pol} = 7.2 \times 10^{-7} * (SSV_{infl} * Q_{infl} - 90{,}000) + 8.7 * (SBH - 1.5)$	23.3	6.7

[a]Actual polymer requirement: 2,000 L pure polymer per month.

preventing the sludge blanket to rise above a height of approximately 1.5 m during the entire evaluation period. Any excess of this setpoint in SBH was given a large cost penalty in the optimization procedure. This was done by incorporation of the residual blanket height above 1.5 m in the cost function with a high weight factor. With a low weight factor the amount of polymer used was incorporated in the cost function. Those strategies where the algorithm did not give any reasonable result due to local minima in the cost function were tuned by trial and error. Table 1 also presents the polymer requirement over the 2,500-h simulation period.

For the different cases, the evolution of SBH and the required polymer dosing are depicted in Fig. 5. Only SBH is depicted because effluent suspended solids concentration was always below 6 mg/L. When the control strategy is only SBH-based, the SBH is generally closer to the limit of 1.5 m than in other strategies. Only the polymer requirement (Table 1) of the control strategies exclusively based on the hydraulic load Q_infl is substantially higher than that of the other strategies. Still, a clear difference can be found in the dosing pattern of the equally effective controls. Strategies using SBH use a more irregular dosing pattern, whereas strategies that do not contain the SBH feedback component follow a smoother behavior.

Presently, it is not known to what extent the parameters in the model will vary as a function of time. However, as sludge settling properties are likely to change over time, the chances are that the parameters will also change. Consequently, a control strategy will most likely have to be retuned from time to time, and therefore, at certain instances, the control strategies will not be tuned optimally. To evaluate the sensitivity of the different strategies to suboptimal parameters, the effect of erroneous tuning on controller performance was studied. To this end, control set points were increased by 10%, proportional factors were decreased by 10% for all control strategies, and the simulations were rerun. In this way a measurement was made that evaluated the use of controllers with far from optimal parameters (a very bad case scenario). The results are given as the cumulative polymer requirements and the time-integrated excess of the SBH above the critical blanket height, and these results are summarized in Table 2. From Table 2 it is apparent that control strategies based on either hydraulic, solids, or sludge volume loading alone are clearly more sensitive toward errors in tuning of parameters.

DISCUSSION

The dynamic 1D settler model used in this paper incorporates the effect of polymer on the settling characteristics. However, it could be argued that some uncertainty remains as to what the fate of the polymer is when it enters the settler. In the Settlometer, a mixing period of 20 s between the dosing of polymer and the initiation of sedimentation is a minimum to allow reliable mixing of polymer and sludge. In a well-designed inlet structure of a clarifier, the mixing time will be higher, whereas the mixing intensity/shear will be lower. Experimental investigation of these phenomena is quite difficult as it entails taking representative samples out of the inlet structure, transferring them to the Settlometer, and homogenizing them before the batch sedimentation starts. Ideally, this procedure should subject the sludge to no additional shear. Still, a properly designed inlet structure should enhance sludge flocculation (Albertson 1992). Therefore, mixing in the inlet structure is not expected to adversely affect the polymer action. Consequently, presently there is no basis to state that the mixing effect used for the simulations is either too positive or too negative. However, full-scale verification remains warranted.

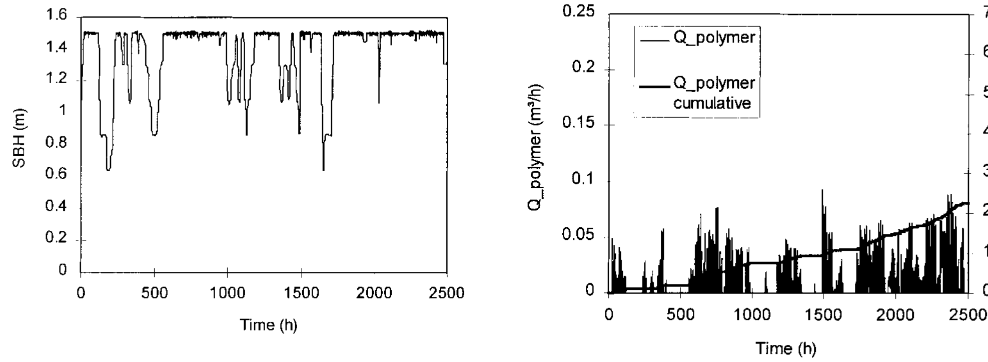
The simulations show that the polymer requirement for most control loops are of the same order of magnitude. The sole control strategy with much higher polymer use is the feedforward (FF) control based on the hydraulic loading. Toward suboptimal controller tuning, the feedback (FB) strategy based on SBH, and particularly, the latter combined with a FF control based on solids loading, or sludge volume loading are the most robust.

Selection of the appropriate control strategy should also take into account the ease and cost of implementation. Considering sensor cost, the following ranking can be made: X_{infl}-sensor < SBH-sensor < SSV-sensor. The advantage of the presented FB control is that only one sensor, namely, the SBH-sensor, is necessary, this is in contrast with the others. Further tuning of the parameters can be done easily as the SBH-level is continuously available. However, there are few references to be found on the reliability of SBH-meters. Grijspeerdt et al. (1996) report that they successfully monitored the SBH for 1 month. At the end of this period, however, the sensor drifted away from the sludge blanket as the blanket was no longer defined as being sharp. The latter was caused by deteriorating sludge settling properties.

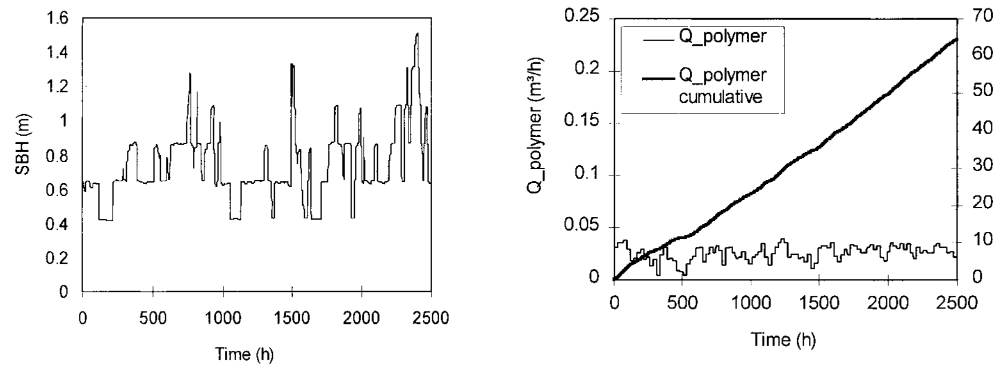
Control on basis of the solids flux to the settler is certainly the most robust control from the sensor point of view. It requires two sensors: One for the flow rate and one for the sludge concentration. Both measurements are quite straightforward and reliable. Moreover, at most treatment installations, the flow rate to the settler is already known because on-line effluent flow measurement combined with the known recycle flow rate yields the settler influent flow rate.

Control on the basis of the sludge volume loading requires measurements of the SSV. This can be done automatically by the Settlometer. At present, only limited experience with its on-line use has been gathered. Still, this sensor could be a promising technique if automated polymer dosing is added to the device. Such a setup would allow one to verify the effectiveness of the polymer. Moreover, the sensor provides the initial settling velocity. This gives the possibility of verifying the clarification criterion that states that the settling velocity of the incoming sludge must be higher than the overflow velocity (Van Haandel 1992). Problems with the location of the blanket (thickening) are more critical compared with the problems induced by violating the clarification criterion (Chancelier et al. 1997), i.e., sludge is lost from the clarifier when the overflow velocity exceeds the settling velocity at the sludge concentration.

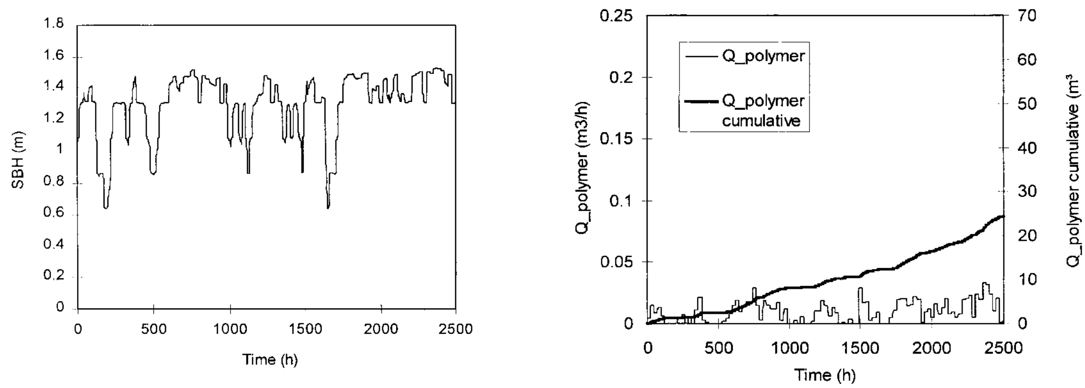
On the one hand, combined control strategies require more sensors, which corresponds with a higher investment and maintenance cost. On the other hand, those combined control strategies are less sensitive toward suboptimal tuning and leave



(a) Control law: $Q_{pol} = 4.1*(SBH - 1.5)$



(b) Control law: $Q_{pol} = 10^{-3}*(Q_{infl} - 140)$



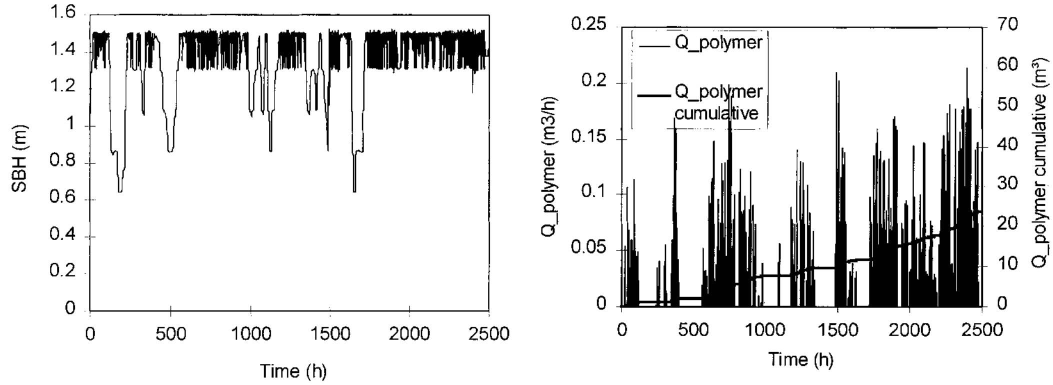
(c) Control law: $Q_{pol} = 1.5 \times 10^{-7}*(X_{infl}*Q_{infl} - 800{,}000)$

FIG. 5. Evolution of SBH (m, Left) and Polymer (0.1%) Dosing Rate (m³/h, right) as Function of Time for Different Control Strategies (Simulation Results)

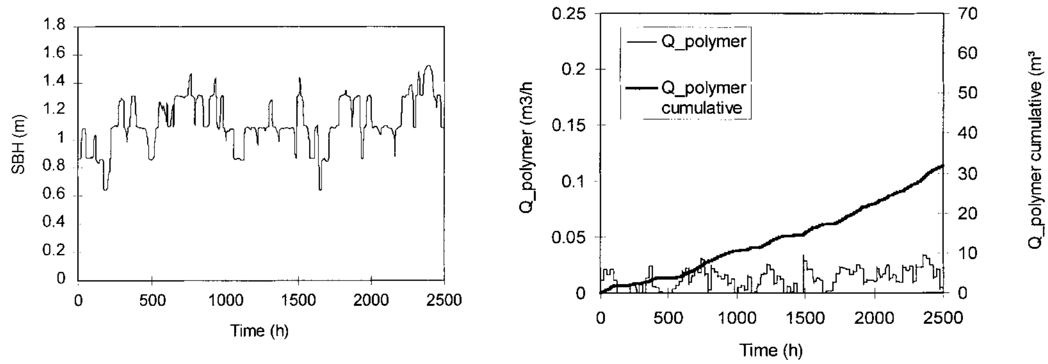
some redundancy for internal fault accommodation: When a sensor failure is detected these strategies allow transferring to a control strategy based on the single remaining sensor.

As a secondary clarifier exhibits rather complex processes (Jeppsson 1996), it is difficult to build a model that is capable of completely describing the settler behavior. Hence, all settler models are more or less a simplified description of reality and certain assumptions are made. The model presented in this paper is no exception to that. In the present study, processes such as shock waves (Bergh and Olsson 1996), rising sludge (Henze et al. 1993), or erosion of the sludge blanket by density currents (Ekama et al. 1997) were not considered. All of these processes may negatively affect X_{eff}. Adverse effects of erosion processes will be reduced when the maximum allowable SBH is adjusted on the basis of full-scale experience with the strategy. It is not expected, nor essential, that this height corresponds to the height used in the simulations. Adverse effects brought on by shock waves cannot be directly tackled by the addition of polymer, but should be dealt with by smooth pumping (Bergh and Olsson 1996). At lower temperatures, rising sludge can be counteracted by reduction of the solids residence time in the settler. This can be realized, for example, by the addition of polymer. Still, at higher temperatures (20°C), only a reduction of the nitrate concentration in the clarifier influent is a viable option (Hinze et al. 1993).

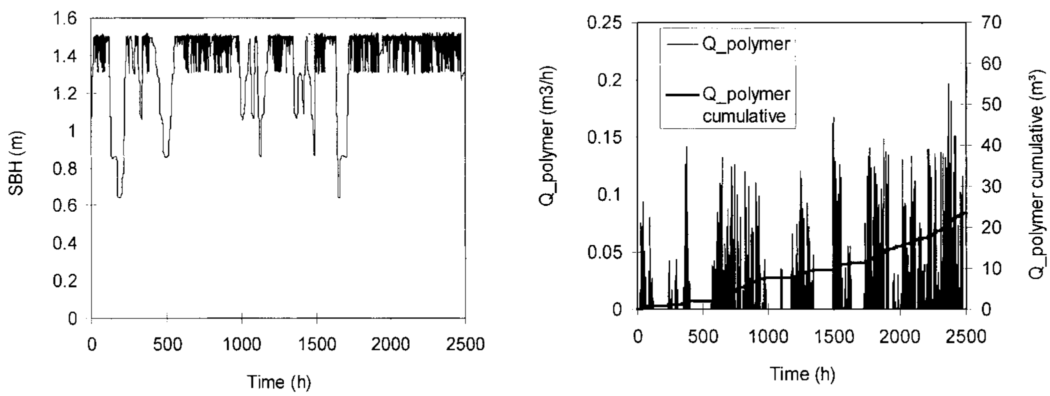
The difference between the amount of polymer (5.4 USD/L) that is currently dosed (2,000 L/month) and what is needed in the automated control strategies (7 L/month) is striking. Different reasons can be put forth. First of all, in the actual clarifier a strong density current exists that erodes sludge from the sludge blanket. This forces operators to keep the sludge blanket below 0.5 m. Note that, with the model a control strategy based on keeping the sludge blanket below this height requires 30 times more polymer than the ones reported in Table 1 (data not shown). This explains an important part of the difference between the full-scale uncontrolled and the fully



(d) Control law: $Q_{pol} = 10^{-7} * (X_{infl} * Q_{infl} - 775{,}000) + 10 * (SBH - 1.5)$



(e) Control law: $Q_{pol} = 2 \times 10^{-6} * (SSV_{infl} * Q_{infl} - 85{,}000)$



(f) Control law: $Q_{pol} = 7.2 \times 10^{-7} * (SSV_{infl} * Q_{infl} - 85004) + 8.7 * (SBH - 1.5)$

FIG. 5. **(*Continued*)**

controlled (model) clarifier. The design of the rectangular clarifier under study promotes density currents and the erosion of the sludge blanket because of the following:

- The clarifier is too shallow. It does not have 3 m of depth (''Arbeitsblat'' 1991). Also, no sludge removal occurs under the effluent weirs that results in the accumulation of solids and a further decrease of the effective height of the clarifier at this critical location.
- The inlet of the clarifier is situated 1.1 m above the clarifier bottom leading to a considerable waterfall effect. Krebs et al. (1995) identify an inlet height of 0.5 m to be beneficial to limit density currents.
- The effluent launders consist of series of double-sided lateral launders that are situated at the end of the clarifier. Such design enhances the erosion of sludge from the blanket to the effluent. Effluent weirs should be about 5 m from the end wall (''Arbeitsblat'' 1991).

Other reasons for the considerable difference in the simulated and actual polymer dosing are that the dosing point of the actual plant layout is far from optimal: There is a considerable period of high turbulent mixing between the dosing of the polymer and the entrance in the clarifier. The experimental data have shown that this may significantly reduce the effectiveness of the polymer.

Presently, the polymer dosing is adjusted only using operator experience. Currently, the operator does not utilize any of the on-line information used in the different control strategies. Neither is the operator continuously present at the clarifier to adjust the polymer pumping rate. Because a massive escape of sludge cannot be tolerated, he is forced to keep polymer dosing at a rather safe/high level.

TABLE 2. Polymer Requirement and Time-Integrated Excess of Critical Blanket Height for Suboptimal Tuned (10% Deviation) Control Strategies and Reference Case

Type of control (1)	Control law (2)	Polymer requirement (0.1%) (m^3) (3)	Time-integrated excess of the critical SBH ($m*h$) (4)
—	Reference (no polymer)	0	672.3
FB	$Q_{pol} = 3.7*(SBH - 1.65)$	22.5 (−0.2)	14.3
FF	$Q_{pol} = 0.9 \times 10^{-3}*(Q\_infl - 154)$	5.9 (−59)	166.5
FF	$Q_{pol} = 1.35 \times 10^{-7}*(X_{infl}*Q_{infl} - 880{,}000)$	6.0 (−18.3)	564.8
FF/FB	$Q_{pol} = 0.9 \times 10^{-7}*(X_{infl}*Q_{infl} - 852{,}500) + 9*(SBH - 1.65)$	31.8 (+8.1)	6.6
FF	$Q_{pol} = 1.8 \times 10^{-6}*(SSV_{infl}*Q_{infl} - 93{,}500)$	6.5 (−25.2)	560.6
FF/FB	$Q_{pol} = 6.5 \times 10^{-7}*(SSV_{infl}*Q_{infl} - 99{,}000) + 7.8*(SBH - 1.65)$	29.2 (+5.9)	7.5

CONCLUSIONS

This study found that the effect of the polymer on the settling properties depends on the mixing time between addition of polymer and initiation of the sedimentation. It was easy to incorporate this into a 1D settler model. Model analysis confirmed that the effluent suspended solids concentration can be held consistently low when the sludge blanket is kept below a critical height. Strategies aimed at doing this can be based on SBH, hydraulic loading, solids loading, or sludge volume loading. In simulations, all of the different control strategies, except for the one based on the hydraulic loading, were found equally effective. Therefore, selection of the control loop should be based on the sensitivity of the control parameters for tuning and the ease at which they can be implemented.

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

k = Vesilind settling parameter (m/h);
n = Vesilind settling parameter (m^3/kg);
P = polymer concentration (ppm);
Q_{infl} = influent flow rate of the clarifier (m^3/h);
Q_{pol} = polymer dosing rate (m^3/h);
SBH = sludge blanket height (m);
SSV = stirred sludge volume (mL/L);
Vs = zone settling velocity (m/h);
X = sludge concentration (kg/m^3);
X_{eff} = effluent suspended solids (mg/L); and
X_{infl} = clarifier feed suspended solids concentration (g/m^3).