Simulation program for wastewater coagulation

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Abstract The lack of comprehensive simulation models for wastewater coagulation is one of the obstacles to achieving optimal coagulant dosing. Two approaches for developing a model to describe the coagulation process are presented. The comprehensiveness in describing the influent quality with several parameters, rather than with one parameter, is identified to give high efficiency in dosing models based on algorithms constructed using the partial least squares method. The concept was tested on two full-scale wastewater treatment plants, with coagulant savings and effluent quality improvements. Significant differences were observed with the increase of online parameters in the models. The second approach is based on distribution of coagulant for particle and phosphate removal processes and is discussed for inert fractions. The concept is integrated into existing simulation software as a module. The calibration results and dosage predictions are demonstrated.

Keywords Coagulation; on line measurements; optimal dosing; real-time-control

Background

Natural variations in the hydraulic load to the wastewater treatment plants (WWTP) represent a number of challenges. While the physical handling of extremely large hydraulic loads is the main challenge, which is often solved by allowing by-pass lines, the disturbances that are created to the treatment process leading to poor treatment efficiencies is an equally important problem. Compared with biological WWTP, the chemical WWTPs are more robust and can theoretically face such variations more efficiently. The simple reason for this robustness is the flexibility to increase the coagulant dosage as required for processing a higher hydraulic load, compared with the limitations of the capacity of microorganisms in a biological WWTP. However, to efficiently utilise this possibility, the chemical WWTPs must have coagulant dosing systems that can efficiently adjust to the changes in the hydraulic loading and the concentration variations. The use of a coagulant dosing control system based on RTC is the only solution for this. This paper presents the establishment, and experiences with such a system, and the advantages of utilising it in an integrated wastewater management strategy.

Chemical coagulation has gained popularity as a leading wastewater treatment concept in many countries. Its efficiency in particle and phosphate removal, flexibility and the robustness for climatic and shock loads are among the major reasons for this popularity. For example, over 75% of all treated wastewater in Norway now goes through a low-load coagulation stage, while in several mega-cities, like Hong Kong, high-loaded coagulation is used, which is also known as chemically enhanced primary treatment. A common requirement for this process is efficient treatment at minimum coagulant dosages, with minimum by-effects to the environment. The inefficient control of the coagulation process may result in high chemical costs, high sludge volumes, negative effects on consequent treatment processes, etc. The optimum coagulation conditions have now become a considerable issue in terms of economy and the environment in the wastewater treatment.
Several studies on process optimisation based on physical/chemical parameters such as the mixing of chemicals, the coagulation pH, the coagulant chemistry and the influence of flocculent-aid, etc. are well documented (Ratnaweera, 1991). Most of these conclusions reported benefits related to the dosing of coagulants in optimum amounts required by the influent quality and the required treatment efficiency.

A survey on the most common coagulant dosing control strategies reveals that most of the wastewater treatment plants do not have the ability either to sufficiently identify the influent water quality or to determine the optimum dosage applicable for it. On the other hand, the wastewater quality fluctuations during a season, a week or a day are known to be very significant (Sagberg et al., 1990), which emphasises the necessity for an efficient coagulant dosing control. Many treatment plants monitor only the flow, while some of them also monitor pH, conductivity and temperature of the influent. However, the turbidity and the phosphates, the two major components in the municipal wastewater treatment, are seldom measured in the influent.

At present, there are no comprehensive physical models for the coagulation process due to its complicated physico-chemical behaviour. Unlike many other industrial processes, the coagulant dosing is difficult to control using feedback concepts, primarily due to the 2–6 hours of sedimentation times and the rapid influent quality fluctuations during that period, for example every 15 minutes. The most widespread coagulant dosing strategies include the dosing proportional to flow and sometimes in combination with the over-run control of pH or conductivity in the coagulated water. Some of the large treatment plants practice dosing of coagulants based on experience curves. On the other hand, there is no simple method to determine the optimum coagulant dosage even if the influent quality is well identified. This situation forces most of the treatment plants to run either with an overdose or an under dosage of coagulants, which results in many adverse effects.

With the developments in the water quality measuring technologies, and using the process knowledge and the process control facilities, the process optimisation in coagulation anticipates radical improvements. Two RTC based optimum coagulant dosage identification approaches are evaluated at full-scale and reported in this paper.

**Experimental methods and procedures**

**First approach**

Using multivariate calibration concepts and related software, it is now possible to analyse large amount of information (Beebe and Kowalski, 1987 and Martens and Naes, 1991). For complicated processes like wastewater coagulation, which involves several variables, these tools are quite valuable.

To demonstrate the first approach, the partial least squares regression (PLSR) concept is used to establish relationships between coagulant dosage \( D \), influent variables \( X_{in} \), and effluent variables \( X_{out} \) as illustrated in the equation below:

\[
D = f(X_{in}, X_{out})
\]

We have conducted experiments at laboratory-scale and pilot-scale tests of wastewater coagulation to generate data series consisting of effluent parameters reacting to various dosages of different influent parameters. The laboratory-scale experiments were conducted using a semi-automated jar-test system, while the pilot-scale tests were performed in a 2 l/min reactor and reported elsewhere (Ratnaweera et al., 1994). Models with feasible prediction abilities were developed. The model correlation coefficients are given in Table 1 for comparison, which demonstrates the weakness of the most common dosing concepts based on flow proportional systems.
Table 1  Correlation coefficients of models with various influent parameters (Q: flow, SED: sedimentation time, estimated as a ratio between flow and tank volumes, TUi: turbidity, OPi: Ortho-P, COi: Conductivity, PHI: pH, T: temperature). Effluent quality is described using only turbidity (TUe)

<table>
<thead>
<tr>
<th>Model structure</th>
<th>Correlation coefficient</th>
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<tbody>
<tr>
<td>Dosage = f(Q, SED, T, TUi, OPi, PHI, COi, TUe)</td>
<td>0.93</td>
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<tr>
<td>Dosage = f(Q, SED, T, TUi, PHI, COi, TUe)</td>
<td>0.91</td>
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<tr>
<td>Dosage = f(Q, SED, T, OPi, PHI, COi, TUe)</td>
<td>0.90</td>
</tr>
<tr>
<td>Dosage = f(TUi, TUe)</td>
<td>0.65</td>
</tr>
<tr>
<td>Dosage = f(Q, TUe)</td>
<td>0.62</td>
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</tbody>
</table>

This paper reports the results of the full-scale experiments in two wastewater treatment plants (WWTP) with coagulation selected as the main process. Two WWTPs are selected to evaluate the effect in WWTPs of different size. Both WWTPs had two process lines giving the possibility for direct comparison of the results.

Although the models developed during the lab- and pilot-scale studies confirmed the feasibility of the concept, they need to be calibrated for these WWTPs. Although these two WWTPs used the same coagulant (JKL, ferric chloride sulphate), the different physical configurations result in various mixing and settling characteristics. The influent qualities of the selected WWTPs were different from each other and also from the lab- and pilot-scale plants. For this reason, calibration data series were collected at the beginning.

Online water quality monitoring instruments for flow, turbidity, pH, temperature and conductivity were mounted in WWTPs, both for the influent and effluent. For manual analysis, automatic samplers were used. A special PLS from ABB instruments, type OP 65, was programmed to receive signals from the monitoring instruments and to calculate the optimal coagulant dosage and to produce a control signal for the coagulant dosing pump.

Toensberg WWTP is a medium-scale WWTP with a design and connected capacity of 60,000 p.e. However, due to heavy periodic discharges from food processing industries the organic load exceeds the design capacity. The treatment plant has grit chambers, input of septic waste, sand traps, flocculation chambers and six sedimentation tanks. The plant has two dosing pumps for the two separate lines. The plant uses empirical, flow proportional constants for each hour of the day with an effluent pH overriding function. The constants and the pH set points are adjusted according to the treatment results and past experiences.

Fredrikstad WWTP is a medium-scale WWTP with a connected capacity of 75,000 p.e. The WWTP also receives industrial wastewater. The treatment concept consists of mechanical and chemical processes. The plant has only one process line, so the comparison is made according to the existing empirical dosing algorithm adjusted manually by the operators.

The experiments were implemented in two phases, where the process data were gathered to calibrate the model, and then to actively run with the new algorithm based on the calibrated model.

Second approach
To present the second approach, some physical concepts were integrated into the empirical model.

This concept proposes that when an inorganic coagulant is added to the wastewater, specific amounts of the coagulant will be allocated for particle removal (AL(PA)), phosphate removal (AL(PO)) together with an inert portion (AL(IN)). The proportion between these three components will be decided based on the nature of the coagulant and the wastewater...
characteristics (pH, particle and phosphate content). Thus, the particle removal efficiency is based on the ratio Al(PA)/Al(PA)opt, where the optimum amount of coagulant required for particle removal is Al(PA)opt, and is only a function of the particle concentration and pH. The particle removal efficiency is finally dependent on the sedimentation characteristics of the plant. The phosphate removal efficiency is given directly as the ratio Al(PO)/Al(PO)opt, where Al(PO)opt is the required coagulant amount to precipitate all phosphates in a given sample. The pH change during the process is calculated and the particulate COD removal is estimated proportionally to the particle removal. The constants for the above relationships are experimentally defined.

The model is then integrated as a specific module in the leading wastewater simulation software, STOAT, with assistance from the Water Research Centre, UK. The module is as flexible as other modules in the software, enabling the creation of any treatment process combining various single processes. The model was calibrated and tested at the Toensberg WWTP and is being tested at the Fredrikstad WWTP at present.

Results and discussion

First approach

Using the influent, effluent and dosing data collected during the first phase, the model was calibrated for two WWTPs. The input variables were limited to flow and turbidity while the only effluent variable was the pH after coagulation. The model had a structure of D = f(Q, influent turbidity and effluent pH). However, upper and lower pH setpoints were introduced to secure dosages during extreme conditions. The estimated dosages by the algorithm beyond these limits were doubled or halved, to keep the pH after coagulation within the normal levels.

Based on the influent and effluent data gathered during one week at the Toensberg WWTP, a simple model based on flow and influent turbidity was constructed. As mentioned earlier, the standard dosage at this WWTP is defined with variable flow proportional constants, which are based on previous experience. The plant personnel additionally adjust the constants depending on the effluent quality. Selected results are presented in Figure 2, and show that the effluent turbidity was more even and mostly below 10 NTU in the experimental line, while the standard line turbidity was often varied and higher.

Figure 3 presents the initial results from the experiments at Fredrikstad WWTP. Despite the considerable variations in the influent turbidity, the experimental line has managed to keep the effluent turbidity below 10 NTU.

In both cases, the coagulant dosage was mostly less in the experimental line compared with the standard lines, although it was the opposite during some periods. Higher dosages were required at times to keep efficient treatment levels. Figure 4 presents the variation of the dosage between two lines at the Toensberg WWTP.

Figure 4 shows the difference between the standard dosage and the experimental dosage
as a percentage. The average reduction of coagulants during the experimental period was about 8%.

The full-scale experiments at these WWTP have verified the applicability of the concept to achieving more-even and improved effluent qualities, often with overall reductions in coagulant consumption. At present the tests continue at the Fredrikstad WWTP to calibrate and verify the model to widely varying flowrates due to the rainy and dry seasons.

**Second approach**

The second approach is evaluated at the Toensberg WWTP. The initial calibration results are presented in Figures 5 and 6, for effluent turbidity and pH, respectively. Reasonable calibration results were also found for phosphates, which are not presented in this paper.

The calibrated STOAT model was then used to predict the coagulant dosage for a data series to result in an effluent of given treatment efficiencies. The variation in the estimated dosages is illustrated in Figure 7.
Conclusions

Coagulation is a widely used wastewater treatment process and with an RTC-based coagulant dosing control system, efficient treatment can be achieved except during extremely high hydraulic loads. By actively controlling the sewers it may be possible to utilise the sewer volumes more efficiently, reducing the peaks and the duration of hydraulic loads. Such systems, integrated with efficient RTC, will enable stable and high treatment efficiencies, independent of the variations in the hydraulic loading.

However, the lack of RTC-based efficient coagulant dosing systems is a disadvantage for integrated wastewater management. Time or flow proportional dosing is the common practice in coagulation in WWTP, often with pH set points to control the extreme high and low dosages. However, the coagulation is dependent on several other critical parameters, the dosing is assumed to be far from optimum.

Using statistical data analysis, like PLSR, it is possible to construct various empirical models to predict the dosage based on selected influent and effluent data. The model structures are described. The validity of the concept was demonstrated in two medium-sized WWTPs. The saving of up to 8% of coagulants was recorded in one of the WWTP for a given period.

Figure 5 Calibration of effluent turbidity with STOAT at Toensberg WWTP

Figure 6 Calibration of effluent pH with STOAT at Toensberg WWTP

Figure 7 Estimated coagulant dosage for a selected year, to achieve the given treatment efficiencies
Using a concept of proportional allocation of coagulants to particle removal, phosphate removal and for the inert fraction, a new dynamic model was established and integrated into a process simulation software. The simulation model was calibrated for a full-scale plant and the dosage predictions are presented.

With the availability of reasonable and robust on-line instruments and modelling facilities, the use of similar models in the wastewater coagulation process have become more accessible to WWTPs.

References