A new approach towards modelling of the carbon degradation cycle at two-stage activated sludge plants

S. Winkler, H. Müller-Rechberger, O. Nowak, K. Svardal and G. Wandl
Institute of Water Quality and Waste Management, Vienna University of Technology, A - 1040 Vienna, Karlsplatz 13/226, Austria (E-mail: swinkler@iwag.tuwien.ac.at)

Abstract A pilot plant has been operated in order to investigate the performance and operating characteristics of the plant concept developed for the extension of the main Vienna STP. Due to the different operational modes included in the plant concept, modelling of the carbon degradation becomes of crucial importance. A new activated sludge model is introduced which combines parts of the carbon degradation model concepts as they have been released in the ASM1-model and the ASM3-model, respectively. A method is presented which utilises results from mass balance calculations and sludge stabilisation experiments to reduce the uncertainty in the determination of the values of the simulation model parameters.

Keywords Activated sludge model; simulation; parameter estimation; mass balance calculation; sludge stabilisation; data validation; HYBRID® concept; BYPASS concept; two stage activated sludge plant; COD storage

Introduction
A pilot plant has been operated in order to investigate the performance and operating characteristics of the plant concept developed for the extension of the main Vienna STP. Additionally, a simulation model has been developed. It is envisaged that this simulation model is utilised for plant operation support of the full stage plant. The existing part of the Vienna STP has been put into operation in 1980. It is an activated sludge plant for carbon removal and comprises a total aeration tank volume of 42,000 m³. The excess sludge is incinerated together with the primary sludge in a sludge incineration plant next to Vienna STP. The goal of the plant extension was to integrate the existing plant into the new plant. Since the available extension area is limited a two-stage concept has been chosen.

New plant concept
The new plant has to fulfil effluent standards according to the Austrian water protection legislation, which stipulates a total nitrogen removal rate of 70% in average over all periods possessing a temperature above 12°C. The maximum NH₄-N effluent concentration is 5 mg/l (T > 8°C, daily composite sample), the maximum total phosphorous effluent concentration is 1 mg/l (yearly average of daily composite samples). Two main operational modes will be possible for the new plant (Mueller-Rechberger et al., 2000):

(1) Operation according to the HYBRID® concept (Matsché and Moser, 1993): The HYBRID®-concept is a special operational mode for a two stage activated sludge plant comprising the exchange of activated sludge between the two plant stages. Highly activated sludge from the first stage is brought into the denitrification zone of the second stage. The sludge withdrawn from the first stage delivers carbon substrate to the denitrification zone of the second stage. Hence, the supply of carbon substrate for denitrification in the second stage is secured. Sludge containing nitrifying bacteria from the second stage enters the first stage and thus enables nitrification in the first stage. The first stage is operated at a sludge age of about one day. If the sludge transfer from the second to the first stage would not be
operated, this sludge age would be too short to grow nitrifiers. The ammonia concentration in the first stage is at a level which allows a maximum nitrification process rate. In HYBRID® mode the first stage yields approximately 70% of the total carbon removal, 15% of the nitrification performance and 40% of the total nitrogen removal rate of the whole plant. The second stage can be built as a small, low load nitrification/denitrification stage and is operated at a sludge age of approximately 6 days.

(2) Operation according to the BYPASS concept: In the BYPASS concept a portion (10–40%) of the plant influent flow is directly transferred to the second stage bypassing the first stage of the activated sludge plant. With this measure a sufficient supply of carbon substrate for denitrification in the second stage is secured.

The excess sludge withdrawal is carried out from the first stage only under normal operating conditions. The excess sludge of the second stage is pumped into the first stage, thus, the benefits of the sludge circulation line 2 are utilised in BYPASS mode as well.

The recirculation line delivers nitrate containing final clarifier effluent back to the first stage. In the first stage sufficient substrate for denitrification is available, thus, the overall nitrogen removal performance of the plant is increased. The recirculation flow is adjusted automatically so that the sum of incoming and recirculation flow is constant. This measure minimises hydraulic load variations to the plant, which minimises the solids loss from the clarifier tanks (Armbruster et al., 2000).

Figure 1 shows the principal layout of the pilot plant and shows all possible operational modes.

Development of a new activated sludge model (The “asmVienna” model)
As mentioned above, one goal of the research project was to develop a simulation model that can be utilised for operational support of the full stage plant. A special problem for such a simulation model is the complex carbon degradation process in the two-stage plant, especially if the HYBRID® mode is applied. In this mode the sludge composition in the two stages is very different, but activated sludge is exchanged between the two stages. Especially the process of carbon substrate transfer to the second stage can hardly be described with the models used today.

Figure 1 Principal layout of the pilot plant of the extended main Vienna STP

Table 1 Description of operational mode specific lines operated at the pilot plant

<table>
<thead>
<tr>
<th>BP</th>
<th>Bypass line</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>Recirculation flow</td>
</tr>
<tr>
<td>SC 1</td>
<td>Sludge circulation line 1</td>
</tr>
<tr>
<td>SC 2</td>
<td>Sludge circulation line 2</td>
</tr>
<tr>
<td>RS</td>
<td>Return sludge</td>
</tr>
<tr>
<td>ES</td>
<td>Excess sludge</td>
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</tbody>
</table>
The ASM1 model (Henze et al., 1987) primarily aims at low loaded activated sludge plants with nitrification and denitrification. In this model no processes are included which describe carbon substrate uptake due to adsorption to the floc or incorporation into the sludge floc. Heterotrophic growth is based on utilisation of readily biodegradable substrate (Sₖ) only. Further it includes the “death–regeneration concept” (Dold et al., 1980). Within this concept the decay of biomass yields inert particulate COD from biomass decay (Xₚ) and slowly biodegradable substrate (Xₕ). Xₕ is hydrolysed to Sₖ and thus becomes available as substrate for heterotrophic growth again.

The ASM3-model (Gujer et al., 1999) comprises a different model concept. There the readily biodegradable substrate (Sₖ) is transferred into particulate substrate (Xₜₒ) which serves as only substrate for heterotrophic growth. The storage capacity of Xₜₒ is not limited.

Also the decay of biomass is modelled differently from the ASM1 model. It is described as endogenous respiration. The decay of biomass (Xₐ or Xₕ) yields inert particulate COD (Xₚ) and causes oxygen consumption. Finally the decay of biomass is linked to a decay of Xₜₒ. Decay of Xₜₒ causes oxygen consumption only. Thus in the ASM3 model four processes related to the carbon degradation cycle cause oxygen consumption: storage of COD, heterotrophic growth, decay of biomass and decay of stored COD.

The idea of the new model is to combine the two model concepts of ASM1 and ASM3 since it is assumed that the combination of both heterotrophic growth models is closest to reality. Also the issue of model calibration is assumed to be of reduced complexity since in the ASM3 model four processes cause oxygen consumption as described above.

The “asmVienna”, like the ASM3 model, includes a particulate COD component Xₜₒ. Xₜₒ is a particulate carbon substrate for heterotrophic growth. It is synthesised from readily biodegradable substrate (Sₖ), the synthesis process causes oxygen consumption which is characterised by the model parameter Yₜₒ. It is assumed that Xₜₒ becomes a part of the sludge floc due to processes like adsorption, accumulation or incorporation into the floc. In the new model the processes “heterotrophic growth on Sₖ,” and “COD storage” compete for the readily available substrate. The “death–regeneration concept” is still included, but an additional component Xₐ has been introduced. From the simulation of sludge stabilisation experiments it has been shown that this component is useful to describe the decrease of COD in the sludge stabilisation vessel (Nowak et al., 1999 a). Decay of heterotrophic biomass yields slowly biodegradable COD (Xₕ) and very slowly biodegradable COD (Xₐ). Hydrolysis of Xₐ yields Xₕ and inert COD from biomass decay (Xₚ). Figure 2 shows the carbon cycle of the “asmVienna” model.

Table 2 COD related model states used in the “asmVienna” model

| Sₖ | Readily biodegradable COD |
| Xₕ | Heterotrophic biomass |
| Xₜₒ | Particulate stored COD substrate |
| Xₚ | Inert COD from biomass decay |

Table 3 Kinetic and stoichiometric model parameters of carbon cycle of “asmVienna” model

| ηₖ | Anoxic growth factor |
| bₗₐ,eₜ | Aerobic heterotrophic decay rate |
| Yₕ | Heterotrophic yield for growth on Sₖ |
| ηₚₜₒ | Anoxic hydrolysis factor |
| bₗₐ,nₐ₂,ox | Anoxic heterotrophic decay rate |
| Yₜₒ | Yield of carbon storage process |
| ηₚₜₒ | Anoxic storage factor |
| bₗₐ,eₜ | Aerobic decay rate of Xₐ |
| Yₕ,tₜₒ | Heterotrophic yield for growth on Xₜₒ |
| fₚₜₒ | Storage rate |
| bₗₐ,nₐ₂,aₜ | Anoxic decay rate of Xₐ |
| Yₚ | Inert content of Xₚ |
| fₚ | Xₚ content of Xₐ |
Material and methods
Mass balances as a tool for data verification and parameter estimation
Mass balances are a useful tool for data verification, operation evaluation and parameter estimation for the application of a simulation model. The principle of mass balancing is to define a system by its inputs and outputs and to monitor the fate of specific system states passing through the system. According to the mass conservation principle the incoming and outgoing load must be equal. For activated sludge systems mass balancing calculations should be carried out over longer periods (2–3 sludge ages) where the operational mode of the plant and the environmental conditions (temperature) remained stable. Accumulation within the system has to be considered (Nowak et al., 1999 b).

Inert soluble organic fraction of the input flow
It can be assumed that the soluble organic fraction of the effluent of an activated sludge plant contains compounds, which cannot be utilised within the system. Thus, this fraction is assumed to be inert. The output load of inert soluble organic matter determined in the effluent must be equal to the input load of inert soluble organic matter.

Sludge stabilisation experiments
Sludge stabilisation experiments yield information about the decay rate of the bacteria and the inert particulate organic fraction of the activated sludge. Sludge is withdrawn from the system and put into a vessel, which is constantly aerated for a couple of weeks. The biomass

Figure 2  Carbon degradation cycle of “asmVienna” model. Numbers in brackets at both ends of arrows symbolize COD units
concentration in the vessel decreases. This is observed through a decrease of the COD and VSS concentration in the vessel. The measured parameters are depicted over time and can be compared with results from a numeric simulation of these experiments.

Simulation model parameter estimation

A strategy has been developed which utilises the results from mass balance calculations, sludge stabilisation experiments and dynamic observations from on-line measurements. To start the determination of the influent fractions and to adjust the model parameters a balancing period is selected which covers a time period before activated sludge was withdrawn for a sludge stabilisation experiment. A simulation model of the activated sludge plant is set up and operated under the characteristics of that balancing period. For the influent concentrations, internal flows and excess sludge flow average values of the selected balancing period are chosen. In this mode of operation the simulation model will reach a steady state. The simulation results for the excess sludge production and the MLSS in the aeration tanks are compared to the results from the mass balance calculation. In order to minimise the divergence of the results primarily the input fractionation is varied. The content of $S_I$ (inert soluble COD) is derived from the mass balance calculation as described previously. The content of $X_H$ (heterotrophic biomass) in the influent is usually very low, in a first approach it can be neglected. The content of $X_I$ (inert particulate COD) primarily influences the excess sludge production. The content of $X_S$ (slowly biodegradable COD) influences the excess sludge production in the first stage and is the limiting factor for denitrification in the second stage. Hence, the distribution of the influent COD to the fractions $S, X_I$ and $X_S$ is the primary step of adjustment to find convergence between the simulation and mass balance calculation results.

The steady state sludge composition derived from the plant simulation applying average input values are used as initial values for the simulation of the sludge stabilisation experiment.

The inert COD which remains at the end of the stabilisation experiment is composed of $X_I$ (inert particulate COD) and $X_P$ (inert COD stemming from biomass decay). The initial concentration of $X_H$ (heterotrophic biomass) of the activated sludge and the value of the parameter $f_P$ determine the concentration of $X_P$ of the stabilised sludge. The model parameter $f_P$ defines the inert content of biomass. If the value for the remaining inert COD derived from the simulation experiment is different from the measurement values derived from the sludge stabilisation experiment an iteration procedure is started. The influent fractionation is re-adjusted, the plant simulation model is run with the new influent fractionation and the new sludge steady state is used as new initial condition for the simulation experiment. The goal of the iteration procedure is to find the best convergence for the results of excess sludge production and the MLSS of the aeration tanks in the plant simulation model on the one hand and the inert COD concentration during the sludge stabilisation simulation on the other hand.

The slope of the COD degradation curve is primarily determined by the value of the heterotrophic decay rate $b_H$. Former research results (Nowak et al., 1999a; Siegrist et al., 1999) showed, that $b_H$ in anoxic milieu is significantly lower than in aerobic milieu. The milieu conditions in the sludge stabilisation vessel are strictly aerobic, therefore only variation of the “aerobic” heterotrophic decay rate $b_{H_{aer}}$ has an influence on the slope of the COD degradation curve derived from the sludge stabilisation simulation. It has been assumed that the ratio between $b_{H_{aer}}$ and $b_{H_{anox}}$ is constant. Hence, $b_{H_{aer}}$ and $b_{H_{anox}}$ are varied simultaneously. Again an iteration procedure is carried out. The plant model is run with the new values for $b_{H_{aer}}$ and $b_{H_{anox}}$, the new steady state is the initial condition for the sludge stabilisation experiment. The goal of this iteration procedure is to find convergence between the measured and the simulated slope for the COD degradation while the calculated and simulated values for the excess sludge production stay convergent. An increase of $b_H$ reduces
the excess sludge production, re-adjustment of the influent fractionation (increase of fraction of $X_S$) can compensate for such reductions.

Finally a dynamic simulation of subsequent balancing periods is carried out. The initial value for this simulation is again derived from the previous simulation applying average input values. The results of the dynamic simulation are averaged and compared to the results of the corresponding balancing period. The goal of the calibration procedure is to minimise the divergence between the results from this “dynamic” balance and the results from the mass balance calculation.

The half saturation coefficient for $S_S$ for heterotrophic growth ($K_{SH}$), for storage of $S_S$ as $X_{STO}$ ($K_{SSTO}$) and the storage rate ($r_{STO}$) are the most significant parameters for the competition of the storage process and the instant respiration of $S_S$.

The parameters $r_{HYD}$ (hydrolysis rate) and $\eta_H$ (denitrification correction factor) have most influence on the denitrification process.

The parameters $Y_H$ (heterotrophic Yield), $Y_{STO}$ (yield of the storage process) and $\mu_H$ (maximum heterotrophic growth rate) are used to adjust the excess sludge production and oxygen consumption in the simulation model.

Figure 3 shows the parameter estimation procedure.
Results and discussion

The calibration method described above has been applied to derive a parameter set which describes the long term behaviour of the pilot plant. It has been pursued to use the same values in both stages for a maximum number of parameters. The storage process has been strongly favoured in the first stage. The parameters responsible for the storage process do not play a significant role in the second stage.

The derived parameter set is applicable to describe the long term behaviour of the pilot plant over a considerable long period. The deviations of the results from the simulation and mass balancing are within tolerable boundaries, considering that all kind of different operational modes and influent temperature ranges are included within this period. Although the storage process has strongly been favoured, which increases the excess sludge production of the first stage, the excess sludge production in the second stage derived from the simulation is lower than the values derived from the mass balance calculation during some periods.

The new activated sludge model “asmVienna” has been applied to carry out a simulation study of the operation of the pilot plant. It turned out that each of the applied tools (mass balance calculation, simulation of sludge stabilisation experiments, dynamic simulation of the plant model) yields specific results, which are sensitive to specific model parameters. With this information it is possible to narrow the boundaries for the uncertainty of the values of the model parameters. The initial values of the model parameters have been chosen according to a “standard” parameter-set for the ASM1-related parameters (Bornemann et al., 1998), the initial values for the ASM3-related parameters were taken from Gujer et al., (1999). It turned out that the initial conditions play a significant role for the results of the dynamic simulation and the sensitivity of certain model states towards the variation of specific model parameters of the dynamic simulation model. The uncertainty with regard to the influent COD fractionation can be decreased significantly combining the results from a

![Excess sludge production, stage 1](image1)

![Excess sludge production, stage 2](image2)

Figure 4 Excess sludge production of both stages of the pilot plant. Comparison of results from simulation and mass balance calculation. The indices “meas” and “calc” indicate the results from the closed and open COD mass balance calculation, respectively. The percentage values in the figure indicate the ESG/OC/ηCOD-ratio of the single balancing periods for both stages. (ESG is excess sludge production, OC is oxygen consumption for carbon degradation, ηCOD is total removed COD load)
simulation of the average conditions over a mass balancing period and the simulation of the corresponding sludge stabilisation experiment. The new method shows a way to deliver the desired results requiring only a moderate number of laboratory measurements and providing a plausibility check of the results since two independent sub-methods are combined.

Figure 4 shows a comparison of the excess sludge production of both stages derived from the dynamic simulation and the mass balance calculation over a period of almost seven months.

The introduction of the additional model state $X_{\text{STO}}$ (particulate stored organic substrate) yields additional flexibility for the model calibration process. It enables to favour the utilisation of $S_S$ (readily biodegradable organic substrate) for purposes of synthesis of $X_{\text{STO}}$ in the high loaded first stage, reducing the COD degradation by means of carbon oxidation in the first stage at the same time. With this measure carbon substrate is transferred into the low loaded second stage for denitrification, enhancing the amount of COD degraded by means of oxidation in the second stage.

Conclusion

It turns out that modelling of the dynamic behaviour of an activated sludge plant simulation model still is a major challenge with the methods available today. The methods introduced are of quasi-steady state character and yield certain boundaries for model parameter estimation and are very helpful for a plausibility check of the operational data of an activated sludge plant.

Still the problem remains that a “final” parameter adjustment has to converge simulation results with results from continuous on-line measurements of specific activated sludge plant states. Most of the on-line monitors applied today deliver measurements of nitrogen or phosphorous related states. On-line measurement of COD related states is still relatively complicated and such instruments are rare at full scale plants today. On-line measurement of the COD concentration by means of the UV-absorption-method yields good results for the diurnal changes of the COD concentration rather than an accurate value of the actual COD concentration. Especially an increased fat content of the medium can cause problems for the UV-absorption-method due to fatty build-up on the probe head.

On-line measurement of the oxygen uptake rate for carbon degradation requires automated dosing of ATH (for inhibition of nitrification) into the respiration vessel. Such an instrument can be classified as rather complex and would require special skills from the operating personal. Further research effort in the field of dynamic model calibration should be targeted towards an improvement of dynamic model parameter calibration strategies. The demand of continuous measurement results for such strategies could initialise a further development of on-line instruments towards more user friendliness.

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