

An extension of ASM2d for modeling external carbon addition in combined CNP activated sludge systems

M. Swinarski, J. Makinia, H.D. Stensel, K. Czerwionka, W. Fordonski

Keywords: activated sludge, ASM, external carbon, mathematical model

Background

External carbon sources are readily biodegradable compounds which are added to enhance the denitrification process (accomplished by “ordinary” heterotrophs) and improve the overall efficiency of N removal within the existing capacities of activated sludge systems. In the combined CNP removal systems, the external carbon sources may also interact with the enhanced biological P removal (EBPR) process (accomplished by Polyphosphate Accumulating Organisms (PAOs)). For optimization of the dosages of external carbon sources, mathematical models have been proven to be useful tools. In the existing activated sludge models for combined CNP systems, readily biodegradable compounds are divided into two groups in order to tackle the problem of competition between “ordinary” heterotrophs and PAOs for the substrates. Fermentation products (S_A) are assumed to be only acetate (although covering a wide range of compounds) and directly available for PAOs, whereas fermentable readily biodegradable compounds (S_F) are not directly available for PAOs but can ultimately be transformed to S_A . In practice, however, there are compounds (e.g. ethanol) which are known to be fermentation products but reported not to be utilized by PAOs (Satoh et al., 2000). These authors proposed a modified conceptual model for anaerobic COD metabolisms that assumes the presence of soluble substrate, $S_{A'}$, which is not utilized by PAOs either directly or via fermentation. The $S_{A'}$ type of substrate becomes, however, available for “ordinary” heterotrophs in the presence of oxygen or nitrate.

The aim of this study, carried out as part of the on-going EU supported project, was first to develop an extension of the IWA Activated Sludge Model No. 2d (ASM2d) considering a new readily biodegradable substrate, not available for the PAOs. The concept was derived from the observations of Swinarski et al. (2009) that some substrates (e.g. ethanol and distillery waste products) had hardly any impact on the behavior of PO_4 -P during nitrate utilization rate (NUR) measurements (in contrast to other substrates, such as acetic acid or readily biodegradable fraction of settled wastewater). Secondly, the new model was compared with the original ASM2d based on predictions of laboratory experiments and field measurements in a full-scale plant (MUCT process configuration).

Material and methods

A conceptual model of the ASM2d extension considering a readily biodegradable substrate ($S_{A,1}$) not available for PAOs is presented in Figure 1. Based on this concept, a mathematical model for CNP activated sludge systems was developed as an expansion of the ASM2d (Table 1). The new model incorporates one new component ($S_{A,1}$) and six new processes, i.e. aerobic and anoxic growth of heterotrophs on $S_{A,1}$, aerobic and anoxic storage of poly-P with $S_{A,1}$, and aerobic and anoxic growth of PAOs on $S_{A,1}$. The component $S_{A,1}$ is termed “other fermentation products” to differentiate from acetate (S_A) and denote that this kind of substrate is not available for PAOs under anaerobic conditions.

GPS-X ver. 5.0.2 was used as a simulator environment for implementing the developed model and running simulations. Field measurements and lab experiments were conducted at the “Wschod” WWTP (570,000 PE) in Gdansk, northern Poland. The ASM2d was calibrated under dynamic conditions with the results of both batch tests with the settled wastewater and process biomass, and a 96-hour measurement campaign conducted in the full-scale bioreactor

(MUCT process configuration). In addition, two types of the batch tests with ethanol and distillery by-products were used to determine the specific denitrification rates including “conventional” measurements (carbon source and KNO_3 added at the beginning) and measurements during phosphate uptake rate under anoxic conditions (carbon source and KNO_3 added after an anaerobic phase with the settled wastewater). The results of these two tests were used to compare predictions of the new model and ASM2d. Finally, the addition of external carbon source to an anoxic zone of the full scale bioreactor was simulated with both models.

Results and significance of the findings

In the NUR measurements with either ethanol or fusel oil, added in the amount of 350-500 g COD/m^3 , there was no significant $\text{PO}_4\text{-P}$ released to indicate anaerobic consumption of these substrates by PAOs (Figure 2a). For comparison, $\text{PO}_4\text{-P}$ was released during similar experiments with the settled wastewater until the readily biodegradable substrate was present in the batch reactor (data not shown). In the two-phase experiments (Figure 2b), the addition of ethanol or fusel oil in the anoxic phase (in the amount of 30-90 g COD/m^3) increased the anoxic PURs compared to the reference experiments without addition of the external carbon sources at the beginning of the anoxic phase (Swinarski et al., 2009).

When the external carbon source (ethanol or fusel oil) was treated as $S_{A,1}$ in the new model, model predictions matched the experimental data by adjusting two kinetic parameters, (i.e. reduction factor for anoxic activity of X_H with $S_{A,1}$, $\eta_{\text{NO}_3, H1}$, and saturation coefficient for growth on $S_{A,1}$, $K_{S_{A,1}, H}$) in the growth process of “ordinary” heterotrophs on the new substrate ($S_{A,1}$). The stoichiometric yield coefficients, Y_{H1} and Y_{PAO} , were directly determined based on the respirometric measurements (Swinarski et al., 2009). For the remaining six kinetic and stoichiometric coefficients in the new model, the same values were assumed as the corresponding parameters in ASM2d (default or calibrated). For comparison, when the external carbon source was assumed to be a fraction of S_A in the calibrated ASM2d, much higher COD utilization rates were predicted under anoxic conditions (Figures 2a-b) and the anoxic PURs in the two-phase experiments were underestimated (Figure 2b).

For simulations of the full-scale bioreactor performance, it was assumed that 1 m^3/d of the external carbon source (at the concentration of 1,600,000 g COD/m^3) was added to the second anoxic zone (Anox 2) of the bioreactor. In spite of the mechanistically inappropriate approach to treat some external sources as the ASM2d components, the original (calibrated) ASM2d predicted $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ concentrations in the full-scale bioreactor only slightly differently from the new model. Apart from $\text{PO}_4\text{-P}$ in the reactor effluent, the relative deviations between both model predictions for $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ did not exceed 10% in all the sampling points (Figure 3a). For example, the predicted effluent $\text{NO}_3\text{-N}$ concentrations were 7.1 and 6.8 g N/m^3 , respectively, for the new model and ASM2d. This similarity was explained by analyzing in detail the modeled process rates for S_{NO} , S_A and $S_{A,1}$ (Figure 3b-d) and finding comparable utilization rates of S_A (ASM2d) and $S_{A,1}$ (new model) in the second anoxic zone (Anox 2), which were 396 vs. 387 g $\text{COD}/(\text{m}^3 \cdot \text{d})$, respectively.

References

- Satoh, H., Okuda, E., Mino, T. and Matsuo, T. (2000). Calibration of kinetic parameters in the IAWQ Activated Sludge Model: a pilot scale experience. *Water Sci. Technol.*, 42 (3-4), 29-34.
- Swinarski, M., Makinia, J., Czerwionka, K., Chrzanowska, M. and Drewnowski, J. (2009). Comparison of the effects of conventional and alternative external carbon sources for enhancing of the denitrification process. *Water Environ. Res.*, 81, 896-906.

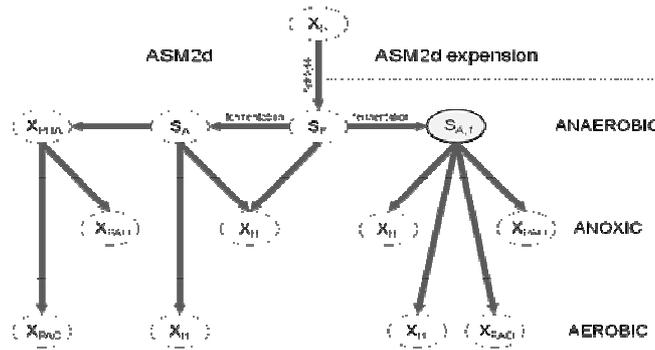


Figure 1. Model concept considering a readily biodegradable substrate not available for PAOs

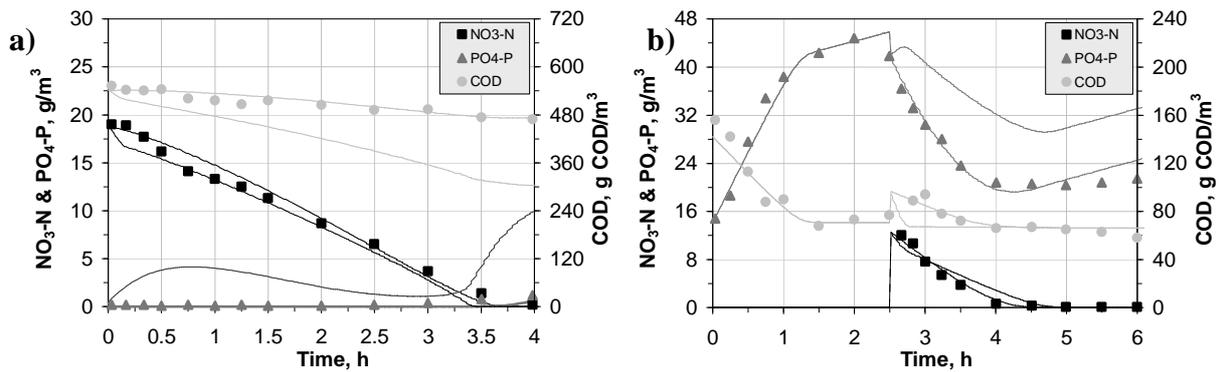


Figure 2. Measured Data vs. Model Predictions of $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$ and COD in Batch experiments with WWTP Mixed Liquor and External Carbon Sources Including Ethanol (the New Model – Solid Lines, ASM2d – Dashed Lines).

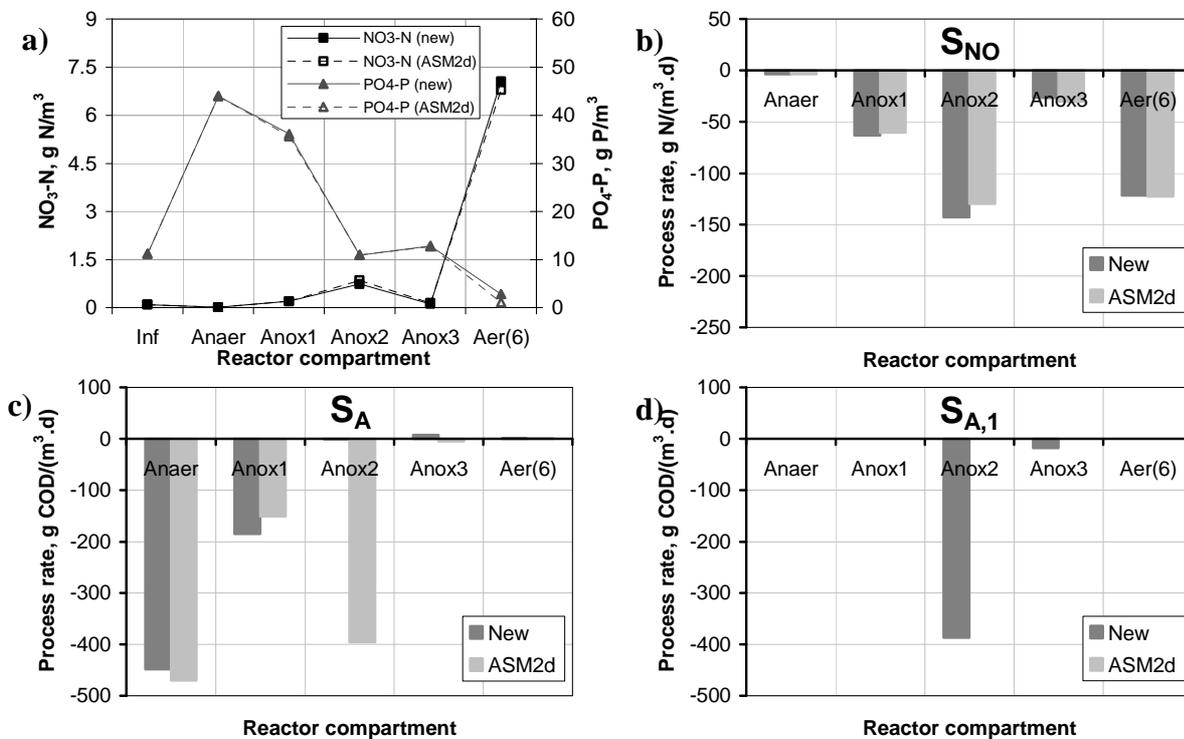


Figure 3. Model (ASM2d and Expanded ASM2d) Predictions of the $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ Concentration Profiles in the Full-Scale MUCT Reactor at the Gdansk WWTP (a), and Predicted Process Rates of $\text{NO}_3\text{-N}$ (S_{NO}), Acetate (S_{A}) and Other Fermentation Products ($S_{\text{A},1}$) (b-d).

Table 1. Stoichiometric Matrix and Process Rates for the Expanded ASM2d Including the New Process Variable ($S_{A,1}$) and Six New Processes.

Process \ Component	S_{O_2}	$S_{A,1}$	S_{NH_4}	S_{NO_3}	S_{PO_4}	X_{PP}	X_H	X_{PAO}
Aerobic growth of X_H on $S_{A,1}$	$-\frac{1-Y_{HI}}{Y_{HI}}$	$-\frac{1}{Y_{HI}}$	$-i_{N,BM}$		$-i_{P,BM}$		1	
Anoxic growth of X_H on $S_{A,1}$		$-\frac{1}{Y_{HI}}$	$-i_{N,BM}$	$-\frac{1-Y_{HI}}{2.86Y_{HI}}$	$-i_{P,BM}$		1	
Aerobic storage of X_{PP} (with $S_{A,1}$)	$-Y_{SA1}$	$-Y_{SA1}$			-1	1		
Anoxic storage of X_{PP} (with $S_{A,1}$)		$-Y_{SA1}$		$-\frac{Y_{SA1}}{2.86}$	-1	1		
Aerobic growth of X_{PAO} on $S_{A,1}$	$-\frac{1-Y_{PAO1}}{Y_{PAO1}}$	$-\frac{1}{Y_{PAO1}}$	$-i_{N,BM}$		$-i_{P,BM}$			1
Anoxic growth of X_{PAO} on $S_{A,1}$		$-\frac{1}{Y_{PAO1}}$	$-i_{N,BM}$	$-\frac{1-Y_{PAO1}}{2.86Y_{PAO1}}$	$-i_{P,BM}$			1

Process	Process rate, ρ_j
Aerobic growth of X_H on $S_{A,1}$	$\mu_{HI} \frac{S_{O_2}}{K_{O_2,H} + S_{O_2}} \frac{S_{A1}}{K_{SA1,H} + S_{A1}} \frac{S_{NH_4}}{K_{NH_4,H} + S_{NH_4}} \frac{S_{PO_4}}{K_{PO_4,H} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,H} + S_{ALK}} X_H$
Anoxic growth of X_H on $S_{A,1}$	$\mu_{HI} \eta_{NO_3,HI} \frac{K_{O_2,H}}{K_{O_2,H} + S_{O_2}} \frac{S_{NO_3}}{K_{NO_3,H} + S_{NO_3}} \frac{S_{A1}}{K_{SA1,H} + S_{A1}} \frac{S_{NH_4}}{K_{NH_4,H} + S_{NH_4}} \frac{S_{PO_4}}{K_{PO_4,H} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,H} + S_{ALK}} X_H$
Aerobic storage of X_{PP} (with $S_{A,1}$)	$q_{PP1} \frac{S_{O_2}}{K_{O_2,PAO} + S_{O_2}} \frac{S_{A1}}{K_{SA1,PAO} + S_{A1}} \frac{S_{PO_4}}{K_{PO_4,PAO} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,PAO} + S_{ALK}} \frac{K_{MAX} - X_{PP}/X_{PAO}}{K_{IPP} + K_{MAX} - X_{PP}/X_{PAO}} X_{PAO}$
Anoxic storage of X_{PP} (with $S_{A,1}$)	$q_{PP1} \eta_{NO_3,PAO1} \frac{K_{O_2,PAO}}{K_{O_2,PAO} + S_{O_2}} \frac{S_{NO_3}}{K_{NO_3,PAO} + S_{NO_3}} \frac{S_{A1}}{K_{SA1,PAO} + S_{A1}} \frac{S_{PO_4}}{K_{PO_4,PAO} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,PAO} + S_{ALK}} \frac{K_{MAX} - X_{PP}/X_{PAO}}{K_{IPP} + K_{MAX} - X_{PP}/X_{PAO}} X_{PAO}$
Aerobic growth of X_{PAO} on $S_{A,1}$	$\mu_{PAO1} \frac{S_{O_2}}{K_{O_2,PAO} + S_{O_2}} \frac{S_{A1}}{K_{SA1,PAO} + S_{A1}} \frac{S_{NH_4}}{K_{NH_4,PAO} + S_{NH_4}} \frac{S_{PO_4}}{K_{PO_4,PAO} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,PAO} + S_{ALK}} X_{PAO}$
Anoxic growth of X_{PAO} on $S_{A,1}$	$\mu_{PAO1} \eta_{NO_3,PAO1} \frac{S_{NO_3}}{K_{NO_3,PAO} + S_{O_2}} \frac{K_{O_2}}{K_{O_2,PAO} + S_{O_2}} \frac{S_{A1}}{K_{SA1,PAO} + S_{A1}} \frac{S_{NH_4}}{K_{NH_4,PAO} + S_{NH_4}} \frac{S_{PO_4}}{K_{PO_4,PAO} + S_{PO_4}} \frac{S_{ALK}}{K_{ALK,PAO} + S_{ALK}} X_{PAO}$