Modification of Activated Sludge Model no. 3 considering direct growth on primary substrate

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Abstract This paper provides the structural framework for the proposed modified version of Activated Sludge Model No. 3 (ASM3), where direct heterotrophic growth on readily biodegradable substrate is included as a new process and provision is made so that growth on internal storage compounds is started sequentially, after the depletion of the external primary substrate pool. The results have provided strong indication that there was a need for considering direct growth on primary substrate as a significant biological mechanism.

Keywords Activated sludge model no. 3 (ASM3); modeling; respirometry

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Introduction

Activated sludge modeling has gained a new perspective with the introduction of substrate storage into activated sludge models. Substantial research has shown that storage mechanism plays an important role under dynamic substrate conditions experienced in treatment plants. Storage phenomena have been encountered in modeling enhanced biological phosphorus removal in ASM2 (Henze *et al*., 1995) and also carbon and nitrogen removal processes in ASM3 (Gujer *et al*., 2000).

Storage of excess substrate available under feast conditions allows microorganisms capable of substrate storage to survive on the accumulated substrate reserves when no external substrate is present (famine conditions). These microorganisms have the benefit of a more balanced growth and an advantage in competition (van Loosdrecht and Heijnen, 1997).

Conceptual approach

ASM3 assumes that storage of readily biodegradable substrate is the preliminary step before growth solely occurs on the stored products. This assumption of simultaneous storage and growth on the storage polymers is not valid mechanistically, since experimentally microorganisms utilize the stored polymers as a carbon and energy source only after the depletion of the primary substrate. This is taken into account in metabolic models predicting that excess substrate is stored while the primary substrate, if present, is utilized for growth (van Aalst-van Leeuwen *et al*., 1997; Dircks *et al*., 2001). ASM3, as it is, can be used to describe the behaviour of activated sludge systems for real cases (Koch *et al*., 2000) but the description is not satisfactory for experimental data obtained for batch tests. It has been reported that a superficially high storage yield (Y_{STO}) value of 0.96 gCOD/gCOD was obtained for filtered domestic sewage due to the definition of readily biodegradable COD and the total storage approach (Karahan-Gül *et al*., 2001). ASM3 also fails to simulate high

rate of oxygen utilization in the feast phase and the lower rate in the famine phase due to the single growth process definition as shown in Figure 2a. From the figure it is clearly seen that two different growth rates are necessary to describe the OUR response of the batch system. A more consistent description could be provided if growth in the feast phase is included in the model (Krishna and van Loosdrecht, 1999a) and thus, one of the main issues that needs to be evaluated in conjunction with ASM3 is heterotrophic growth on primary substrate, which occurs as a competing mechanism with storage. This mechanism could play an important role when different reactor and treatment plant configuration and flow regimes are considered or temperature varies (Krishna and van Loosdrecht, 1999b).

Model development

Storage of readily biodegradable COD by heterotrophs under aerobic conditions involves two different mechanisms; (i) storage of poly-β-hydroxybutyrate (PHB) when acetate is fed to the system, (ii) storage of glycogen when glucose is the carbon source. PHB metabolism has been described by van Aalst-van Leeuwen *et al*., 1997 and the stoichiometry and kinetics have also been studied by Beun *et al*., 2000. The metabolic model of PHB storage shown in Figure 1a, suggests that acetate is taken up and converted to acetyl-CoA, which is used to produce biomass and for PHB synthesis. Acetyl-CoA is also used as the energy source. When all the acetate is taken up, stored PHB is hydrolyzed to generate acetyl-CoA under famine conditions. Growth yields under feast conditions have been reported as 0.47 and 0.41 g cellCOD/gCOD; the storage yields as 0.73 and 0.69 gCOD/gCOD and the growth yields on PHB as 0.60 and 0.57g cellCOD/gCOD by Aalst-van Leeuwen *et al*. (1997) and Beun *et al*. (2000), respectively.

Dircks *et al*. (2001), investigated the stoichiometry and kinetics of glycogen metabolism in mixed cultures. The glycogen metabolism is described as shown in Figure 1b. Glucose is taken up and Glucose-6-phosphate (G6P) is produced, which is then converted into glycogen and used for biomass production. G6P is also used for catabolic reactions consuming oxygen. After the depletion of primary substrate, glycogen is used for the synthesis of G6P. Dircks *et al*. (2001), have reported the storage yield of glycogen as 0.91 gCOD/gCOD and the growth yield in the feast phase as 0.57 g cellCOD/gCOD. The growth yield in the famine phase was given as 0.60 g cellCOD/gCOD.

Based on the scientific background suggested by metabolic models, the addition of the growth process on the primary carbon source to ASM3 was proposed. The modeling studies conducted by Krishna and van Loosdrecht (1999a) resulted in a better description of the system where the storage yield was adopted as 0.73 gCOD/gCOD; direct growth yield as 0.50 g cellCOD/gCOD; the growth yield on PHB as 0.65 cellCOD/gCOD and the rate of storage was given as 10 d^{-1}, similar to the value reported by Koch *et al*. (2000).

The modified version for the carbon removal processes of ASM3 has been prepared in this study, based on existing scientific information reported in the literature and is given in Table 1. The proposed model consists of hydrolysis, endogenous respiration of biomass and respiration of storage products processes, as described in ASM3. Storage of readily biodegradable substrate and primary growth processes were described as simultaneous

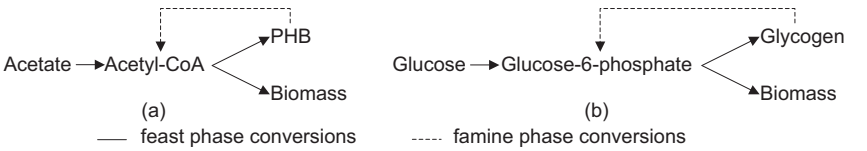

Figure 1 Metabolic pathways for (a) PHB and (b) Glycogen storage

processes, competing for substrate and electron acceptor. Both processes have reaction rates defined according to Monod kinetics, where the growth process has ammonia nitrogen and bicarbonate limitations. The secondary growth process is inhibited when primary substrate is present in the system, uses stored products as substrate and process kinetics was defined as surface reaction kinetics similar to ASM3.

The model simulation of an OUR curve generated using the proposed model shows the relative impact of direct growth and storage mechanism on O_2 utilization for a set of batch OUR experiments conducted on acetate, evaluated for a selected range of kinetic coefficients (Table 2). As shown in Figure 2, the results have provided strong indication that there was a need for considering direct growth on primary substrate as a significant biological mechanism.

Materials and methods

Experimental studies were conducted with 2 l double jacketed SBR equipped with pH and dissolved oxygen electrodes with a cycle length of 4 hours. The system was operated at pH 7, 20°C and with SRT of 5 days. The culture was enriched on starch and for the batch experiments SBR was fed with glucose during 3 minutes after an idle period of 10 minutes. Aeration and mixing was carried for 130 minutes and sludge was withdrawn in 2 minutes.

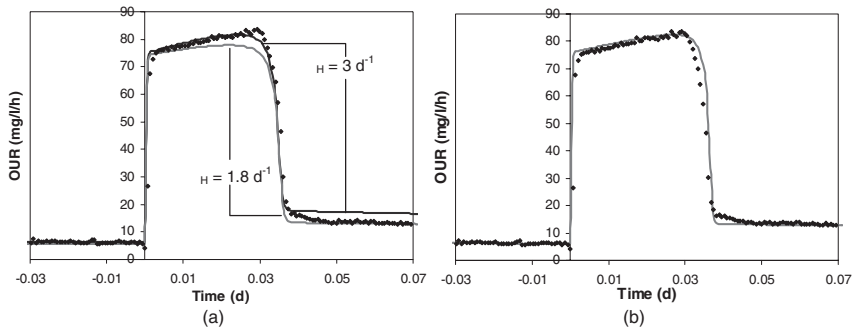

Figure 2 OUR simulations performed using (a) ASM3 for two different growth rates and (b) modified ASM3

Table 1 Matrix representation of the proposed model structure

Component / *Process*	S_O O_2	S_I COD	S_S COD	X_I COD	X_S COD	X_H COD	X_{STO} COD	*Rate*
Hydrolysis		f_{SI}	1–f		–1			$k_H \frac{X_S/X_H}{K_X + X_S/X_H} X_H$
Aerobic storage of COD	$-\frac{1-Y_{STO}}{Y_{STO}}$		$-1/Y_{STO}$			1		$k_{STO} \frac{S_O}{K_O+S_O} \frac{S_S}{K_S+S_S} X_H k_H \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
Growth on S_S	$-\frac{1-Y_{H1}}{Y_{H1}}$		$-1/Y_{H1}$			1		$m_{H1} \frac{S_O}{K_O+S_O} \frac{S_{NH}}{K_{NH}+S_{NH}} \frac{S_{HCO}}{K_{HCO}+S_{HCO}} \frac{S_S}{K_S+S_S} X_H$
Growth on X_{STO}	$-\frac{1-Y_{H2}}{Y_{H2}}$					1	$-1/Y_{H2}$	$m_{H2} \frac{S_O}{K_O+S_O} \frac{K_S}{K_S+S_S} \frac{S_{NH}}{K_{NH}+S_{NH}} \frac{S_{HCO}}{K_{HCO}+S_{HCO}} \frac{X_{STO}/X_H}{K_{STO}+X_{STO}/X_H} X_H$
Endogenous respiration	–(1–f_I)				f_I		–1	$b_{H,O2} \frac{S_O}{K_O+S_O} X_H$
Respiration of X_{STO}	–1						–1	$b_{STO,O2} \frac{S_O}{K_O+S_O} X_{STO}$

Table 2 Kinetic and stoichiometric coefficients obtained for OUR response for a batch test with acetate

Model coefficient	ASM3	Modified ASM3
K_{STO} (d^{-1})	16	14
K_S (mgl^{-1} COD)	4	3
Y_{STO} (gCOD/gCOD)	0.80	0.80
$\mu_{H1,}$ (direct growth) (d^{-1})	–	4
$\mu_{H2,}$ (growth on PHB) (d^{-1})	3 and 1.8	3
K_{STO}	1	0.4
Y_{H1} (direct growth) (g cellCOD/gCOD)	–	0.65
Y_{H2} (growth on PHB) (g cellCOD/gCOD)	0.63	0.75
b_{STO} (d^{-1})	0.24	0.24
b_H (d^{-1})	0.24	0.24
f_l (gCOD/gCOD)	0.20	0.20

The settling phase was 90 minutes and the effluent of 1 l was withdrawn in the last 8 minutes of the cycle. Glucose concentration was adjusted to 180 mg COD/l and the nutrients were supplied in excess amounts. ATU was added to the reactor in the beginning of the cycle to prevent nitrification. The analyses were done as described in the study of Dircks *et al*. (2001).

Experimental results

Experiments conducted with 182 mg COD/l glucose resulted in the depletion of substrate in 33 minutes (Figure 3) and the corresponding glycogen storage was measured as 109 mg COD/l as shown in Figure 3. The amount of ammonia nitrogen consumed for growth in the feast phase was 3.5 mg NH_4-N/l (Figure 3). Assuming a biomass composition of $C_5H_7NO_2$, the corresponding net amount of biomass generated was estimated as 40 mg cellCOD/l. These results for the feast phase were used to calculate the yield for storage of glycogen as 0.90 gCOD/gCOD and the growth yield on glucose was 0.67 g cellCOD/gCOD. Under these experimental conditions 66% of the glucose fed to the system was stored as glycogen and the remaining 34% was used for direct growth. The amount of glycogen consumed in the famine phase was measured as 52 mg COD/l with a corresponding ammonia nitrogen consumption of 1.5 mg NH_4-N/l and an estimated net biomass generation of 17 mg cellCOD/l.

The proposed model was simulated for the experimental conditions of the SBR system using AQUASIM® (Reichert *et al*., 1998). The model results are given in Figure 4 together with the experimental data.

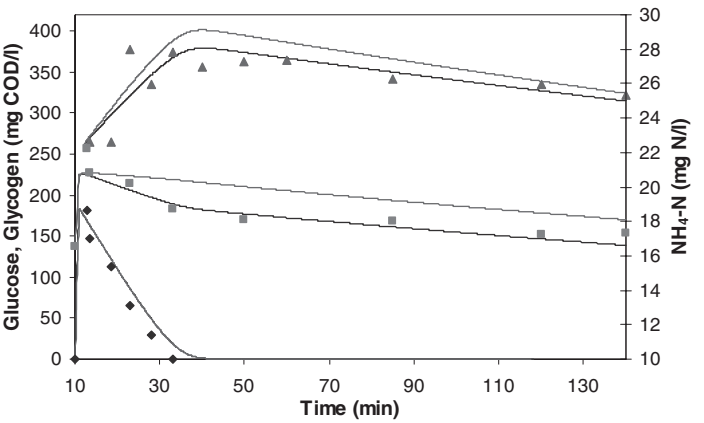

Figure 3 Experimental data for ◆ glucose, ▲ glycogen and ■ ammonia and the model simulation results for — ASM3 and — modified ASM3

Respirometry has been extensively used for the experimental assessment of activated sludge models. In this context an OUR profile obtained from the reactor was a useful tool to differentiate ASM3 from its modified version including direct growth on primary substrate competing with storage. The OUR response of the system and the results of model simulation performed for ASM3 and modified ASM3 with the kinetic and stoichiometric coefficients given in Table 3 are presented in Figure 4.

Discussion

The experimental results obtained and the simulations performed with the proposed model have yielded good correlation in terms of the amount of glycogen stored, ammonia nitrogen consumed and the biomass produced. The simulations with ASM3 however, resulted in higher glycogen storage, less ammonia consumption and therefore less biomass production. The substrate utilization and the OUR response of the system under feast conditions were equally well simulated with both models, however ASM3 could not cope with the decrease of the OUR level in the famine phase. It is clearly seen from the experimental results obtained from ammonia measurements that the feast phase growth rate is higher than that of the famine phase. Thus two different growth rates are necessary to simulate the system response which can also be observed from the OUR data.

The two different growth rates observed in the system are due two different growth processes occurring, namely growth on primary substrate and growth on storage products. ASM3 with only one growth process can neither predict the amount of sludge produced, nor simulate lower electron acceptor utilization rate in the famine phase. The proposed model with the addition of the growth process on primary substrate, resulted in two different specific growth rates, where the specific growth rate in the famine phase was 33% of that of the feast phase as shown in Figure 5. ASM3 generates a lower growth rate throughout the experiment which gives a lower biomass yield.

Table 3 Kinetic and stoichiometric coefficients obtained for SBR system fed with glucose

Model coefficient	ASM3	Modified ASM3
$k_{STO}(d^{-1})$	12	8
K_S (mgl^{-1} COD)	18	18
Y_{STO} (gCOD/gCOD)	0.88	0.90
$\mu_{H1,}$ (direct growth) (d^{-1})	–	2
$\mu_{H2,}$ (growth on glycogen) (d^{-1})	2.5	2.5
K_{STO}	1	1
Y_{H1} (direct growth) (g cellCOD/gCOD)	–	0.67
Y_{H2} (growth on glycogen) (g cellCOD/gCOD)	0.60	0.70
b_{STO} (d^{-1})	0.10	0.10
b_H (d^{-1})	0.20	0.20
f_I (gCOD/gCOD)	0.20	0.20

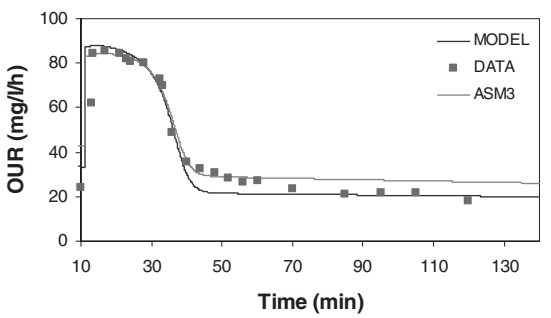

Figure 4 OUR data and the model simulation results for proposed model and for ASM3

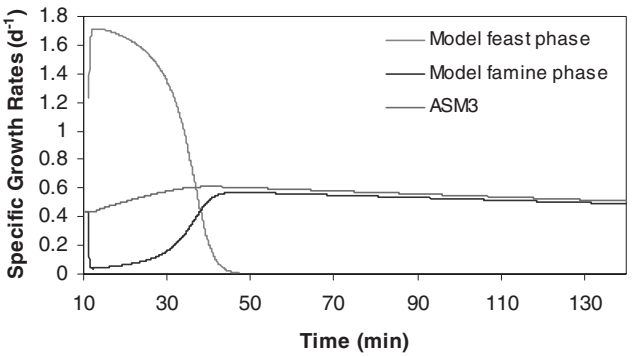

Figure 5 Specific growth rates obtained for proposed model and for ASM3

The modeling results for tests conducted with acetate provided a good description of the OUR response. However, the yields of the two growth processes have been found to be higher than those presented in the literature, since higher endogenous decay rates were assumed for this study according to ASM3, whereas much lower decay rates have been reported for enriched cultures fed with acetate. The modeling results of SBR system fed with glucose yielded a maximum secondary growth rate (μ_{H2}) higher than primary growth rate (μ_{H1}) due to the definition of the secondary growth process in terms of Monod kinetics.

Conclusion

The main assumption of ASM3 stating that all the readily biodegradable COD is stored and growth only occurs at the expense of storage polymers is not mechanistically valid, since the growth metabolism on the stored products is only activated when external substrate is depleted. Hence, growth on primary substrate occurs simultaneously with substrate storage under dynamic conditions and thus should be taken into account in activated sludge models.

Although ASM3 can be used to describe the behaviour of activated sludge treatment plants, it fails to simulate the experimental data obtained from batch experiments. The simulation results have shown that, ASM3 predicts higher glycogen storage, lower ammonia consumption and thus lower biomass production. ASM3 cannot cope with the low level of oxygen utilization in the famine phase due to the single growth process, with an average lower specific growth rate. Therefore, the real case applications of ASM3 can have misleading results for sludge production, storage polymer (e.g. glycogen) content of excess sludge and ammonia utilization for heterotrophic growth.

In order to have better predictions for real case applications and batch tests for model parameter determination, ASM3 has to be modified in terms of storage and growth process descriptions. The results have provided a strong indication that there was a need for considering direct growth on primary substrate as a significant biological mechanism. This study involves a proposed version of ASM3 where a new growth process on external substrate is added. The proposed model gave a better description of the results obtained for batch test in terms of O_2 utilization, glycogen generation and biomass production compared to ASM3 for a selected range of kinetic coefficients.

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