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A new interpretation of endogenous respiration profiles for the evaluation of the endogenous decay rate of heterotrophic biomass in activated sludge

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ABSTRACT

In current activated sludge models aerobic degradation, resulting in loss of activity and mass of activated sludge is expressed with only one process called decay. The kinetics of this process is regarded to be first order and constant with respect to the loading conditions. In this work twelve aerobic digestion batch experiments were conducted for the activated sludge of seven different water resource recovery facilities (WRRFs). An analysis of the obtained respirograms shows three clearly distinguishable phases. The first phase is assumed to be due to the degradation of stored material (X_{STOR}) and active biomass simultaneously. The second phase is exclusively due to the degradation of active biomass that is regarded to consist mainly of ordinary heterotrophic biomass (X_{OHO}). The first order decay rate is slower than the degradation rate in phase 1 and varies between samples. The decay rate correlates with the activity of the activated sludge expressed as the ratio of initial heterotrophic OUR and the initial organic fraction X_{ORG} of the activated sludge. This second phase was detectable until day 5 of most of the experiments. After that time within phase 3 the OUR decrease slows down and the OUR even increased for short intervals. This behaviour is thought to be due to the activity of higher organisms and the adaptation of microorganisms to starvation.

1. Introduction

One of the main objectives of activated sludge modelling is the prediction of sludge production in WRRFs. On the one hand, sludge production is the result of biomass growth and unbiodegradable material accumulation. On the other hand, particularly in systems with a longer solid retention time (SRT), growth antagonistic processes play an important role. These processes are generally described as lysis or decay of active biomass and slow degradation of other organic material (Henze et al., 2000).

Experimentally it is common practise to use aerobic batch digestion experiments to gain information about the processes that are involved in degradation of activated sludge (Spanjers and Vanrolleghem, 1995, 1996). The assumption is that this information is representative to describe decay in an environment where decay and growth takes place simultaneously. The metabolic explanation of these processes is expressed in concepts like endogenous respiration (Gujer et al., 1999), death-regeneration (Dold et al., 1980), maintenance (Loosdrecht van and Henze, 1999) or predation (Moussa et al., 2005). All these concepts are based on the assumption

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that organic material (X_{ORG}) in activated sludge consists of a biodegradable fraction ($X_{ORG,DEG}$) and an unbiodegradable fraction ($X_{ORG,U}$).

$$XORG = XORG,DEG + XORG,U \ (mg\ COD/l) \quad (1)$$

To convert organic material that is measured as volatile suspended solids (VSS) into chemical oxygen demand (COD) units typically a constant factor $f_{CV} = 1.42$ g COD/g VSS is used (Henze et al., 2000).

The biodegradable fraction (f_{DEG}) of X_{ORG} in long SRT systems consists overwhelmingly of ordinary heterotrophic organisms (X_{OHO}), whereby for reasons of simplicity the very small fraction of autotrophic active biomass is included in X_{OHO}. However, X_{OHO} has an unbiodegradable fraction f_U that is called endogenous residue ($f_U{}^*X_{OHO}$) and is a left over from the degradation of active biomass X_{OHO}.

$$X_{ORG,DEG} = X_{ORG} \cdot f_{DEG} = (1 - f_U) \cdot X_{OHO} \ (mg\ COD/l) \quad (2)$$

The pool of unbiodegradable organic material ($X_{ORG,U}$) is fed by unbiodegradable organic compounds from the influent ($X_{ORG,U,inf}$) and by X_{OHO} in terms of endogenous residue.

$$X_{ORG,U} = X_{ORG,U,inf} + f_U \cdot X_{OHO} X_{ORG,DEG} = X_{ORG} \cdot f_{DEG} = (1 - f_U) \cdot X_{OHO} \ (mg\ COD/l) \quad (3)$$

In the endogenous respiration concept the biodegradable fraction of X_{OHO} is regarded as a homogenous substrate that undergoes self-destruction in the absence of external substrate. The degradation process of X_{OHO} is modelled with Eq. (4) and Eq. (5), where the rate constant of degradation is generally called the decay rate parameter (b). In activated sludge models, the decay rate parameter is assumed to be constant.

$$\frac{dX_{OHO}}{dt} = -b_{OHO} \cdot X_{OHO} \quad (4)$$

$$X_{OHO(t)} = X_{OHO(0)} \cdot e^{-b_{OHO} \cdot t} \ (mg\ COD/l) \quad (5)$$

The concentration of X_{ORG} at any time within a degradation experiment can be expressed with Eq. (6) and is referred as the VSS based method to determine the decay rate b_{OHO} (Ramdani et al., 2010):

$$X_{ORG(t)} = X_{ORG,U,inf} + f_U \cdot X_{OHO} + (1 - f_U) \cdot X_{OHO(0)} \cdot e^{-b_{OHO} \cdot t} X_{OHO(t)} = X_{OHO(0)} \cdot e^{-b_{OHO} \cdot t} \ (mg\ COD/l) \quad (6)$$

The endogenous respiration is limited by the internal carbon source that is $(1 - f_U)^*X_{OHO}$. The endogenous respiration rate $OUR_{OHO}(t)$ during the aerobic degradation experiment is modelled with Eq. (7) and Eq. (8) and refers to the OUR based method to determine the decay rate b_{OHO} (van Haandel et al., 1998; Ramdani et al., 2010):

$$OUR_{OHO}(t) = (1 - f_U) \cdot \frac{X_{OHO}}{dt} \quad (7)$$

$$OUR_{OHO}(t) = (1 - f_U) \cdot X_{OHO}(0) \cdot b_{OHO} \cdot e^{-b_{OHO} \cdot t} \ (mg\ O_2/(l * h)) \quad (8)$$

Solving Eq. (8) for t = 0 yields:

$$OUR_{OHO}(0) = (1 - f_U) \cdot X_{OHO}(0) \cdot b_{OHO} \ (mg\ O_2/(l * h)) \quad (9)$$

Rearranging Eq. (9) for b_{OHO} shows, that a constant decay rate implies a constant ratio of $OUR_{OHO}(0)$ to $X_{OHO}(0)$.

$$\frac{OUR_{OHO}(0)}{(1 - f_U) \cdot X_{OHO}(0)} = b_{OHO}(h^{-1}) \quad (10)$$

It is important to note that in this model the degradation characteristics of X_{OHO} are independent of the loading of external substrate in the WRRF. Therefore the endogenous decay rate parameter is independent of the F/M ratio and independent of the SRT.

Experimental evidence for the validity of the endogenous respiration model comes from Marais and Ekama (1976). Using the OUR method, the value of b_{OHO} was found to be 0.24 d^{-1} and independent from SRT in the range of 2.5–30 days. Similar results were obtained by van Haandel et al. (1998), who extended the measured parameters by the degradable VSS, the formed nitrate and the loss of alkalinity. In a more recent work of Ramdani et al. (2010), activated sludge was fed with acetate and produced a decay rate of 0.23 d^{-1} for a SRT of 5 and 10 days for both the VSS and the OUR method.

However, from the literature review that is summarized in Table 1 it can be stated that:

The reported **endogenous decay rates** b_{OHO} vary significantly between values of 0.059 d^{-1} and 0.500 d^{-1}.

Data for heterotrophic decay rates were reported for four **methods**. The largest number of reported decay rates are based on the above described OUR and VSS based method. There are a few references that show decay rates which were determined with the OUR_{max} method, where not the endogenous respiration but the respiration at substrate saturation was measured and linearized over the time of an aerobic digestion batch experiment. Two references used the DNA concentration instead of respiration as a parameter to correlate the active biomass concentration in the liquid. The method used in the respective experiment appears to have an influence on the decay rate. In general the OUR and the VSS based methods yield higher decay rates than using the DNA concentration or the OUR_{max} at substrate saturation to describe the decay process. This observation indicates that there might be a difference in endogenous degradation of VSS and in the reduction of activity or viability of active biomass.

The **quality** of the degradation experiments are mostly expressed in terms of R^2 with respect to the linearized data. Thereby it is common practice to regard a reaction with data of $R^2 > 0.95$ as a first order reaction and the substrate that is used up as homogenous. In reality the data can reveal even at higher R^2 a series of different degradation characteristics. However, crucially only a small number of references published the results of the COD balance over the experiment although this is a very important method to show the reliability of the data. Especially the use of open respirometers results in the intrusion of oxygen via the open liquid surface and will affect the COD balance and the decay rate parameter.

There is very little information in the literature about the **initial characteristics of** the used **activated sludge**. From Eq. (10) it is evident that OUR(0) and VSS(0) associated with the degradable fraction of VSS is a very important additional information to explain the measured decay rate.

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Table 1 – Literature review of decay rates and additional information of determination.

Author	Method	$b20$	R^2	Temp.	T corr.	SRT	Test-time	Surface	Origin WW	ATU	COD-Bal
		1/d	–	°C	–	d	d	–		mg/l	8
DWA A131 (2000)	n.i.	0.241	n.i.	n.i.	1.072	n.i.	n.i.	n.i.	n.i.	n.i.	n.i.
Gujer et al. (1999)	n.i.	0.200	n.i.	n.i.	1.072	n.i.	n.i.	n.i.	n.i.	n.i.	n.i.
Henze et al. (1987)	n.i.	0.240	n.i.	n.i.	1.121	n.i.	n.i.	n.i.	n.i.	20	n.i.
Henze et al. (1995)	n.i.	0.155	n.i.	n.i.	1.072	n.i.	n.i.	n.i.	n.i.	n.i.	n.i.
Metcalf and Eddy (2004)	n.i.	0.100	n.i.	n.i.	1.023	n.i.	n.i.	n.i.	n.i.	n.i.	n.i.
Benedek et al. (1972)	OURe	0.112	n.i.	20	1.072	n.i.	n.i.	Open	Municipal	No	n.i.
Lee et al. (2003)	OURe	0.240	0.987	20	n.i.	20	10	Open	Municipal	No	n.i.
Lee et al. (2003)	OURe	0.310	0.987	20	n.i.	10	10	Open	Municipal	No	n.i.
Marais and Ekama, 1976	OURe	0.240	n.i.	14	1.029	2–25	10	Open	Municipal	n.i.	n.i.
Ramdani et al. (2010)	OURe	0.233	0.990	20–24	1.029	5–10	21	Closed	Synthetic	No	97–103
Siegrist et al. (1999)	OURe	0.500	n.i.	10	1.070	16	7	Open	Municipal	n.i.	n.i.
van Haandel et al. (1998)	OURe, VSS, NO_3, Alk	0.246	0.970	20	1.040	3–10	6	Open	Municipal	n.i.	n.i.
Adams et al. (1974)	VSS	0.325	n.i.	n.i.	n.i.	n.i.	17	n.i.	n.i.	n.i.	n.i.
Ramdani et al. (2010)	VSS	0.238	0.990	20–26	1.029	5–10	21	Closed	Synthetic	No	n.i.
Avcioglu et al. (1998)	OUR_{max}	0.075	0.965	18	n.i.	15	n.i.	Open	Industrial	Yes	n.i.
Hao et al. (2009)	OUR_{max}	0.148	0.990	25	1.072	10	7	Closed	Synthetic	5	n.i.
Lavallée et al. (2002)	OUR_{max}	0.400	>0.900	20	n.i.	5–7	21	Closed	Municipal	25	n.i.
Brands et al. (1994)	DNA	<0.100	>0.980	20	n.i.	low + high	21	Closed	n.i.	n.i.	n.i.
Liebeskind et al. (1996)	DNA	0.136	0.950	20	n.i.	2	10	Closed	Municipal	n.i.	n.i.
Liebeskind et al. (1996)	DNA	0.099	0.960	20	n.i.	6	10	Closed	Municipal	n.i.	n.i.
Liebeskind et al. (1996)	DNA	0.080	0.960	20	n.i.	9	10	Closed	Municipal	n.i.	n.i.
Liebeskind et al. (1996)	DNA	0.059	0.890	20	n.i.	24	10	Closed	Municipal	n.i.	n.i.

n.i. = no information, OURe = OUR due to endogenous respiration

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There are no specific studies available that describe the **influence of allylthiourea (ATU)** on the heterotrophic metabolism. Therefore it is possible that inhibition of heterotrophic activity occurs to a certain degree in addition to that of nitrification. For instance the work of Lavallée et al. (2002) has to be evaluated in relation to this specific background.

The data for the **temperature dependency** of the aerobic degradation process expressed as Van't Hoff-Arrhenius temperature correction factor (θ) range from a very low value of $\theta = 1.029$ in Marais and Ekama (1976) and Ramdani et al. (2010) to very high values of $\theta = 1.121$ in Henze et al. (1987). Therefore it is difficult to compare decay rates that were determined at different temperatures.

There are two references that show a direct dependency of the decay rate on the **sludge age**. Lee et al. (2006) used the OUR method for activated sludge with 10 d and 20 d sludge age and found values for b_{OHO} of 0.24 d^{-1} and 0.31 d^{-1} respectively. Liebeskind et al. (1996) using the DNA method tested activated sludge of four different sludge ages from 2 d to 24 d and observed decay rates from 0.136 d^{-1} to 0.059 d^{-1}.

Taking the above aspects into account it is the focus of this study to find an answer to the following questions:

1. Is the substrate that is used up in aerobic digestion batch experiments as homogenous as initially suggested?
2. Do the active organisms lack the ability of adaptation during the course of the experiment?
3. Is the heterotrophic decay rate constant and independent from the sludge age of the activated sludge in the WRRF?

2. Materials and methods

2.1. Method used

In this investigation the OUR based method was used. Experimental details are best explained in Ramdani et al. (2010). It was decided not to run the VSS based method in parallel because the data density of OUR values is much higher and allows more insight into the particular degradation processes. Throughout the experiments no nitrification inhibitor was used.

2.2. Origin and characterisation of activated sludge

The activated sludge for the aerobic digestion batch tests was drawn from the return sludge of seven different full scale activated sludge WRRFs ranging from 15.000 to 400.000 PE. With the exception of plant G all WRRFs are equipped with a primary settler. The characteristics are summarized in Table 2. The time from sampling to the start of the experiment was not longer than 1.5 h. The sludge was diluted with effluent and the temperature adjusted to 20 °C. The SRT was taken from operator reports and partially from own investigations. However, the determination of the SRT relies often on assumptions, like the TSS in the waste activated sludge (WAS) and not on measurements. Because of this uncertainty in this study the initial specific OUR(0) (spOUR(0)) in mg O_2/(g VSS*d) of the activated sludge sample is regarded more suitable for describing the loading state of the particular activated sludge. In this context a high F/M ratio (low sludge age) corresponds to a high spOUR(0).

Table 2 – Characteristics of activated sludge used in aerobic digestion batch experiments.

Nr.	Origin	TSS	VSS	VSS/TSS	OUR(0)	spOUR(0)
		g/l	g/l	%	mg O_2/(l*h)	mg O_2/(gVSS*h)
1	A	3.16	2.32	73	13.9	6.0
2	B	3.03	2.24	74	12.3	5.5
3	C	2.96	2.10	71	18.5	8.8
4	A	3.02	2.08	69	10.3	5.0
5	D	3.12	2.30	74	20.6	9.0
6	D	3.44	1.98	70	15.3	6.7
7	E	3.05	2.28	75	16.9	7.4
8	A	2.95	2.07	70	10.2	4.9
9	A	4.31	2.95	69	13.8	4.7
10	F	4.13	3.02	73	20.3	6.7
11	A	3.65	2.55	68	14.7	6.0
12	G	3.94	3.04	77	14.5	4.8

2.3. Experimental setup

The respirometer consists of a reactor, an oxygen measuring device (WTW 320i), an aquarium aerator (compressor and fine bubble aerator stone) and the software based on the Labview software package. The compressor was switched on if DO dropped below a chosen low limit and was switched off if DO exceeded a definable upper limit. The oxygen limits in the batch test where 4 mg O_2/l (lower limit) and 6 mg O_2/l (upper limit). The slope (time from the upper to the lower limit) was computed as OUR in mg O_2/(l*h).

The reactor configuration is shown in Fig. 1. It consists of a glass flask of 2.5 l volume and a glass ball on top of that flask to take up the expanded sludge volume during the aeration periods. This arrangement minimizes DO diffusion through the

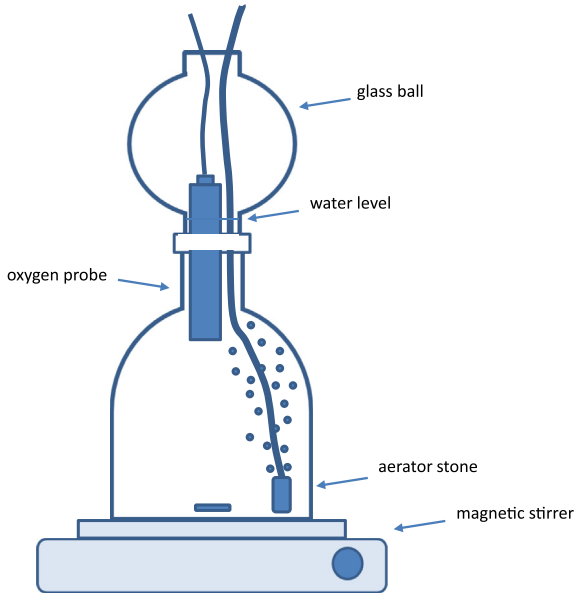

Fig. 1 – Reactor configuration of the respirometer.

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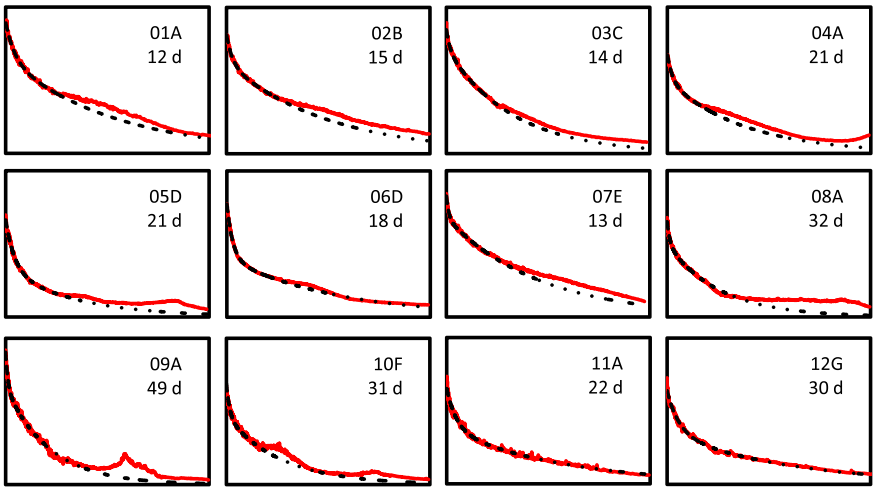

Fig. 2 – Respirograms of aerobic digestion batch tests with OUR measured (solid line) and OUR modelled (dashed line).

open surface during the DO decline period as the space between the oxygen probe and the aeration tube is very small. Oxygen intrusion was measured by filling the reactor with tap water and adding a small amount of Na_2SO_3 to reduce the DO to zero. The tap water was aerated until the DO started to rise above 0 mg/l and the aerator was switched off. The oxygen intrusion was measured at a certain rotation speed of the mixer as DO increase over the time and was less than 0.01 $mgO_2/(l*h)$. With this reactor configuration it is possible to measure OUR values of less than 0.2 mg $O_2/(l*h)$ with a high degree of linearity of the decreasing DO.

The temperature was controlled via room temperature and varied between 20 °C and 22 °C. However all OUR values were corrected with a Van't Hoff-Arrhenius temperature correction $b_T = b_{20}{}^*\theta^{(T-20)}$, with $\theta = 1.072$, following the majority of the authors from the literature review.

The pH was controlled manually by adding NaOH to prevent a pH decrease below 7.0.

2.4. *Analytical methods*

The TSS was measured with 100 ml test volume and an ash free filter. To determine the TSS the sludge was filtered and dried in a microwave (DWA, 2003) for 8 min at 700 W. To determine the VSS the dried filter with sample was burned in rapid incinerator SVR/E (Harry Gestigkeit GmbH) at 550 °C for 2 h.

To account for the nitrogen, that was released and nitrified, nitrate was measured at the end of the experiment. This was done using a quick test kit from Hach-Lange LCK 340.

2.5. *COD balance*

To check the quality of the experiment a COD balance was performed using the following relationship:

$$\begin{aligned} \text{COD} - \text{Balance} &= \text{COD}_{\text{start}} - \text{COD}_{\text{end}} + \text{COD}_{\text{loss}} \\ &+ \text{Integral OUR}_e + (\text{NO}_3\text{–N}_{\text{end}} - \text{NO}_3\text{–N}_{\text{start}}) \cdot 4.57 \end{aligned} \quad (11)$$

The COD loss is obtained by collecting the TSS that was sticking at the sidewalls of the glass ball on top of the reactor. In average this loss was 2% of the initial TSS. The nitrate in the sample at the beginning of the experiment was always zero due to anoxic sample transportation.

Eight out of these twelve tests had a duplicate test with high reproducibility and good COD balances. Most of them were alike and lead to the same component portions and rates. However, since the COD balance of all tests was close 100% it was not thought to be necessary to display and discuss duplicate respirograms.

3. Results and discussion

3.1. *Structural analysis of the respirograms*

The OUR profile of all respirograms as summarized in Fig. 2 were analysed. Fig. 3 shows an example for a typical respirogram in more detail. 3 different phases could be distinguished: Phase 1 was characterized by a rapid OUR decrease that lasts for 0.5–4.0 days. It was directly followed by Phase 2 that shows for a couple of days a true exponential decrease of the endogenous respiration rate. This rate was found to be much

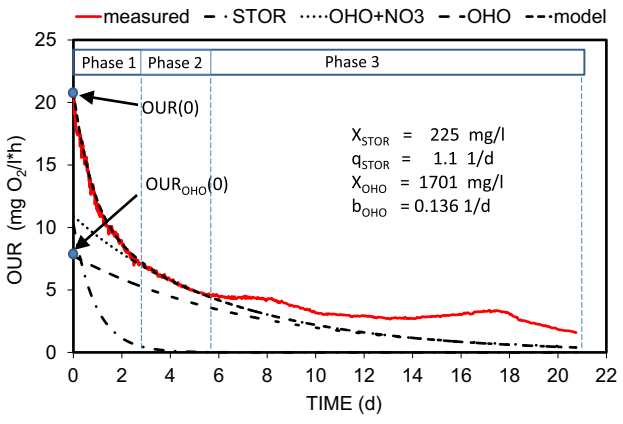

Fig. 3 – Respirogram (5D).

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lower than the OUR decrease of phase 1. Phase 3 was regarded to be the remaining part of the respirograms. In general the OUR of this phase was even slower as in phase 2 and had sometimes but not always increasing and more rapid decreasing sections.

From the above analysis it became obvious that for the OUR of phases 1 and 2 a distinct reaction rate was detectable. However the reduced decrease and even the increase of OUR in phase 3 could not be related to the characteristics of phase 1 or phase 2. It is likely that adaptation of active biomass to starvation and the temporary proliferation of higher organisms (predators) lead to deviations from the model of phase 2. However, experiments 11 and 12 did not show these disturbances and phase 2 lasted to the end of the experiment.

3.2. *Modelling OUR*

With regard to phase 1 there are two options to explain the high initial OUR. For option 1 it was hypothesised that within the first rapid reaction storage products (X_{STOR}) e.g. PHA's could have been used up. The theory is supported by the fact that the highest amount of stored and aerobically degraded substrate was found in the sludge of the only WRRF that was run successfully with excess biological phosphorus removal. As option 2 it can also be hypothesised that biodegradable particulate material ($X_{B,inf}$) from the influent is responsible for the high initial OUR. However, in this case a direct correlation of OUR of phase 1 and the spOUR(0), indicative of loading conditions, would have been observed. This could not be verified. Therefore option 1 was preferred to explain the OUR of phase 1. The $OUR_{STOR}(t)$ was modelled with a first order reaction kinetic according to Eq. (12):

$$OUR_{STOR}(t) = q_{STOR} \cdot X_{STOR}(0) \cdot e^{-q_{STOR} \cdot t} \ (mg\ O_2/(l * h)) \quad (12)$$

The second, slower reaction of phase 2 was assumed to be due to the degradation of heterotrophic biomass (X_{OHO}) and thus corresponds to the endogenous decay rate. It was further assumed, that this reaction is active from the beginning of the experiment to the end. The OUR_{OHO} was modelled with Eq. (8) and an endogenous residue fraction $f_U = 0.2$ (Dold et al., 1980). Since no nitrification inhibitor was used, the oxygen uptake with respect to nitrification of nitrogen that was released during the degradation of biomass has to be considered. The fraction of nitrogen released was determined by using the nitrate concentration that was built up during the experiment in relation to the COD that was consumed within the experiment (integral of measured OUR). On average the nitrogen fraction (f_N) was 0.063 g N/g COD with respect to the degraded activated sludge. The OUR_{NO3} is modelled according to Ramdani et al. (2010):

$$OUR_{NO_3}(t) = 4.57 \cdot f_N \cdot (1 - f_U) \cdot b_{OHO} \cdot X_{OHO}(0) \cdot e^{-b_{OHO} \cdot t} \ (mg O_2/(l * h)) \quad (13)$$

The measured OUR is given by:

$$OUR_{model} = OUR_{STOR} + OUR_{OHO} + OUR_{NO_3} \ (mg\ O_2/(l * h)) \quad (14)$$

To fit the measured OUR data with the model of Eq. (14) the parameter of q_{STOR}, X_{STOR}, b_{OHO} and X_{OHO} were obtained by nonlinear regression parameter estimation and are summarized for all batch tests in Table 3. Eq. (1) can now be rewritten:

$$X_{ORG} = X_{STOR} + X_{OHO} + X_{ORG,U} \ (mg\ COD/l) \quad (15)$$

The fraction of stored substrate f_{STOR} and the fraction of active biomass F_a where obtained by

$$f_{STOR} = \frac{X_{STOR}(0)}{X_{ORG}(0)} \quad (16)$$

and

$$F_a = \frac{X_{OHO}(0)}{X_{ORG}(0)} \quad (17)$$

respectively.

As opposed to Henze et al. (2000), not a constant f_{cv} conversion factor was used in this investigation. The f_{cv} factor was calculated for the particular experiments as shown in Table 3 from the ratio of the integral of measured OUR to the

Table 3 – Results of the aerobic digestion batch tests.

Nr.	Time			COD		N	Storage			Decay			
	Test	Phase 1	Phase 2	Balance	f_{cv}	Content	q_{STOR}	X_{STOR}	f_{STOR}	b_{OHO}	X_{OHO}	$OUR_{OHO}(0)$	F_a
	d	d	d	%	g O_2/g VSS	% COD	1/d	mg/l	%	1/d	mg/l	mg O_2/(l*h)	%
1	12	2.0	3.4	105	1.15	7.6	1.9	46	1.3	0.155	1446	7.5	54
2	15	1.5	4.0	104	1.37	5.8	2.4	30	0.9	0.132	1677	7.4	55
3	14	0.8	3.8	104	1.34	6.5	4.1	16	0.5	0.218	1523	11.0	54
4	21	1.8	3.2	105	1.29	7.2	1.9	33	1.1	0.125	1367	5.7	51
5	21	4.2	5.5	103	1.43	5.6	1.1	225	6.9	0.136	1701	7.7	52
6	18	2.3	5.0	102	1.52	6.9	1.9	94	3.2	0.101	1823	6.1	61
7	13	0.5	3.0	105	1.38	6.9	6.6	11	0.3	0.167	1873	10.4	59
8	32	1.5	6.2	102	1.52	5.4	3.2	16	0.8	0.121	1428	5.7	45
9	50	2.0	10.0	102	1.51	5.0	1.8	47	1.0	0.094	2499	8.0	56
10	30	2.1	5.0	101	1.57	5.9	1.7	65	1.4	0.125	2702	10.8	57
11	22	4.5	22.0	104	1.46	5.0	1.0	137	3.6	0.081	2285	5.7	58
12	30	5.0	30.0	104	1.50	6.3	0.8	172	3.8	0.077	2260	5.8	50

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VSS degraded. However, this f_{cv} conversion factor was not constant for all experiments but represents directly the COD of the degraded organic material.

The following conclusions can be drawn from the modelling results:

3.2.1. *Degradation of* X_{STOR}

The degradation rate of stored compounds q_{STOR} was observed to fall between 0.8 and 6.6 d^{-1} with a mean of 2.4 d^{-1}. This value matches well the magnitude of the hydrolysis rate parameter of activated sludge models. The fraction f_{STOR} was in average 2.1% for the examined activated sludge. One sludge sample exhibited a higher portion of 6.9%. No correlation of q_{STOR} to b_{OHO} was found. It is suggested that the magnitude of X_{STOR} is not a result of the F/M-ratio of the particular sludge, but rather that of the treatment process in the WRRF.

3.2.2. *Initial heterotrophic* $OUR_{OHO}(0)$

Modelling the OUR_{OHO} of the first days of the batch test as suggested makes it possible to identify the true initial endogenous heterotrophic respiration rate ($OUR_{OHO(0)}$) of the particular activated sludge, by excluding OUR_{STOR}.

3.2.3. *Heterotrophic decay rate* b_{OHO}

According to Eq. (10), the heterotrophic decay rate b_{OHO} corresponds to the ratio of the heterotrophic endogenous respiration rate and the degradable fraction of the activated sludge. From the presented data this ratio is not constant between samples and therefore b_{OHO} is not constant. This observation is different from the theory of Marais and Ekama (1976), van Haandel et al. (1998) and Ramdani et al. (2010). There are two ways to explain this observation:

(A) Regarding X_{OHO} from the substrate point of view

With an decreasing ratio of OUR to active biomass (X_{OHO}), which occurs in low F/M-ratio systems, degradability characteristics of heterotrophic cell mass in activated sludge reduces, so that the rate of degradation (endogenous decay rate) decreases.

(B) Regarding X_{OHO} from the organisms point of view

Activated sludge is a highly complex ecosystem and accommodates living organisms that have many strategies to deal with changing environmental conditions. Therefore it is rather likely that organisms from low F/M-systems are more prepared to deal with starvation and thus die slower with a reduced endogenous decay rate.

3.2.4. *Correlation of* b_{OHO} *to* $spOUR_{OHO}(0)$

From the empirical point of view the measured endogenous decay rate parameters are shown in Fig. 4 in relation to the specific endogenous respiration rate of X_{OHO} at the beginning of the experiment with respect to the concentration X_{ORG}. Note, that the results from experiment 08A was considered an outlier.

From the slope (0.053) of the line that fits the data best an estimate of the degradable fraction ($(1 - f_U)^*X_{OHO}$) of X_{ORG} can be derived by inserting Eq. (2) into Eq. (10) and converting hours to days as well as grams to milligrams.

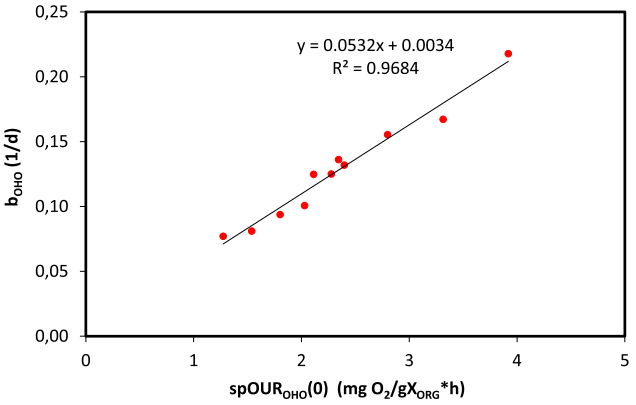

Fig. 4 – Correlation of b_{OHO} and $spOUR_{OHO}(0)$.

$$\frac{OUR_{OHO}(0)}{X_{ORG}(0)} \cdot \frac{24}{f_{DEG} \cdot 1000} = b_{OHO}(d^{-1}) \quad (18)$$

Then in this batch of experiments the degradable fraction of X_{ORG} is:

$$f_{DEG} = \frac{24 \cdot 100}{0,053 \cdot 1000} = 45,3\% \quad (19)$$

From the data of this investigation it can be concluded that X_{OHO} is rather constant and the decay rate varies with loading conditions. This is in contrast to the recent theory that the decay rate b_{OHO} is constant and the active biomass in terms of X_{OHO} varies with loading conditions of the activated sludge.

Adding the portion of degraded stored material of in average 2.1% a total degradable fraction of about 47% of X_{ORG} can be calculated from the presented data. This degradable fraction lies within the range as reported for aerobic degradation of activated sludge in Metcalf and Eddy (2004). It is assumed, that degradation rates exceeding 47% are due to further adaptation of X_{OHO} to starvation and the activity of predators. This additional degradation takes place in the phase 3 of the aerobic digestion batch experiment.

4. Conclusion

The objective of this study was to find out whether the analysis of endogenous respiration profiles lead to a constant decay rate on the basis of the degradation of a homogenous degradable activated sludge fraction. From the observed data and the modelled results the following can be concluded:

1. A structural analysis of endogenous OUR profiles revealed that the endogenous decay during the first two days is overlain by a faster reaction that degrades most likely stored substrate.
2. In most of the experiments after 5 days of digestion the exponential decrease of OUR slows down, does not show an exponential behaviour and can even increase temporarily. This behaviour is thought to be the consequence of

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proliferation of higher organisms and adaptation of active biomass to the conditions of severe starvation.

3. The degradable material of the activated sludge can be clearly separated into two fractions; that is easily degradable storage compounds X_{STOR} and slower degradable active heterotrophic biomass X_{OHO}.
4. In general the values of b_{OHO} in this study were smaller than reported elsewhere in the literature.
5. The decay rate b_{OHO} of X_{OHO} was not as constant between samples as regarded in the current theory of activated sludge modelling. In this study it was found that b_{OHO} decreases in a strong correlation with a decreasing activity of the activated sludge expressed as the ratio of the $OUR_{OHO}(0)$ to $X_{ORG}(0)$. An important consequence of this correlation is that the fraction of X_{OHO} in the examined activated sludge remains rather constant over a wide range of loading conditions.

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