Sludge production in membrane bioreactors under different conditions

J. Wagner and K-H. Rosenwinkel

Institute of Sanitary Engineering and Waste Management, University of Hannover, Welfengarten 1, D-30167 Hannover, Germany

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Abstract With membrane bioreactors, the production of surplus sludge is lower than with conventional activated sludge systems, a fact that has been confirmed in a large number of analyses. There is, however, no consensus about the dimension of the reactions and their respective causes. In order to examine these, at the University of Hanover a pilot plant with a capacity of 220 l was run for one year without any extraction of surplus sludge. The plant was started with 2 g MLSS/l; after one year, this value had risen to approximately 18 g MLSS/l. In order to be able to set the plant for different sludge loads (0.04 to 0.2 kg COD/(kg MLSS · d)), the wastewater was artificially stocked up. The emerging result was that in contrast to conventional systems the sludge growth was lower, but still continuously existing. Then, comparisons with theoretical approaches were run – among others with the ASM1-Model – which confirmed the findings. One possible reason could be the different biocoenoses, which was assumed to be the cause after several microscopic examinations had been run.

Keywords Membrane bioreactor; sludge growth; surplus sludge

Introduction

It is a fact confirmed in several publications that the use of membrane bioreactors for aerobic wastewater treatment makes for lower surplus sludge amounts than with conventional activated sludge systems. Some scientists even claim that no surplus sludge whatsoever is produced. The consequence of this assumption would be that those systems for municipal wastewater treatment which are universally acknowledged could for economical reasons partly be replaced by membrane activation plants. However, the results published in the reference literature (Chaize and Huyard, 1991), (Canales *et al.*, 1994), (Muller, 1994), (Günder, 1997), (Brands and Reetz, 1998) are contradicting each other.

It is partly assumed that the ascertained low surplus sludge productions are exclusively due to the high sludge age or the low sludge load, respectively; other examinations show that an increased oxygen partial pressure (for instance when pressure reactors are used) are responsible for the phenomenon in question. Furthermore, the different degrees of sludge growth found in the different analyses must be regarded as inconsistent.

The effects of a changed surplus sludge production, however, are not inconsiderable: on the one hand, it might become necessary in some cases to change and adapt the existing dimensioning parameters; on the other hand, it could be possible to reduce the, at times rather heavy, costs for sludge disposal, which would make the membrane activation methods increasingly economically viable.

Materials and method

Within this project, the pilot plant shown in Figure 1 has been run since the middle of August 1998. The reactor has an active volume of 220 l and is equipped with five submerged micro-filtration membranes (Submerged Membrane System) of the Kubota company. The membranes are designed as plate membranes and sport a pore size of 0.2 μm; they are supposed to effect a complete biomass retention. The membrane surface amounts to 0.6 m^2. The plant is kept at a temperature of 20ºC in order to exclude any impact of changing

Table 1 Operation data of the pilot plant

Pore size	0.2 µm
Installed membrane surface	0.63 m^3
Membrane material	Cellulose
Membrane carrier	5 plate modules
Crossflow	slight overflowing through aeration
Pressure conditions	atmospherically (reactor and module)
Module aeration	~ 4 m^3/h
Permeate flux	~ 14.5 l/(m^3/h)
Principle of the biol. Stage	nitrification
Active reactor volume	220 l
Hydraulic retention time	~ 24 h
Temperature	~ 20°C
Inflowing water	primary settled municipal wastewater

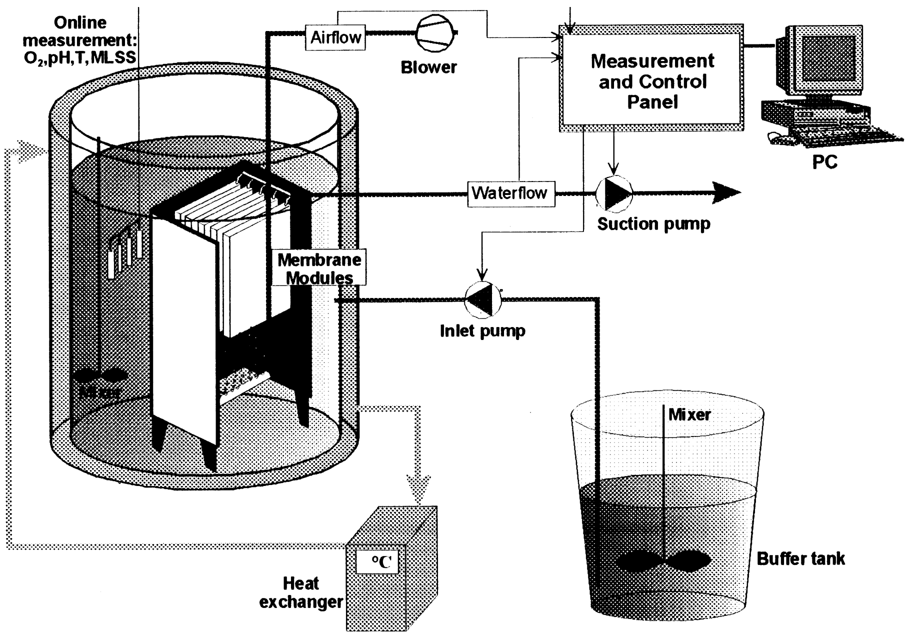

Figure 1 Pilot plant

temperatures on the biological conversion processes. To support the aeration in order to guarantee complete intermixing, a mixer was installed on Day 40. Table 1 contains a summary of the main operation data.

Of the physical parameters, the flowrate of water and air amounts, the content of oxygen and mixed liquid suspended solids (MLSS) were recorded online as well as the pH-value and the temperature. From influent and effluent, samples were taken daily and checked for all relevant chemical parameters.

The plant was initiated with sludge from the municipal wastewater treatment plant Hannover-Herrenhausen. In the first test stage, the plant was fed with primary settled municipal wastewater from the same plant. In the following test stages, from Day 95, this wastewater was artificially stocked up with a substrate consisting of peptone, apple juice, and urea, blended with a mineral salts solution, the composition of which is shown in Table 2.

Table 2 Composition and concentrations of the added synthetic substrate

Ingredients for 1 litre substrate:	[g]	Substrate Concentrations:		
Apple juice	150	COD	[mg/l]	60,000
Peptone	30	BOD	[mg/l]	36,000
carbamide	5	TKN	[mg/l]	6,500
NaCl	3.6	NH_4–N	[mg/l]	38
$CaCl_2 \cdot 2H_2O$	2	P_{total}	[mg/l]	90
$MgSO_4 \cdot 7H_2O$	1	pH	[–]	6.4

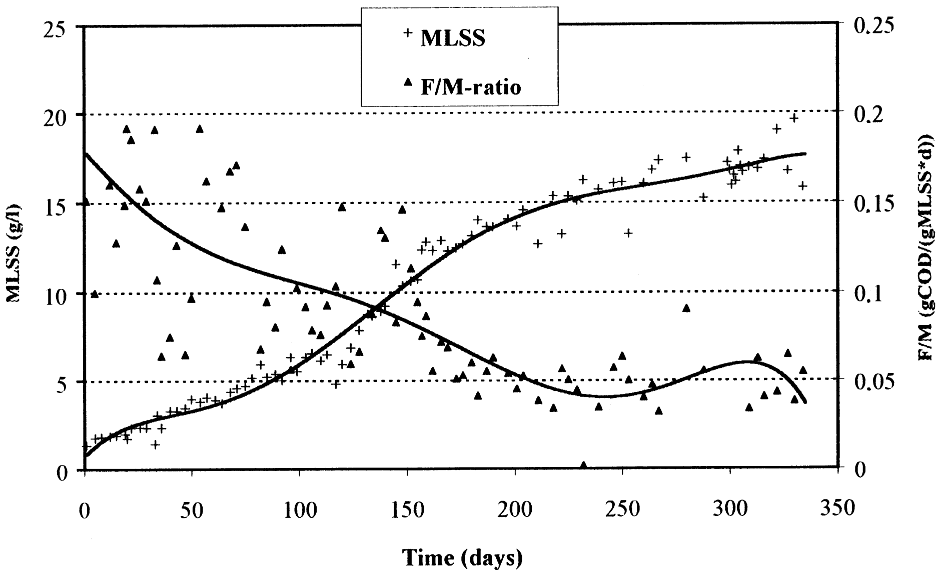

Figure 2 Development of the MLSS and the F/M ratio over the test period

Results and discussion

Development of the MLSS in the membrane bioreactor

Over a period of 300 days, samples from the plant were taken daily. Throughout the test period, no dry solids whatsoever were taken from the reactor, apart from small amounts for the purpose of sampling. Figure 2 show the development of the dry solids and the sludge loads.

The principal connection between F/M ratio and sludge growth is easily recognisable. What we have here, however, is a very elastic system which flexibly adapts to the respective conditions. Thus, it was in this case not possible to fix an exact sludge load at which the sludge growth ceases, which several other authors have claimed to lie between 0.02 and 0.1 kg COD/(kg MLSS · d).

It is assumed that the viable part of the MLSS will diminish with growing sludge age. This is caused partly by the accumulation of inert material and partly by the production of endogenous residue. This process could be expected to take place in a MBR with total solids retention and infinite sludge age. Conversely, an increasing MLVSS ratio was observed which was stabilised at approximately 72% after day 150. From the fixed suspended solids (FSS) load measured from Day 157 to Day 180, only 32% were accumulated. The investigation for trace elements in the sludge did not reveal any accumulation than those usually expected. A sludge with ultra high retention time provides good conditions for microorganisms to develop.

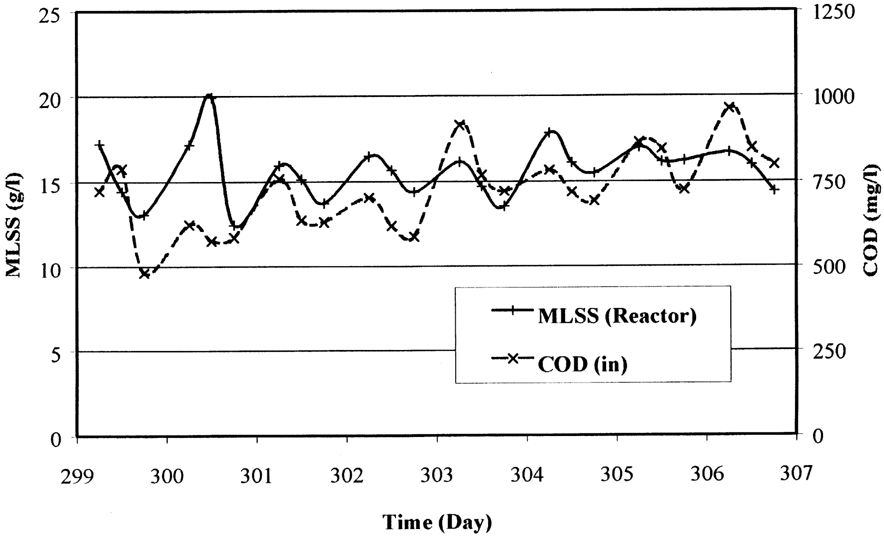

Figure 3 Relation between COD load and sludge growth

Figure 3 shows the results from an eight-week period of intensive sample taking. In this case, as well, the relation between sludge growth and sludge load are clearly recognisable again. Of particular interest are the daily variations of the MLSS, for which no unequivocal explanations have yet been found.

Microscopic analyses

The sludge was twice microscopically investigated, first on Day 91 and second on Day 167. In the first sample, there were no free cells, hardly any filamentous bacteria, protozoa and metazoa observed. Distinct occurrence of "Aelosoma", an oligochaet, is an indicator for an extremely low loading rate. Occasionally, this species can occur in sludge in such large numbers that their contribution to sludge reduction is evident.

At first, a relatively small and compact flocs distribution was observed in the reactor, which changed to larger, weak flocs with filamentous bacteria in the biomass. This result does not correlate with observations made by (Brands and Reetz, 1998) and (Muller *et al.*, 1995), who described a dense suspension of free cells with very small flocs (<50 µm). The mechanical stress of cross-flow operation wrecked filamentous organisms, as well as protozoa and meatazoa. Typical micro-organisms for low loading rate systems were only observed in the biofilm clinging to the basin wall (Brands and Reetz, 1998).

It is difficult to ascertain the ultimate reason for this entirely different sludge structure. Yet, it seems to be possible to operate a micro-filtration unit with a sludge structure corresponding to conventional processes.

Comparison of the results with a batch test

Since a direct determination of the yield coefficient is not possible, a variety of indirect methods have been developed. One of them is to observe the oxygen uptake rate in comparison to substrate utilisation. The yield coefficient of the heterotrophic biomass Y_H was determined in a batch test, the method of which had successfully been applied (Scheer, 1996). MO [mg O_2/l] is the amount of oxygen consumed and is calculated from the area closed by the measured respiration rate curve. Δ COD(filtr.) corresponds to the amount of COD consumed during the respiration phase determined from a filtrated sample. Δ PHB-

Table 3 Determination of the yield of heterotrophic micro-organisms Y_H

No.	Δ COD (filt.) [mg/l]	Δ PHB–COD [mg/l]	MO [mg O_2/l]	Y_H [g/g]
1	222.4	129.5	39.00	0.58
2	148.8	26.6	51.29	0.58
3	227.5	139.4	25.41	0.71
			Mean value:	0.62

COD corresponds to the amount of COD stored as Poly-hydroxy butyric acid (PHB) during the respiration phase.

$$Y_H = (\Delta\, COD\, (filt.) - \Delta PHB - COD - MO) / (\Delta\, COD\, (filt.) - \Delta\, PHB\text{-}\, MO)$$

Three batch reactors were run simultaneously with the same sludge, and two different substrates were applied. Since the MBR was fed with peptone in a mixture with domestic wastewater, a good adaptation of the micro-organisms to this substrate could be assumed. However, the test was conducted according to (Scheer, 1998), who had applied acetic acid for the determination of Y_H. To have comparable results, the determinations were conduct simultaneously with peptone and acetic acid in order to consider the possible affinity of the micro-organisms. The sludge was taken from the MBR on Day 126.

Two evaluated batch tests result in an identical yield coefficient Y_H=0.58, a result that can be considered as reliable (Table 3). It should be stressed that two different substrates were used. Yield coefficients between Y_H=0.54 and 0.55 have been determined with batch tests in conventional activated sludge treatment plants. A high yield coefficient value was not expected, since no sludge had been wasted for 126 days and the calculated average cell residence time was not determined/infinite in the sludge. It must also be considered that the sludge had been 126 days under the stress of famine. However, the determined volatile suspended solids (VSS) ratio was at 68%, which is a prerequisite for high micro-organisms concentration. MBR sludge with high sludge retention time has been previously compared with conventional activated sludge. Yield coefficients have been determined with the DNA method, with the tests verifying the correlation of increasing sludge age with increasing yield coefficient (Brands and Reetz, 1998). This correlation has also been observed in a steady-state experimental investigation (Liebskind *et al.*, 1996). The yield coefficients determined in a MBR had values between Y_H=0.63 and 0.69 which shows a relatively decent correlation with these measurements.

A large yield coefficient indicates a high growth potential of the sludge; yet, the objective of our experimental investigation was to limit growth as much as possible. It is assumed that a sludge with high retention time has developed a high degree of endogenous respiration and that a sludge at a low F/M ratio uses a comparatively large amount of energy in maintenance. Both factors contribute to reduced sludge production. However, the theory of maintenance is not completely explored and further investigation will be necessary.

Which is the viable fraction of the sludge? Previously, a decrease in the viability assumed was related to increased sludge retention time. This thesis is not supported by the fact of an increasing yield coefficient. Moreover, when this result is compared with the actual sludge production rates in conventional and MBR plants, the discrepancy is obvious. An extremely low sludge production was measured in the laboratory-scale test reactor. However, it is obvious that an identical influent load cannot be generated, with the SS load being another important factor which presumably is removed with the excess sludge from conventional treatment processes (Palmu, 1999).

Comparison of the results with theoretical approaches

The results of the pilot plant were compared to several dimensioning approaches: the two German approaches according to Arbeitsblatt A 131 (ATV, 1991) of the Abwassertechnische Vereinigung, as well as the so-called University Group Approach (HSG) (Dohmann *et al.*, 1993), which was developed by a work group of scientists from several German universities. Furthermore, the results were compared to the ASM1-Model of the IAWQ (Henze *et al.*, 1986).

The different approaches sport different degrees of suitability of their application to membrane activation methods. This degree is determined by whether the plant can be run close to the so-called Preservative Metabolism. The phenomenon of the Preservative Metabolism, however, was not considered in the examined approaches anyway. In those cases where a significant surplus sludge production is available, all three approaches seem to be suitable to give at least an estimate of the average surplus sludge production over a longer period, provided that all necessary parameters are sufficiently known. Then, a detailed description of the biomass as done with the ASM1 can lead to more exact results. This model, however, has one disadvantage: if not all characteristic parameters are sufficiently known, the complex structure may produce minor detail mistakes which add up. This problem is non-existent with a relatively simple approach like the A131. The compromise in the shape of the University Group Approach may serve as a practicable solution for conventional activation plants; however, it turned out to be not very meaningful, due to the fact that this dimensioning approach reacts over-proportionately strongly to the adaptation of the heterotrophic dying-off rate, while other biomass properties related to this become only indirectly part of these calculations. This is the background before which the results compiled here have to be considered.

For these analyses, three test stages were selected: Period 1 from Day 94 to Day 116; Period II from Period 119 to Day 152; and Period III from Day 152 to Day 180.

In contrast to the surplus sludge production of the pilot plant, which for the different test periods had been found to range from 0.002 to 0.032 kg/d, the calculations using the A131 approach yielded values in the area from 0.027 to 0.067 kg/d for the surplus sludge production. The respective values found by the University Group Approach ranged from 0.043 to 0.053 kg/d with discrete calculation with adapted parameters, or respectively from 0.026 to 0.069 kg/d for the calculation of the average input parameters over the respective

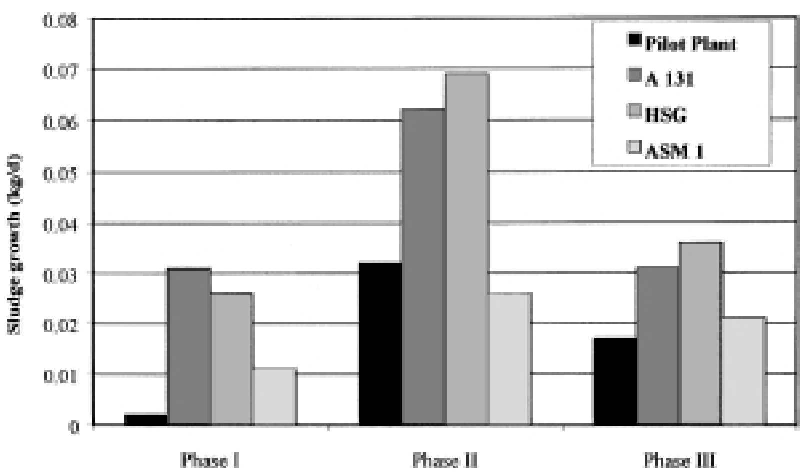

Figure 4 Ascertained surplus sludge production of the pilot plant and according to the different theoretical approaches

test stage duration. The results ascertained with the ASM 1 were overall lower than the results of the two other dimensioning approaches at 0.011 to 0.026 kg/d. Figure 4 shows the ascertained results for the three selected test stages.

Carbon balance

In order to ascertain a carbon balance, an intensive measuring period over eight days was run in June 1999, with the input and exhaust air being checked in a gas chromatograph. Moreover, both influent and effluent as well as the sludge in the reactor were checked for TOC and other parameters. Because of the low influence of the autotrophic organisms in this system, here only the TOC is shown. The results of this balance-taking are shown in Figure 5.

The carbon balance over the test period is positive with an average amount of 63 mg C/h, that is, this carbon remains in the reactor and must have been used for the growing of the biomass. Figure 6 shows the development of the MLSS, but also of the contents of TOC, COD and TKN in the reactor. It is apparent that all parameters do generally show a tendency to increase, give or take a few minor variations. Because of the high DS contents, the TOC contents within the reactor can be ascertained only rather imprecisely, but this parameter does increase like the others during the test period.

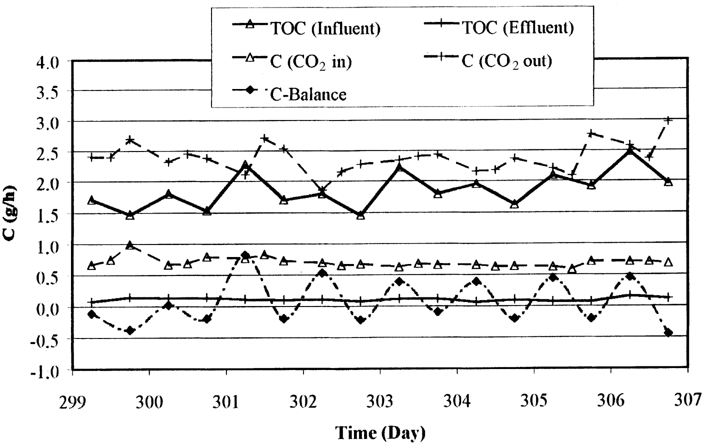

Figure 5 Carbon balance

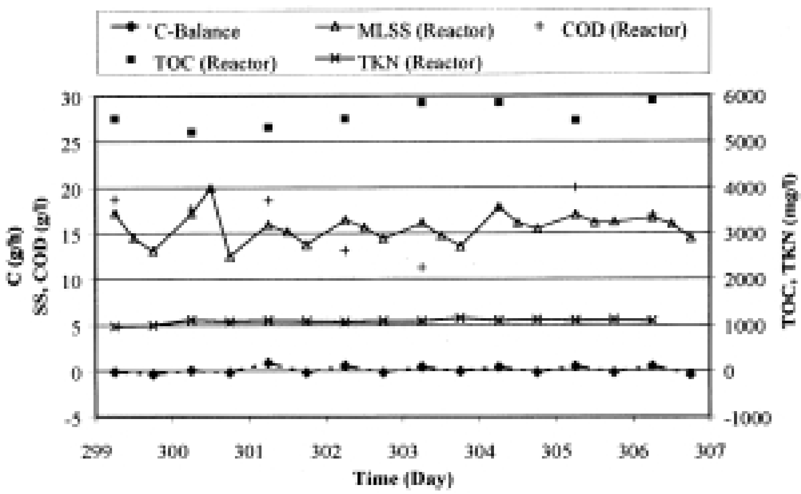

Figure 6 Carbon balance in comparison to other parameters

Conclusions

The MBR pilot plant described here was run over a period of approximately one year. During this period, no surplus sludge whatsoever was extracted, apart from minute amounts for analysis purposes. Throughout the test time, a low sludge production could generally be observed. Recognisable was also the relation between sludge load and sludge production. The system membrane bioreactor reacts very flexibly to different loading rates; due to the low basic load of 0.04–0.2 COD/(kg MLSS · d) and the resulting high sludge age, the sludge growth is generally rather sluggish; the biomass is close to the Preservative Metabolism.

The comparison of the measured values with theoretical approaches, such as the ASM No. 1, yielded lower results for the membrane biologies. Still, in contrast to some previous publications, any plant operation without the production of surplus sludge could not be achieved. The reasons for this could not be ascertained - one possible cause is the low shearing load of the sludge and thus the varying biocoenosis. This would also explain the different results of the different authors, because depending on the respective membrane reactor type (cross-flow or submerged, one reactor or preliminary denitrification with sludge recycling through several pumps) the biomass is subjected to different strains.

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