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The anaerobic MBR for sustainable industrial wastewater management

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ABSTRACT

Anaerobic high rate processes are considered cost and resource efficient solutions for treating wastes and wastewaters. Referring to the global current "energy discussion," anaerobic conversion processes recover "organic waste enclosed energy" to the gaseous energy carrier CH_4, whereas no energy is required for stabilizing the waste organic matter. Considering the ongoing trends in industries to reduce specific water consumption, and thereby drastically changing the process water characteristics, membrane bioreactor (MBR) application opportunities are expected to grow in the future. Compared to aerobic MBR technologies, anaerobic MBR (AnMBR) systems do have the same energy benefits as all other anaerobic systems with regard to treatment of organic pollutants, but do also create an absolute barrier for the biomass. By using ultrafiltration membranes, both the dissolved and nondissolved organic matter are retained in the bioreactor preventing that they will leach out with the effluent or digestate. This makes further degradation and transformation of organic matter into biogas possible, and provides very clear and reusable water. These combined benefits provide an attractive economic and ecological perspective to treat industrial aqueous waste streams. Operating an AnMBR pilot plant for the wastewater from a salads factory has shown that the side stream (gaslift) anaerobic MBR system can operate stable at a significant higher flux levels (around 20 l/m^2-h) than the submerged AnMBR. Moreover, due to the absolute barrier to biomass, more organic material is converted to biogas (conversion rates up to 90% are achieved) compared to the conventional Upflow Anaerobic Sludge Bed systems (typically around 70% conversions). The effluent is clean and free of suspended solids allowing easy reuse of water or the discharge costs will be lower.

Keywords: Membrane bioreactor; Anaerobic; Industrial wastewater; Water reuse; Biogas; Side stream; Ultrafiltration

1. Introduction

Anaerobic high rate processes are considered cost and resource efficient solutions for treating wastes and wastewaters. Referring to the global current "energy discussion," anaerobic conversion processes recover "organic waste enclosed energy" to the gaseous energy carrier CH_4, whereas no energy is required for stabilizing the waste organic matter. Frankin [1] reviewed more than 1,000 full-scale

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high-rate anaerobic reactors, which have been built for the treatment of industrial effluents since the 1970s throughout the world. An overwhelming majority (>75% of all plants) of the existing full-scale plants are based on the Upflow Anaerobic Sludge Bed (UASB) or Expanded Granular Sludge Bed (EGSB) design concept developed by Lettinga and co-workers in the Netherlands [2]. At present, anaerobic high-rate technology is applied worldwide to a range of different kinds of wastewaters, mostly from food and beverage processing industries [3]. These wastewaters are generally characterized as moderately concentrated with a high biodegradability. Many wastewaters have, however, characteristics that limit the stable formation of microbial aggregates. The latter is a condition for an efficient, successful, and cost-effective application of current anaerobic high-rate technologies to wastewater treatment. Such problematic wastewaters are e.g. characterized by high salt concentrations, extreme temperatures, chelating organic compounds, specific surfactants, etc. It is expected and supported by current trends that the quantity of such types of extreme wastewaters will increase in the near future, owing to a reduction in industrial water consumption and the general strategy towards industrial water loop closure. For such conditions, membrane enhanced biomass retention represents an alternative way to concentrate active biomass in anaerobic wastewater treatment systems.

Although the membrane represents a highly efficient way for biomass retention, it inevitably involves higher operational and investment costs, compared to granular sludge-based or biofilm-based technologies. Obviously, membrane bioreactors (MBR) feasibility under anaerobic conditions will most likely be determined by the techno-economic benefits that the membrane enhanced biomass retention can provide. The potentials of anaerobic MBR (AnMBR) systems are of particular interest for the following applications:

(1) The treatment of extreme (industrial) wastewaters that hamper satisfactory biofilm formation, whereas stable long-term operation of granular sludge bed or biofilm-based technologies treating such wastewaters is questionable.
(2) The treatment of wastewaters containing high concentrations of organic solids, since no solids washout will occur with a membrane barrier.
(3) Accumulation of specific bacteria required for the conversion of recalcitrant and slowly biodegradable compounds.
(4) The combination of MBR technologies with other membrane post-treatment systems, avoiding the generally applied aerobic post-treatment step.
(5) The integration of AnMBR technologies in industrial closed loop systems.

In literature, several small-sized AnMBR systems are reported, especially in operation in Japan. More recently, Christian et al. [4] presented the successful upgrading of a sequencing batch reactor treating wastewater produced from salad dressings and barbeque sauce at a factory in the USA to an AnMBR using the submerged membrane technology of Kubota (Japan). The AnMBR operates at a membrane flux rate ranging from 0.05 to 0.10 m^3/m^2-d (design flux of 0.10 m^3/m^2-d) and a mixed liquor suspended solids concentration up to 45,000 mg/l. Although the operation of the system is very stable at low transmembrane pressures (no citric acid cleaning events were reported in the first 20 months of operation), the flux level is very low compared to aerobic submerged MBR systems (typically 36 m^3/m^2-d). A disadvantage of aerobic (submerged) MBR, however, is the high net energy input required for the aerated cleaning of the membrane.

A comparable energy input is required for the side stream AirLift MBR system which, however, operates at a significantly higher flux (typically 150 m^3/m^2-d) [5]. The idea of the research project described in this paper is to develop a side stream gaslift anaerobic MBR operating at significantly higher fluxes (typically 75 m^3/m^2-d) than the submerged concepts filling the current and future technology gap in industrial water reclamation techniques. In addition, it is expected that water loop closure is more easy to achieve using side stream anaerobic MBR systems in combination with nanofiltration (NF) or reverse osmosis (RO) systems.

2. Conceptual background

Biological treatment systems can be divided in various subgroups depending on the type of bacteria and the way they survive.

First division is the separation between biofilm systems and the suspended systems. In the biofilm systems, the bacteria lives on a carrier, usually an artificial added surface for their adhesion. In these biofilms, several bacterial species forms together a sort of consortium. In wastewater treatment systems, the biofilms grow on a these carriers which latter stays in the reactor while the water flows through the reactor. In suspended systems, bacteria form colonies which are suspended in a tank. After the process in the bioreactor, the activated sludge (bacterial suspension) is separated into a concentrated stream with the bacteria and another stream with the treated water. A high sludge concentration in the bioreactor is commonly maintained by returning the bacteria to the bioreactor.

The availability of oxygen is the second criterion to biological systems in the aerobic (with oxygen) system and the anaerobic (without oxygen) system. The aerobic system is widely used for the treatment of municipal wastewater. The anaerobic system is mostly used for industrial treatment and is also used for municipal wastewater treatment in tropical regions.

The last level to differentiate the different biological families is the forms of the biological flocks:

- Flocculent: the bacteria live in fluffy open flocks (Fig. 1(a)).
- Granular: the bacteria form large (maximally 10 mm) dense clusters which settle easily (Fig. 1(b)).

Using granular or flocculent sludge has the following impact on the treatment process:

- The formation of granules only occurs when flocculent bacteria are continuously flushed away, so they are not able to develop a significant community. When the flocculent bacteria are flushed away, colloidal waste is also removed, granular system are not able to treat wastewaters containing particulated and colloidal material. When flocculent bacteria are not flushed away they will take over the system finally.
- In contrast to granular systems, flocculent sludge is able to capture colloidal material within the sludge flock matrix.
  Based on the division into aerobic/anaerobic and flocculent/granular, the following 4 systems can be distinguished:
  (1) anaerobic granular;
  (2) anaerobic flocculent;
  (3) aerobic flocculent; and
  (4) aerobic granular.

The first three systems are already commercially applied for many years, while the last one has only been introduced recently under the conceptual name Nereda^{TM} based on scientific work carried out in the mid-2000s [6].

The aerobic flocculent sludge system is by far the biggest group. There are three reasons to choose an aerobic flocculent system for the treatment of municipal wastewater:

(1) Effluent quality: the aerobic pathway provides more energy to the micro-organisms enabling the removal of lower concentrations of organics from the water.
(2) Nutrient removal: the removal of nitrogen and phosphorus is generally required to meet the discharge standards, where an anaerobic system is not able to achieve these requirements.
(3) Temperature limitation: an anaerobic system has to be operated at least at 18˚C; in order to supply energy (heat) to the water without an external energy source a chemical oxygen demand (COD) level is required of around 2,000 mg/l whereas COD levels for municipal wastewater are typically between 300 and 1,000 mg/l.

Disadvantages of aerobic systems are:

(1) Energy consumption: for optimal growth conditions it is necessary to supply oxygen as an external source.
(2) Sludge production: due to the oxygen supply the micro-organisms spend a significant part of the energy for their physical growth.

Most anaerobic systems are of the granular type:

(1) UASB: in the UASB reactor the wastewater enters the reactor by a distribution grid at the bottom of the reactor. The organics are converted to methane, while the water flows through the granular sludge to the top of the reactor. At the top of the

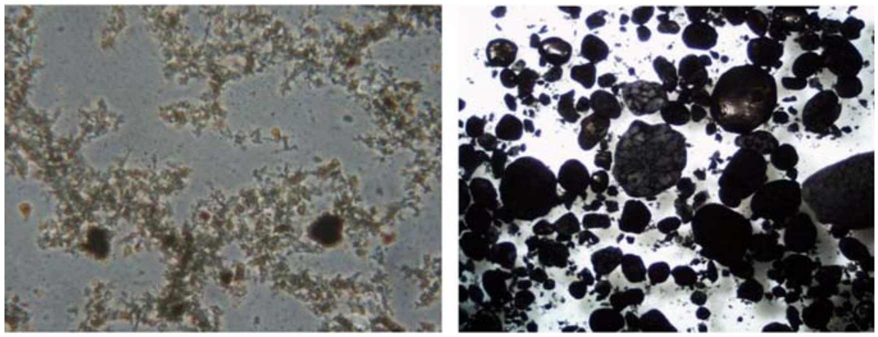

Fig. 1. Anaerobic sludges: (left) flocculent and (right) granular (photos by: Pentair).

reactor the gas is separated from the liquid. While most of the sludge forms a sludge bed at the bottom of the reactor, the upper part of the reactor functions as a settler to remove the last solids.

(2) EGSB and Internal Circulation (IC) reactor: in an UASB reactor the conversion rate is limited by the incomplete mixing. To improve the mixing the upflow velocity is increased, concepts known as EGSB and IC. The price paid for this improvement is the need for an additional settler in the top of the reactor.

Because the granules cannot entrap colloidal and particulated material (such as oil and fat), these components cannot be treated by these systems.

Flocculent anaerobic systems are mainly built as once-through completely stirred tank reactors (CSTR). In these systems, no retention of biomass is required. The high strength wastewater is fed to the reactor, while a part of the sludge water mixture is extracted to a separator to maintain a constant level. Here the solids are removed from the water. Both streams are removed from the system. Drawback of the CSTR system is the necessity to have a feed with a high COD (to maintain a high biomass concentration in the reactor) which, however, also results in the advantage of a high energy production.

In the above description of the three different treatment systems, two limits for the feasibility can be distinguished:

(1) the COD level of the feed and
(2) the amount of solids in the feed water.

If only the removal of organics is being viewed, it is possible to plot the areas of application in a total solids–COD diagram (Fig. 2).
Fig. 2 shows 4 typical areas:

(1) In this area, the COD levels are low, so the good effluent quality of these aerobic systems is the reason to choose for this technology. When the COD level increases, the cost for aeration and sludge removal are the limiting factors for the application of these techniques.
(2) In this area, the COD is available as soluble material, so granular anaerobic systems are the best choice. When the COD level is above a certain level (typical 25 g/l) the formation of granular sludge becomes more difficult limiting the applicability.
(3) In this area, the COD level is high enough for economic operation of a CSTR system.

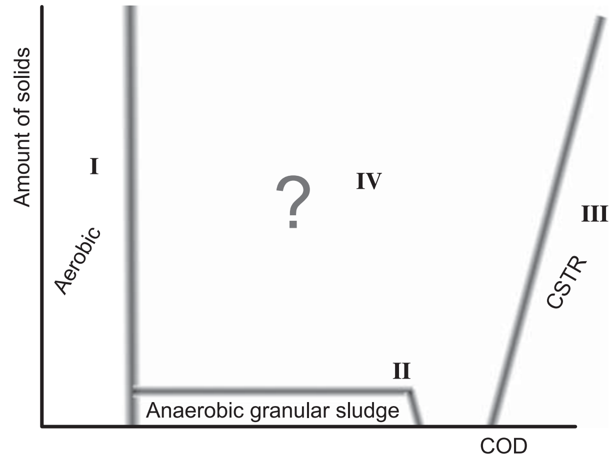

Fig. 2. Graphical illustration of the different biological treatment systems.

(4) The question mark area indicates the lack of a proper technique to cover this area currently. Various options are chosen, such as aerobic treatment at high costs, or extensive pretreatment followed by an anaerobic granular system, or large but inefficient CSTR reactors. Sometimes, even more extreme solutions are chosen such as distillation and burning, or thickening followed by dumping.

A new solution is the introduction to the side stream (gaslift) AnMBR which can:

- handle particulated COD;
- handle oil and grease;
- operate at high activated sludge levels;
- be based on little unit operations; and
- be easily installed and operated.

The AnMBR is not a new concept as has been discussed before. A breakthrough has, however, never been made so far due to the high energy cost and the high membrane prices. Another problem reported in the literature is the decreasing biological activity, because the sludge is damaged by the high shear forces in the membrane module. Based on our long-term experience with the side stream aerobic AirLift MBR concept the anaerobic equivalent concept has been developed successfully.

3. Experimental

As proof of principle an AnMBR system has been installed at a manufacturer of sandwiches and salads (in the Netherlands). To allow for a good comparison

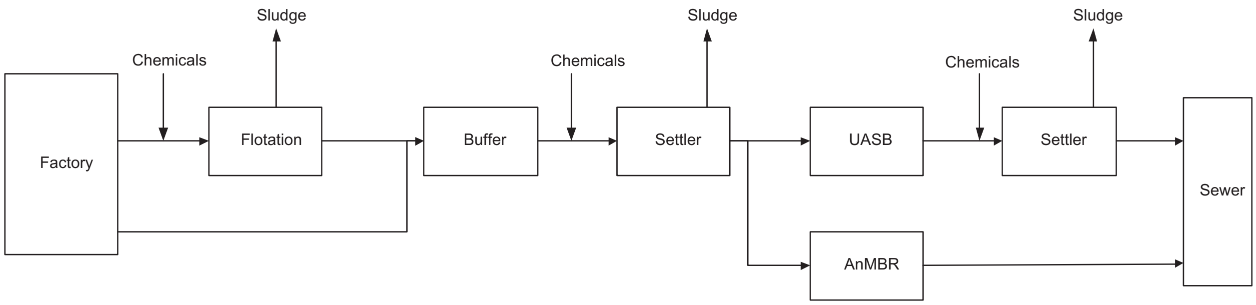

Fig. 3. Schematic view of the process for the anaerobic wastewater treatment: location for the UASB and the AnMBR pilot.

with existing technology, the system has been placed in parallel to the existing UASB reactor (Fig. 3). The pilot makes use of the same pretreatment as is used for the UASB reactor, so the feed water quality will be the same. The feed flow rate to the pilot, however, will be controlled independently in relation to the UASB reactor.

The AnMBR installation consists of an insulated reactor with a gross volume of 100 l (Fig. 4). The reactor is fed pulses (typically 1 min on – 5 min off) with a peristaltic pump (P-100). The pH is checked continuously and adapted through a caustic dosing pump (P-200). For every 30 min, it is checked if the level in the bioreactor is above the starting level of filtration. If so, sludge is pumped from the bottom of the reactor by means of a worm pump (E-16) into the membrane module. The membrane module is filled with tubular ultrafiltration membranes (Pentair X-Flow type F4385); the membranes are 2.2 m in length with an internal hydraulic diameter of 5.2 mm having a total filtration area of 0.35 m^2. The permeate is withdrawn using a hose pump (P-360) with a constant speed. To prevent building up a too thick cake layer on the membrane surface the sludge is circulated over the bioreactor. Next to this slight cross-flow an option is present to supply biogas at the bottom of the module (not shown). The resultant gas bubbles cause extra turbulence and higher shear forces on the cake layer. If after a while the total resistance over the membrane has reached a certain preset value, the direction of the permeate pump (P-360) is reversed and the module is backwashed for a short time (typically 6 s) with a high-speed rewind. If the level in the bioreactor is low enough, no new filtration will start and the module is emptied, filled with permeate, and put offline till the next level check. After the next 30 min check, if the

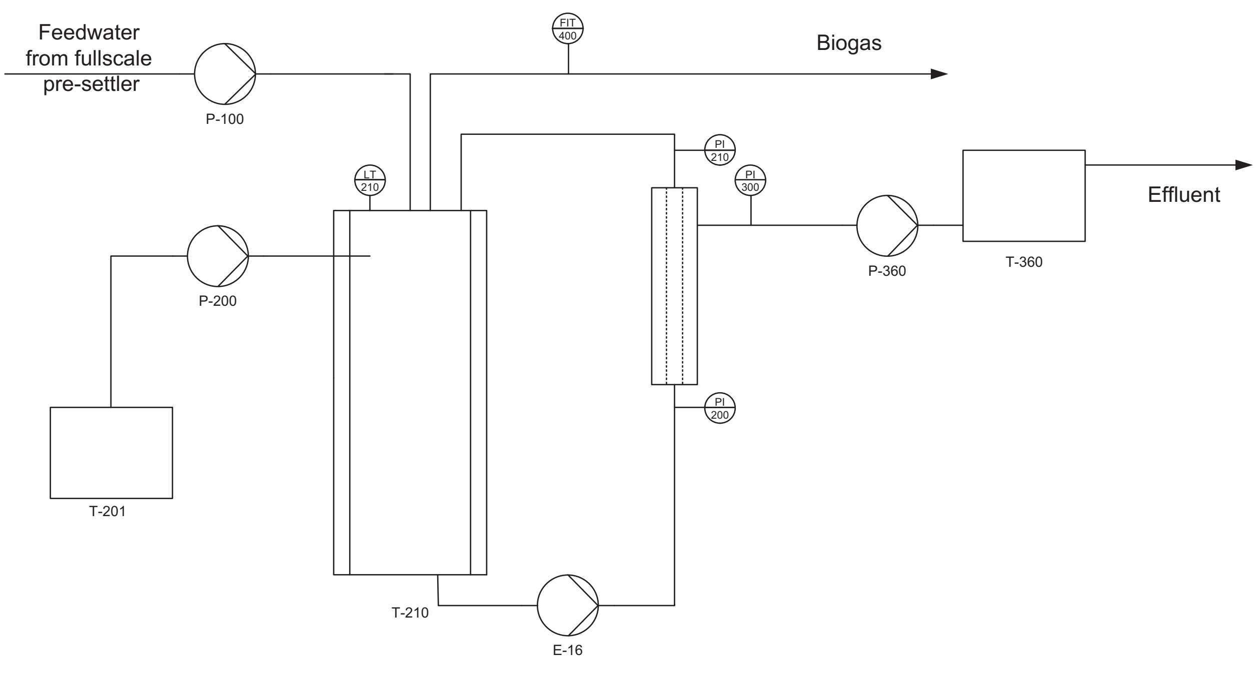

Fig. 4. Schematic representation of the AnMBR pilot.

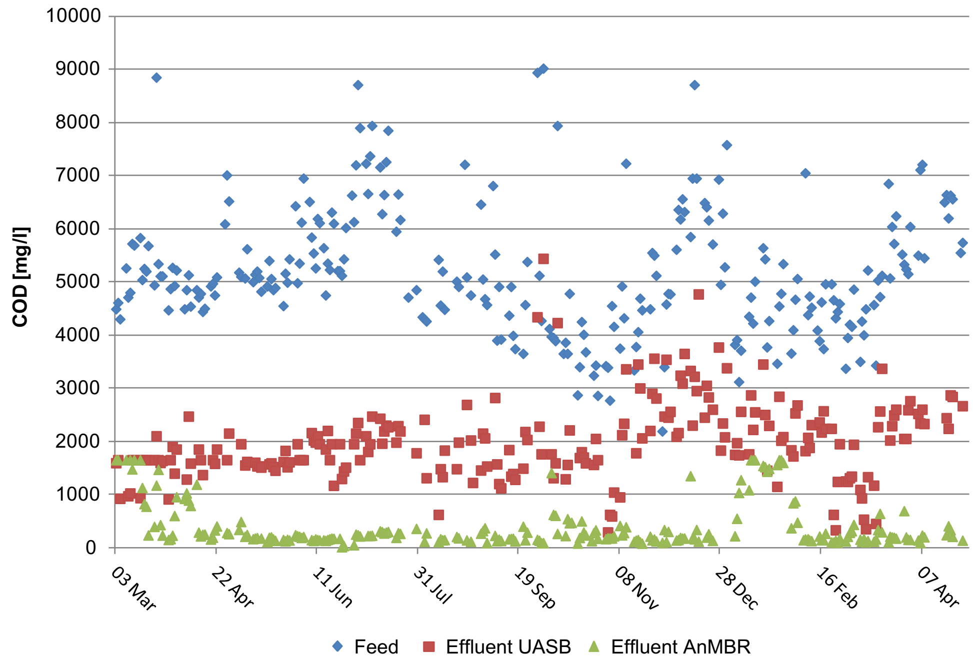

Fig. 5. Biological performance measured in COD: (blue squares) the feed water; (red squares) the effluent of the UASB; and (green triangles) effluent of the AnMBR pilot.

bioreactor level has been increased the membrane filtration will start again.

For a successful application of a AnMBR system two important conditions should be met:

(1) The bioreactor must convert efficiently the organic food to carbon dioxide and methane. During this process no accumulation of potentially harmful or inert substances should occur. Special attention should be paid to the possible reduction of the conversion rate due to mechanical stress on the sludge caused by the circulation over the membrane system.
(2) The membrane filtration flux should be stable and sufficiently high level to make the AnMBR concept economically viable. A stable AnMBR operation is not specifically characterized by the total elimination of cake layer formation, but more by the possibility to control the removal of this cake layer in an efficient way.

During this study, the flux and the biological conversion were tested independently as much as possible. This implies, however, that in some periods the feed flow into the biology is limited by the capacity of the membrane installation, but throughout most of the tests the filtration capacity of the membrane system is larger than that of biology. Therefore, the membrane system is stopped regular intervals automatically. In practice the same holds, a membrane system is designed normally at a maximum expected capacity, which is larger than the rated capacity so that the membrane system will be regularly in stop mode.

4. Results and discussion

In discussing the results, it was decided to show the biological data as a continuous period, while the

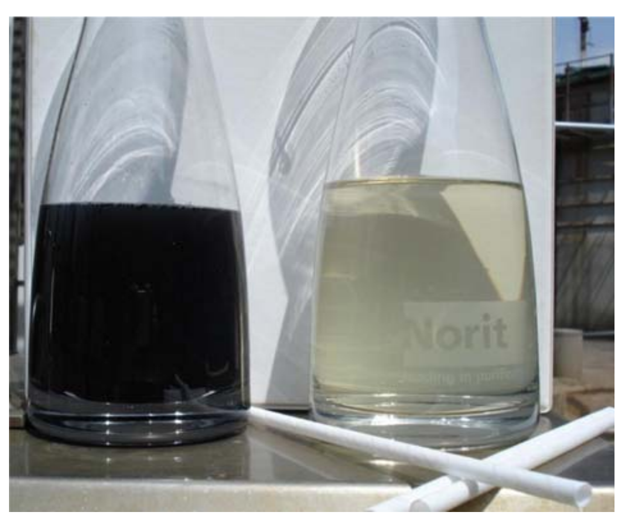

Fig. 6. Comparison of the effluents qualities: (left) UASB and (right) AnMBR pilot.

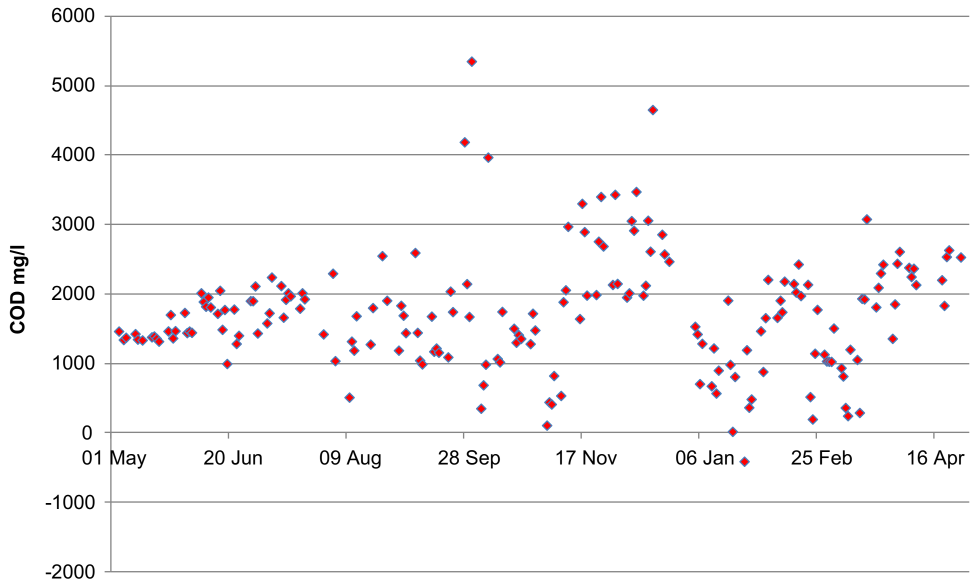

Fig. 7. Additional COD removal of the AnMBR system compared to the existing UASB system.

membrane results are presented as a series of separate experiments in order to determine the optimum settings for the membrane system. As a logical consequence the membranes have been loaded severely and sometimes the operational limits have been crossed which means that the membranes are cleaned more frequently than under normal operational conditions. The shown membrane performance figures will not cover the entire operational period, but the operating flux has always been above 20 l/m^2-h also during the nonshown periods.

4.1. Bioreactor performance

The most important parameter regarding the performance of purification is the biological treatment efficiency. Fig. 5 shows the composition of the feed water and the effluents that is let out from the the full-scale UASB reactor and the AnMBR pilot. Except for the first half of March, the treatment efficiency of the AnMBR is higher than that of the UASB. This difference is also clearly visible as shown in Fig. 6.

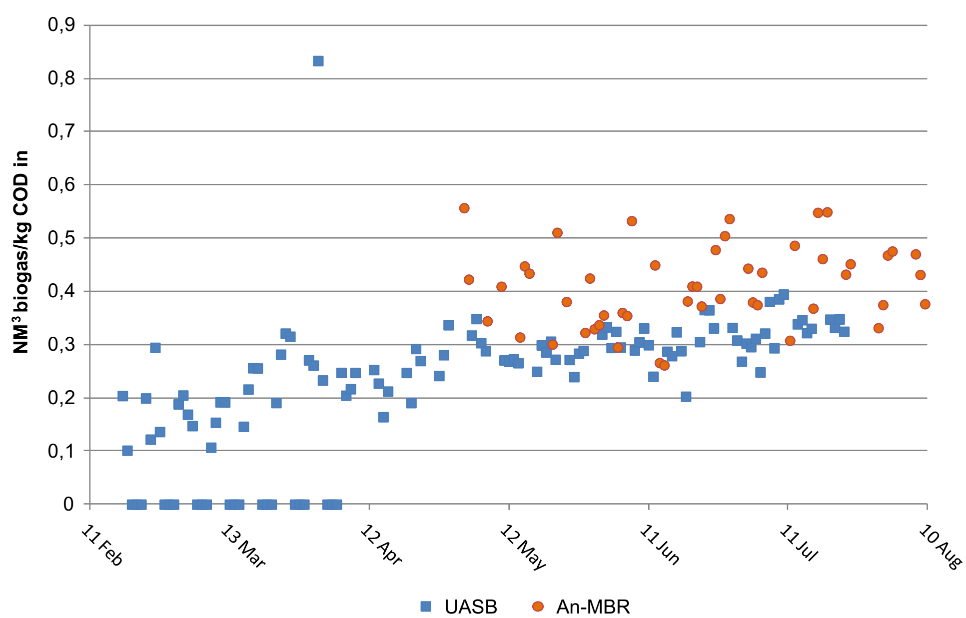

Fig. 8. Comparison of the specific biogas production between an AnMBR (red circle) and UASB (blue square).

The relatively poor performance of the AnMBR in the first half of March is due to organic overloading. The effluent is mainly composed of fatty acids. The peak concentration in July is due to the large production of potato salads. In general, the composition of the feed water changes during the complete year due to changes in the product portfolios: in winter the factory produces typically fish, meat and egg salads, while in summer salads based on potatoes are popular. Regarding the performance of the conventional system, there is also the turnaround point from old to new potatoes in July, which is, however, not explicitly visible in these test results.

At the end of October, an unexpected peak loading to the wastewater plant occurred, which is clearly visible in the performance of the UASB system. The AnMBR pilot, however, reacts in a much milder way. At the end of November, the biological treatment efficiency of the UASB system droped so much that there was hardly any efficiency which was caused by a flush out of activated sludge. The performance of the AnMBR pilot was not influenced negatively at this point.

An important argument for choosing an AnMBR instead of a conventional UASB system is the improved treatment efficiency. Fig. 7 shows the significant difference in the COD removal between the

Table 1
Process parameters

Membrane module length	2.20 m
Cross-flow velocity	0.9 m/s
Biogas dosing	Either 0 or 30%
Total solids bioreactor	22 g/l
Typical sludge loading	0.2 kg COD/KG-TSS/day
Typical volumetric loading	6 kg COD/m^3-day
Remarks	The flux is adapted automatically from day 70

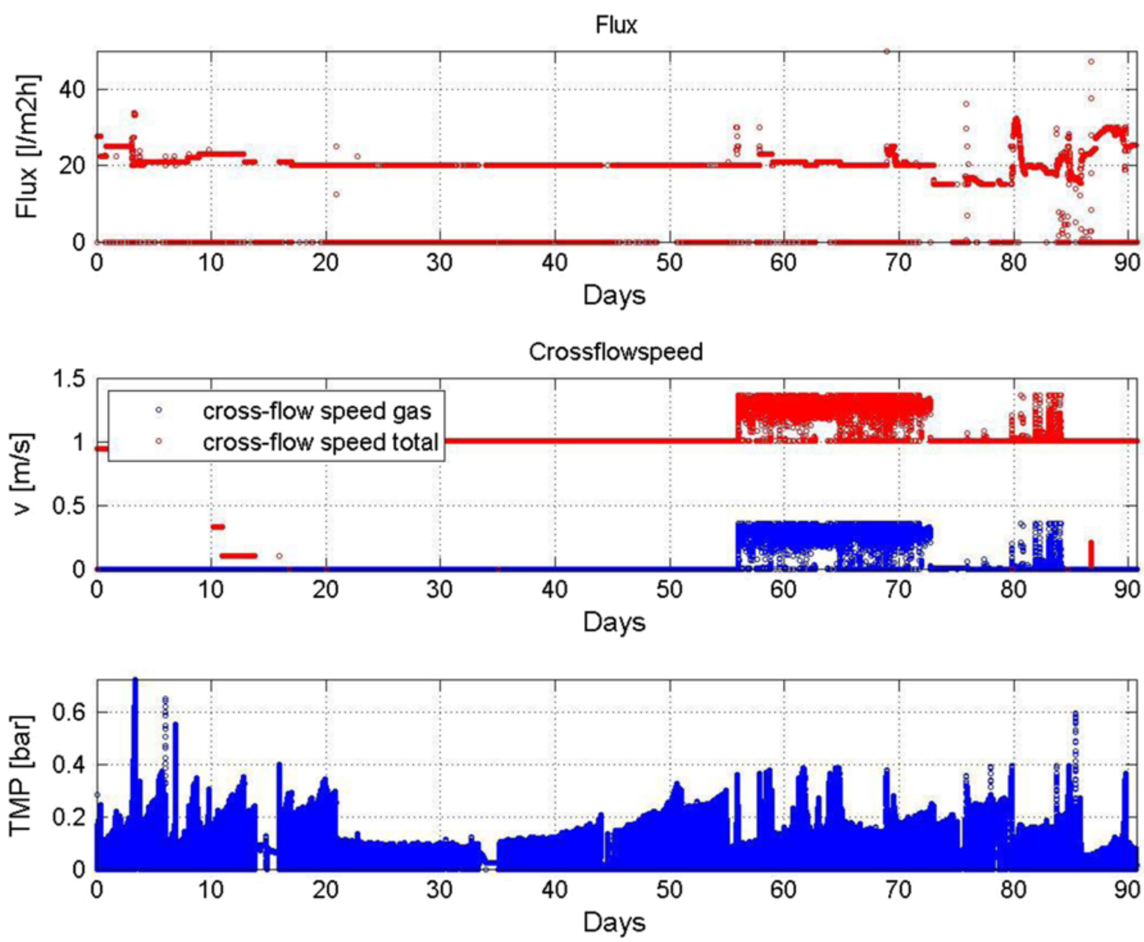

Fig. 9. AnMBR performance over three months of operation: (top) flux; (middle) overall cross-flow velocity; and (bottom) transmembrane pressure.

AnMBR and the UASB system. Fig. 8 compares the biogas production of the AnMBR with the UASB using the specific biogas production defined as the produced Nm^3 biogas per kg COD fed to the reactor.

4.2. Membrane performance

To demonstrate the long-term performance of the AnMBR system, the flux was fixed at $20\,l/m^2$-h for an experimental period of three months. Table 1 summarizes the main process conditions. During this period, minimal interventions were conducted: between day 55 and 72 the gaslift was switched on temporarily, and from day 72 to day 90 the flux control was adapted automatically.

Fig. 9 shows that the cake layer slowly forms during this period. Taken this kind of build-up in mind a monthly chemical cleaning should be sufficient to guarantee stable operation. Moreover, the introduction of gaslift as an additional cleaning aid results in a lower average transmembrane pressure, but the original "clean" conditions cannot be recovered. More research is required to find out the positive effect of gas scouring in relation to the additional investment.

5. Conclusions

Based on the above results it is concluded:

- It is possible to run an AnMBR installation stable for at least three months, after which the accumulated deposit layer can be removed by a chemical cleaning; the translation to normal operation will result in a monthly chemical (maintenance) cleaning.
- The stable, operational flux varies between 20 and $25\,l/m^2$-h.
- The volumetric conversion capacity AnMBR reactor is larger than 6 kg COD/m^3-day.
- The biological removal efficiency of the AnMBR is significantly higher than that of the UASB reactor: in average 98% for the AnMBR vs. in average 70% for the UASB.
- The AnMBR effluent contains an average of 200 mg/l COD compared to 1,500–2,000 mg/l for the UASB reactor; moreover the effluent is also clear and free of bacteria and suspended solids, making it suitable for direct reuse or supply to NF/RO filtration.
- The AnMBR produces significantly more biogas per kg COD in the feed water: $0.4\,Nm^3$/kg COD vs. $0.3\,Nm^3$/kg COD for the UASB.

Although the results for the side stream AnMBR are very promising, there are still possibilities to improve the performance. These improvements focus on increasing the flux levels, the suspended solid level, and the sludge loading. Therefore, research will continue to make this new concept even more economically viable.

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