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Direct sludge filtration: sustainable municipal wastewater treatment

Harry Futselaar[a,]*, Patrick van Lierop[b], Rob Borgerink[a]

[a]*Pentair Water Process Technology B.V., P.O. 741, 7500 AS Enschede, The Netherlands*
Tel. +31 0 53 428 7000; email: harry.futselaar@pentair.com;
[b]*Pentair X-Flow B.V., P.O. 739, 7500 AS Enschede, The Netherlands*

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ABSTRACT

After the successes of ultrafiltration (UF) capillary membranes in well water, surface water, seawater and wastewater effluent polishing, a new membrane concept is introduced that is capable to treat sludge from the biological reactor directly. The technology is called "direct sludge filtration" and is simple, clean and maintenance poor. Based on the successful 0.8 and 1.5 mm hydrophilic polyethersulfone (PES) UF membranes, a unique 3.0-mm capillary PES UF membrane has been developed. Using this membrane it is possible to filter water with suspended solid levels up to 15,000 mg/l (15 g/l). The new membrane is mounted in a complete new system layout for a significant reduction in footprint, building time and process complexity. This plug-and-play compact package design offers a flat slab erection without a lot of civil works reducing capital expenses importantly and is very suitable for (decentralized) wastewater treatment. In this paper, two examples of membrane bioreactor system (MBR) projects in the Netherlands will be discussed showing how an existing conventional activated sludge system has been upgraded successfully by integrating MBR systems. It will be shown that these combinations offer a cost-effective solution for purification of municipal wastewater into high quality effluent suitable for safe discharge into the environment and for durable urban water chain management.

Keywords: Direct sludge filtration; Municipal wastewater; Urban water reuse; Membrane bioreactor; Airlift; Ultrafiltration

1. Introduction

The Dutch water boards are responsible for the quality and quantity of water in their catchment areas, defined normally through the basin of one or more rivers. Through an extended sewer system, the wastewater of the different municipalities is collected and treated in centralized wastewater treatment plants (WWTP). After treatment, the effluent is discharged into several local streams which end up finally in the rivers leaving the catchment area of the water boards. In order to cope with the new legislation (European Water Framework Directive 2015; WFD2015) and measures to prevent the negative effects of draught, the water boards in the Netherlands have been developed in cooperation with several municipalities' restructuring plans. In these plans, the urban water chain/cycle will be integrated into an ecological water management approach.

*Corresponding author.

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1.1. Sketch of the situation

Waterboard Regge and Dinkel (WRD) is responsible for the quality and quantity of water in the catchment area of the rivers Regge and Dinkel in the eastern part of the Netherlands which is called Twente. In this region, WRD owns several centralized WWTP for the treatment of the wastewater which is collected by the different municipalities through an extended sewer system. After treatment, the effluent is discharged into several local streams which end up finally in the two rivers leaving the catchment area of WRD. Two projects will be discussed: the membrane bioreactor system (MBR) of the municipality of Dinkelland and mega block system of the residential area of Glanerbrug.

1.2. MBR Ootmarsum

The Ootmarsum WWTP is situated in the municipality of Dinkelland and was built in 1974 originally. After intensive studies it was decided to restructure the WWTP completely resulting in the choice for a so-called hybrid system. The hybrid system combines a conventional system followed by a sand filter with a MBR in parallel. The MBR has a limited hydraulic capacity. The idea is that a relatively large part of the dry weather flow (DWF) will be treated with the membranes. During periods of rain weather flow (RWF) the excess rainwater will be channeled via the intermediate buffer to the conventional active sludge system and the final settling tank. In this way, the surface area of the membranes can be considerably reduced in comparison with a complete MBR plant, and the membranes can be used at their optimal working point. With a hybrid MBR, the costs can be reduced relative to those of a complete MBR plant without making many concessions in terms of effluent quality. After the described system a down-stream ecological filter has been installed consisting of a unit which is ecologically integrated into the landscape, and in which the "sterile" effluent is transformed to make it ecologically compatible with the surface water into which it is discharged.

1.3. WWTP Glanerbrug

The WWTP Glanerbrug located in the residential area of Glanerbrug being a part of the city of Enschede is outdated (built in 1984) and has to be modernized. From the technological point of view, the hydraulic capacity of the WWTP has to be decreased, which, however, will lead to an increase in the dehydration of the catchment area of the Glaner brook. Moreover, a new residential area is under construction, in which the water system is integrated with the following functions:

- Collection, storage, and drain of the water from the urban area.
- Prevention of dehydration.
- Experience water for an attractive urban landscape and recreational use (by e.g. children).

The use of naturally available water has, however, both quantitative (in dry times) and qualitative challenges which can be faced by reusing the WWTP effluent as an additional water source to supply to this residential area. In order to guarantee that the effluent requirements fulfill both the forthcoming European legislation as well as the use as experience water, the application of a MBR system is being studied through a full-scale demonstration installation.

2. Technology

The first (industrial) MBR systems were based on the cross-flow mode due to the relatively high solids content. The advantage is a better control of the cake layer build-up resulting in a more constant flux; drawbacks are a more complex system and the higher energy costs. The application of the MBR for municipal wastewater was not attractive due to the large flow with relatively low solid contents to be treated. This technique, however, became more attractive for larger flows with the introduction of systems where the refreshing of the feed along the membrane is not realized anymore by hydraulics but by pneumatics (aeration). The energy cost can be reduced significantly if the membranes are cleaned by means of air scouring and not anymore by cross flowing of the feed solution. Moreover, permeation is no longer forced anymore by over-pressure, but by under-pressure (suction).

Current developments are in the direction of the subdivision of the total MBR system into (at least) two main parts, one being the tanks for the biological processes, and the other being the tanks for installing the membranes. The original advantage of creating a very compact system by installing the membranes in (a part of) the aerobic section is not valid anymore, which is caused by the call for more flexible systems.

The AirLift MBR system consists of a bioreactor with an external loop with membranes outside of the bioreactor vessel (or basin) [1]. This side-stream way of sludge filtration enables almost all the possibilities to optimize individually the bioreactor and the membrane system, such as a large flexibility in coping with changes in hydraulic capacity and optimal distributions of flow over the different sections in the bioreactor. The distinguished process parts make the membrane inspection and replacement very easy without removing complete cassettes with membranes out of the bioreactor. In industrial applications this way of applying membranes in separation of water from sludge has lead to very compact units with highly efficient transition of the waste. The introduction of air-driven sludge circulation instead of hydraulic circulation has reduced the energy consumption to typically around 0.25 kWh/m^3 which is nowadays fully compatible with the submerged systems. The inside-out principle of membrane operation leads to a high membrane performance with typical fluxes between 55 and 65 l/(m^2 h).

The original AirLift MBR concept consists of a series of staggered skids which can be tailored flexibly to the customer's needs due to its modular design (Fig. 1 (a)). The new generation Airlift MBR has been redesigned completely to enlarge the output, to improve the process stability, and to offer more process flexibility, while lowering the CAPEX/OPEX balance; decreasing the system footprint; and reducing energy, chemical use and waste production. This new AirLift Mega Block Reactor configuration is designed in block-form enabling a simple "clamp on" method of additional blocks until the required capacity is achieved (Fig. 1(b)). The preengineered block characteristic of this next generation MBR significantly reduces plant design and onsite construction time. The plant can be up and running quicker at lower cost requiring less space and operates in a clean, sustainable manner.

3. Description location

The MBR Ootmarsum was commissioned successfully in October 2007 [2,3], while the upgrading of the WWTP Glanerbrug has started in 2010 and will end in the middle of 2012.

3.1. MBR Ootmarsum

The MBR at the Ootmarsum WWTP will treat 50% of the total amount of sewage in periods of DWF, when the hydraulic capacity is only 23% of the RWF. The maximum hydraulic capacity of the MBR will be 150 m^3/h, while the total sewage inflow to the WWTP under RWF conditions is 650 m^3/h (Fig. 2). In front of the MBR system, an intermediate buffer will serve as a preliminary settling tank. During prolonged periods of RWF, the buffer will have insufficient capacity and will therefore overflow. The overflow water (max. 175 m^3/h) will be treated in the conventional system. In this situation, the conventional system will have to treat a maximum of 500 m^3/h. A notable aspect of this configuration is the large variation in the hydraulic load of the conventional system.

3.2. WWTP Glanerbrug

The WWTP Glanerbrug is an oxidation ditch system (AT = aeration tank) with a design capacity of 18,000 population equivalents a 54 g BOD RWA and a capacity of 1,200 m^3/h (Fig. 3(a)). The capacity of the two existing final sedimentation tanks (CT = clarification tank) is insufficient to process 1,200 m^3/h. Under current effluent standards, the hydraulic load may not exceed 450 m^3/h per settling tank meaning a future

Fig. 1. Airlift side-stream MBR system: (left) skid mounted; (right) Mega Block.

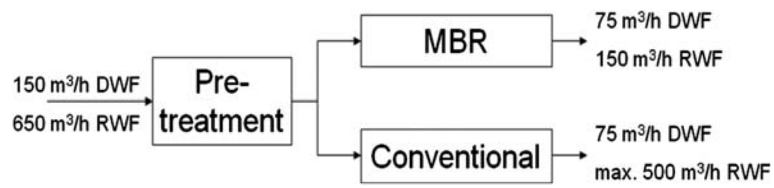

Fig. 2. Process flow diagram MBR Ootmarsum.

settling capacity of 900 m^3/h maximally. Next, measures should be taken to optimize the emission of nutrients and other substances as required by the WFD2015.

The hydraulic capacity of the WWTP is maintained at 1,200 m^3/h by introducing a membrane filtration unit with a capacity of 300 m^3/h for sludge/water separation, which is sufficient to process for about 80% of the time the daily wastewater flow (Fig. 3(b)). The membrane filtration unit is directly linked to the existing activated sludge tanks and operates parallel to the existing sedimentation tanks. This means that the process technical situation (such as aeration system and sludge concentration) and the biological procedure of the bioreactor will not change, because the sludge characteristics have to be such that sedimentation stays as smoothly as possible. Important advantages are that the bioreactor and the process control do not have to be adjusted enabling a simple "add-on" concept for the realization of additional and more effective sludge/water separation. This allows easy integration into an existing treatment plant. This concept is called "direct sludge filtration" (DSF) and is a compact solution for sustainable urban water chain management performing clean, safe and efficient.

Additional reduction of phosphorus is based on biological phosphate removal by the introduction of an anaerobic tank before the activated sludge tanks

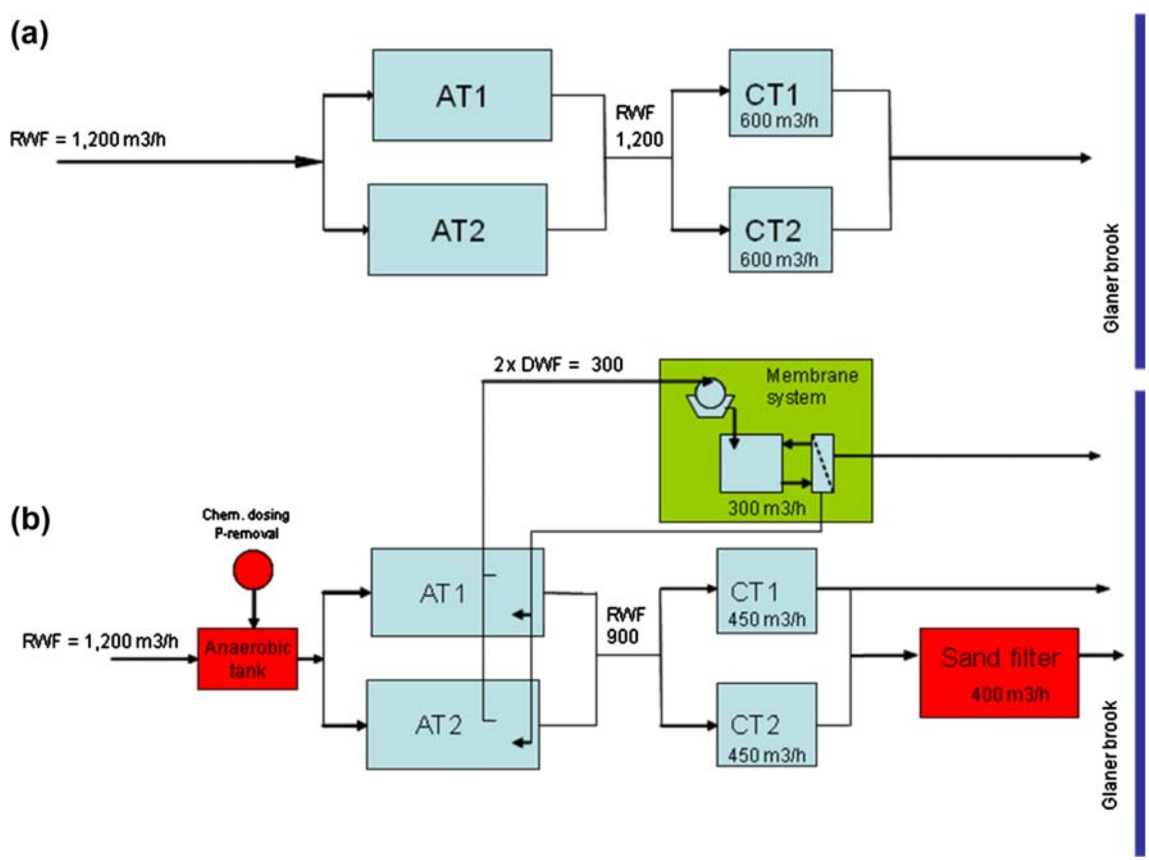

Fig. 3. Process flow diagram WWTP Glanerbrug: (a, top) current situation: (b, bottom) upgraded situation (under investigation).

and on downstream effluent polishing by sand filtration. Moreover, a system is added for chemical phosphate removal in situations where the biological phosphate removal could be inadequate. The larger nitrogen removal should be achieved through improved process control of the activated sludge process in combination with the aforementioned sand filtration for effluent polishing. These measures would be appropriate for achieving the WFD2015 values for nutrients.

4. Results

Typical results for the MBR Ootmarsum will be presented, while for the WWTP Glanerbrug full-scale pilot results will be discussed.

4.1. MBR Ootmarsum

In October 2007 the AirLift MBR Ootmarsum was commissioned successfully having a maximum hydraulic capacity of 150 m^3/h. The principle of the AirLift MBR is based on the same basics as used for the cross-flow principle, however, the turbulence within the tubular shaped membranes is achieved by sparging air into the vertically mounted membranes (Fig. 4). The recycling flow propelled from the activated sludge tank at a velocity ranging from 0.3 to 0.5 m/s is enhanced in turbulence by adding air underneath the module with an additional 0.3–0.5 m/s. The permeate output is controlled by a dedicated pump. A regular back pulse (typically every 10 min) is executed to maintain the membranes performing at a steady state. For every cubic metre of permeate in average a factor of 15 has to be recirculated as feed flow over the membrane system.

The Ootmarsum plant consists of 6 stacks in parallel each of them equipped with 14 membrane modules of the type 38PRV/F4385 (Fig. 5). This PVDF-based membranes are rigidly enforced, backflushable membranes having a track record of more than 15 years. The module dimensions are 8 inch in diameter and 3 m in length having nowadays 33 m^2 membrane area per module (in the case of Ootmarsum still 29 m^2).

Fig. 6 shows a typical year performance of the MBR Ootmarsum. The temperature-corrected permeability for all the six stacks varies between the 500 and 200 l/(m^2 bar h) running at flux levels between the 55 and 60 l/(m^2 h). Remarkable point: no chemical cleaning was performed in the period: 1 July–31 December 2008.

Since the commissioning, the operation of the MBR has been optimized considerably. Table 1 shows the energy savings by decreasing the sludge circulation from the bioreactor over the membrane modules significantly, while simultaneously decreasing the aeration. The energy required for the permeate and backwash pump as well as for other utilities has been summed under "Other." Currently, the energy consumption is comparable to the submerged systems being in the range of 0.25 kWh/m^3.

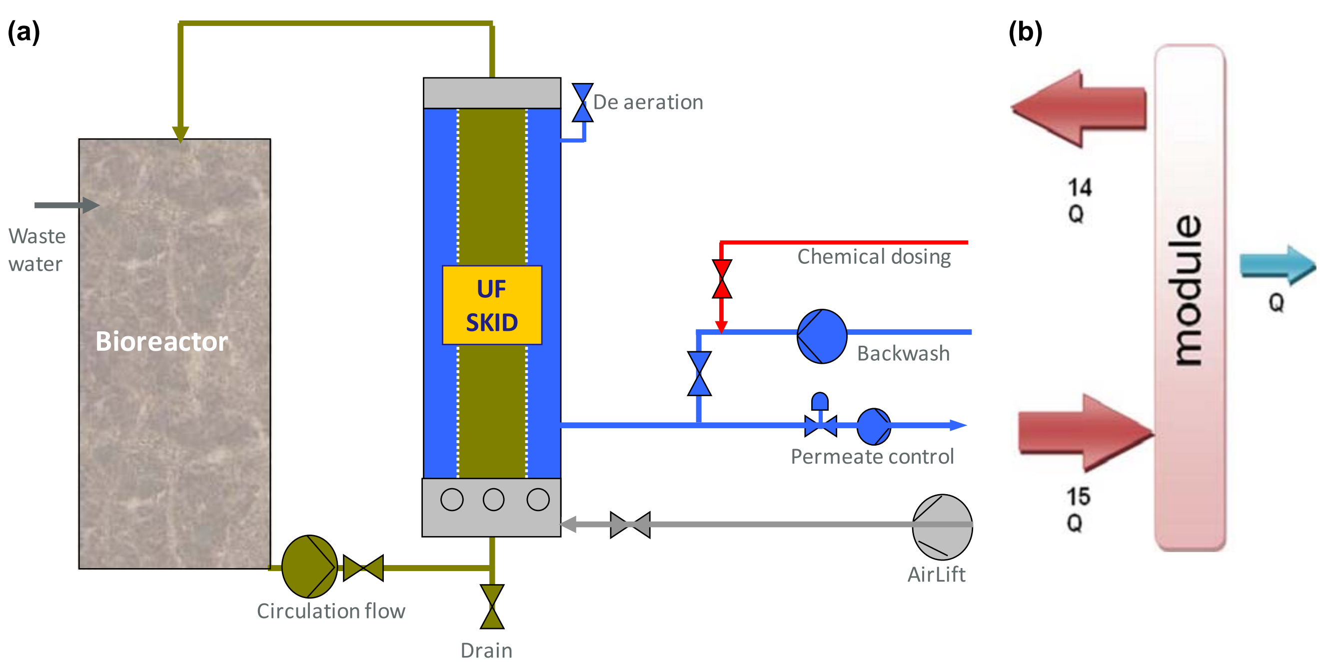

Fig. 4. MBR Ootmarsum: (a) Basic principle of the AirLift MBR system; (b) overall flow rates.

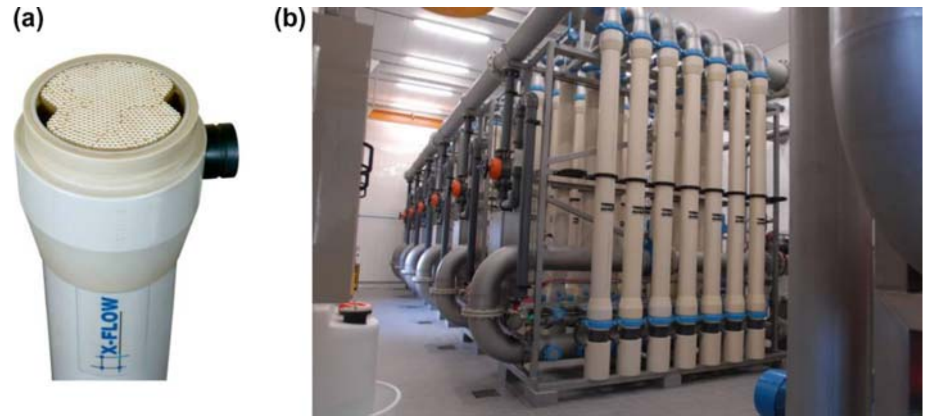

Fig. 5. MBR Ootmarsum: (a) 8´´ X-Flow COMPACT membrane module and (b) system overview.

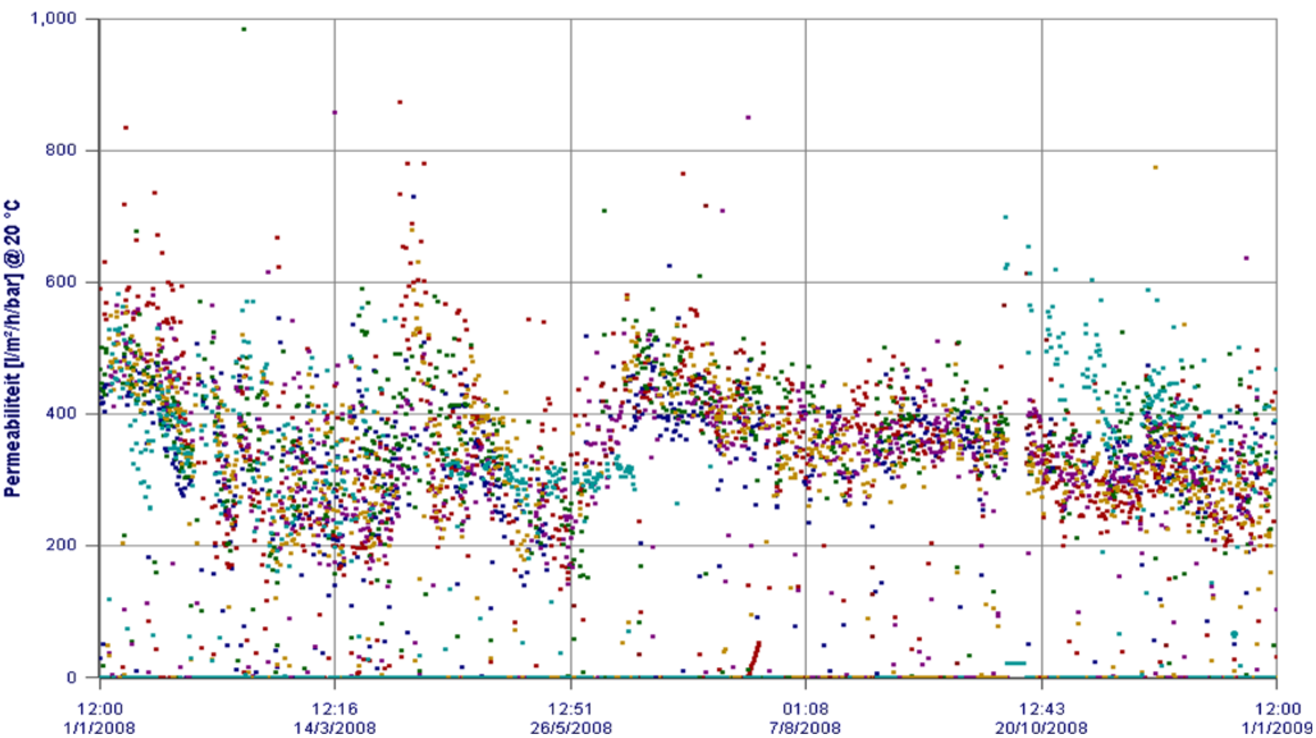

Fig. 6. MBR Ootmarsum: typical performance (normalized permeability vs. time) for the six stacks.

4.2. WWTP Glanerbrug

The upgrading of the WWTP Glanerbrug started in the autumn of 2010 and the first phase will finish in the middle of 2012. The first phase extension (as demonstration unit) consists of the erection of a 150 m^3/h Mega Block Reactor which is a totally new design for the sidestream AirLift skid mounted concept. Main improvements are:

- The feed recycle unit has been integrated in the Mega Block Reactor eliminating a large recycle flow to the bioreactor. Through the internal

Table 1
MBR Ootmarsum: overview of the optimization of the energy consumption

Energy consumption	2003 (design)		2008		2010	
	DWF	RWF	DWF	RWF	DWF	RWF
UF circulation	0.24	0.18	0.12	0.09	0.06	0.08
UF aeration	0.30	0.23	0.22	0.17	0.15	0.14
Other	0.01	0.01	0.01	0.02	0.01	0.02
Total (kWh/m^3)	**0.55**	**0.42**	**0.35**	**0.28**	**0.22**	**0.24**
Reduction vs. design	–	–	**36%**	**33%**	**60%**	**43%**

recycle the membrane unit can be operated independently of the flows from and to the bioreactor allowing the membranes to operate in optimal mode. The internal recycle reduces the feed flow rate to only 4–5 times the product flow (depending on the running MLSS level of the reactor). By doing so, the piping/connection requirements are reduced to minimal sizes (Fig. 7).

- A newly developed polyethersulfone (PES) ultrafiltration (UF) wastewater membrane being based on the large track of comparable membranes used in the production of drinking and process waters; these membranes have an improved morphology which has been combined with an improved hydraulic module design increasing the average net flux with 10% (Fig. 8(a)).

The Glanerbrug MBR plant consists of two segments in parallel each of them equipped with 36 membrane modules (Fig. 8(b)).

To prepare the final design of the MBR Glanerbrug, extensive pilot plant studies were carried out to investigate the performance of the newly developed membrane and the improvements in the process design. Especially the performance during winter conditions was examined extensively; the pilot studies were carried out at the WWTP Hengelo (Fig. 9). Fig. 10 shows some typical results of the long-term test which were carried out during the years 2009 and 2010. The base line flux was set on 60 l/(m^2 h), on which several peak fluxes were superposed: 70 l/(m^2 h) (for typically 9 h) and 80 l/(m^2 h) (for typically 3 h). During the base load operation, a slight increase in transmembrane pressure is visible, which is, how-

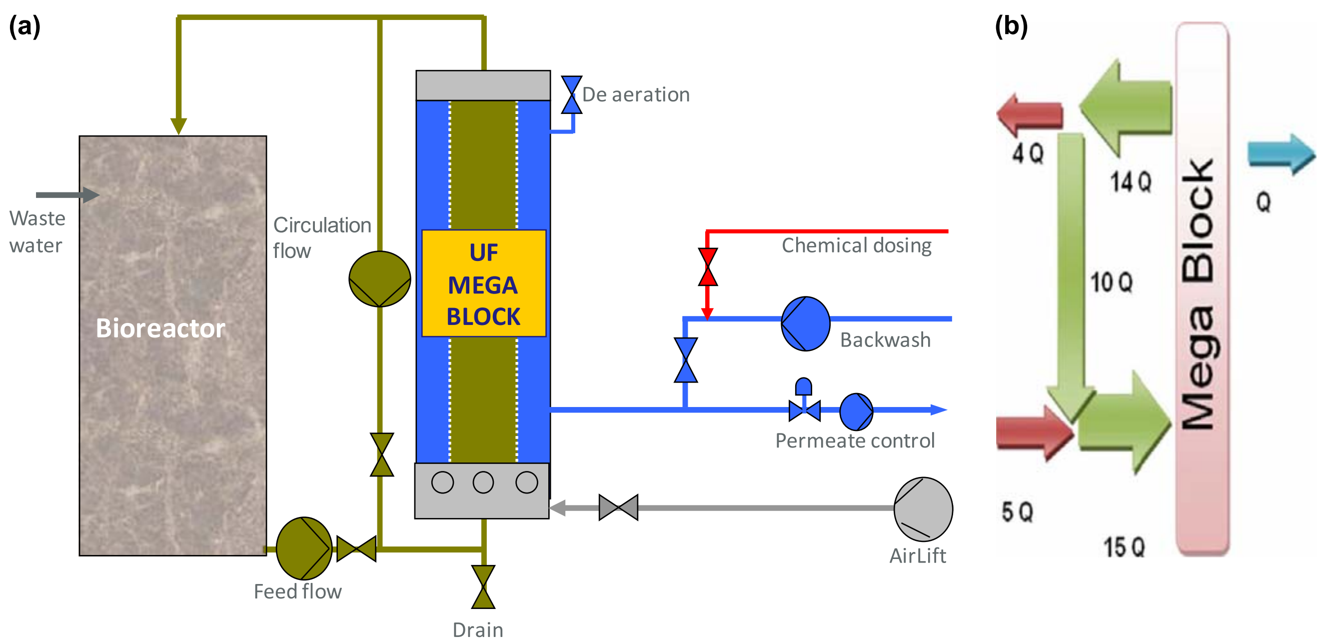

Fig. 7. MBR Glanerbrug: (a) basic principle of the AirLift MBR system and (b) overall flow rates.

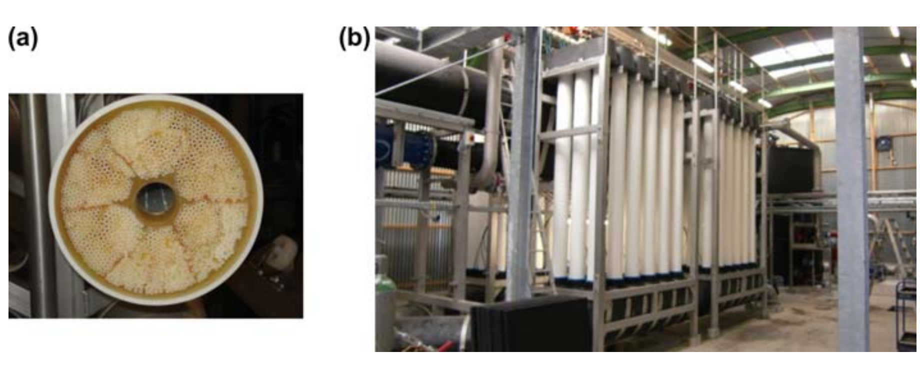

Fig. 8. MBR Glanerbrug: (a) 8´´ X-Flow CAPFIL membrane module and (b) system overview (under construction).

Fig. 9. Pilot MBR at WWTP Hengelo.

ever, constant in time due to a very effective backwash after every filtration run. During the peak load operation, the differences between the transmembrane pressure at the start and the end of a filtration cycle are more pronounced and a steady increase in overall transmembrane pressure is noticeable, which is, however, fully caused by reversible fouling. After returning to the base load the original transmembrane pressure difference is recovered after some filtration runs without any operator interference.

Table 2 shows the projected energy consumption, which has still to be optimized during the commission of the full-scale system.

5. Conclusions

This study presents the results of the new "DSF" concept combining the advantages of commonly known direct filtration successfully applied for the treatment of potable and process water with the

Table 2
MBR Glanerbrug: projected energy consumption (based on pilot studies at WWTP Hengelo)

Energy consumption	2009 (design)	
	DWF	RWF
UF circulation	0.20	0.24
UF aeration	0.10	0.10
Other	0.01	0.01
Total (kWh/m^3)	**0.31**	**0.35**

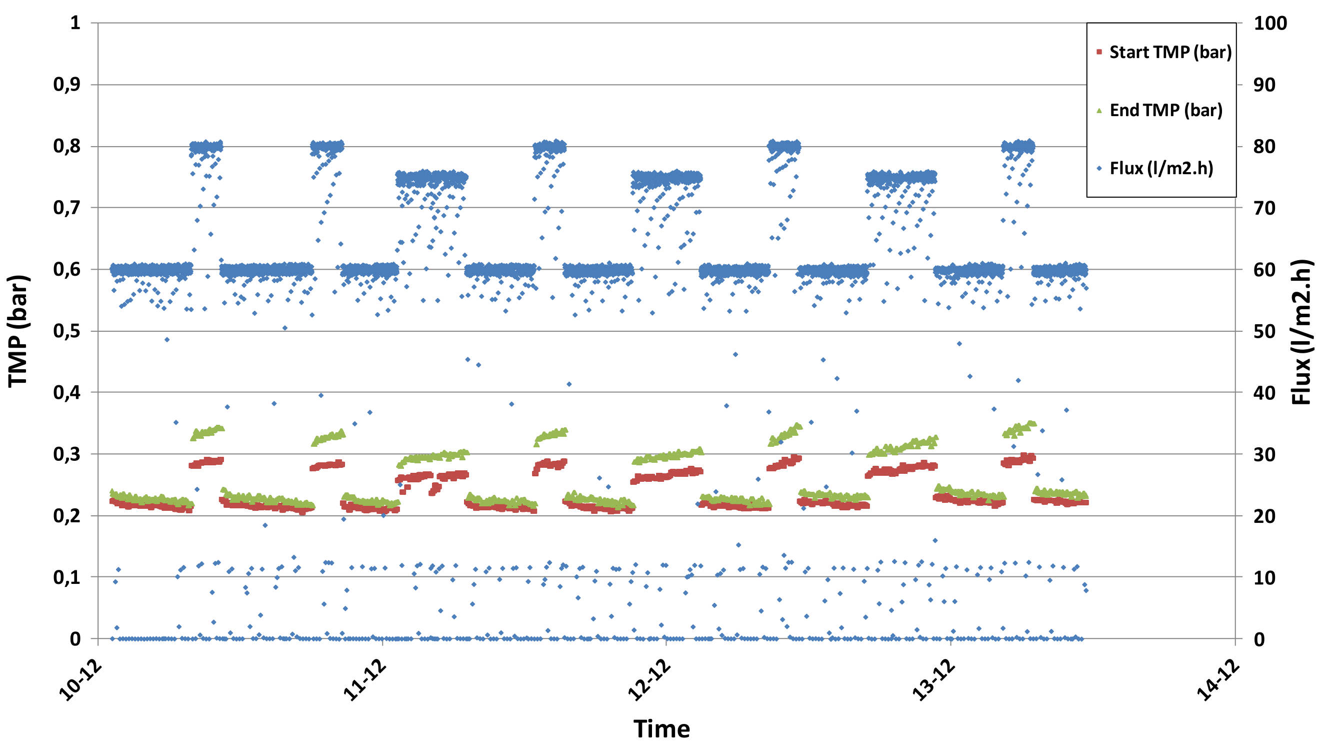

Fig. 10. Typical performance MBR pilot at WWTP Hengelo: flux (blue line; top line) and transmembrane pressure (red = start level and green = end level; bottom lines) vs. time.

advantages of traditional MBR systems. Both discussed sidestream AirLift MBR projects in the Netherlands show how an existing conventional activated sludge system was upgraded successfully by integration of a MBR system.

A sidestream MBR system layout reduces the footprint, building time, and process complexity, where a plug-and-play compact package design offers a flat slab erection without a lot of (local) civil works reducing capital expenses importantly. The sidestream systems are completely closed, so there will be no chance on direct operator contact with activated sludge during (cleaning) operation.

It was demonstrated that an MBR is an effective extension to run at high flux levels of typically 60 l/(m^2 h) enabling to process DWF rates without any problem. Moreover, it was shown that peak leads due to RWFs can be handled by increasing the flux levels temporarily after which the transmembrane pressure levels recover to a stable continuous level reversibly.

Due to an optimized membrane morphology enabling high flux rates, and proper module and aeration hydrodynamics resulting in the well-defined flow channels for very effective air scouring the energy consumption for a sidestream AirLift MBR system is in the range of 0.25–0.35 kWh/m^3 permeate being fully competitive compared to submerged MBR systems.

Integrated internal feed recycle and the low sludge content of the out-of-the-bioreactor placement of the membrane modules cause a minimal interference between biological and membrane processes resulting in good effluent qualities for water reuse.

The complete filtration sequence of filtration and backwashing is fully automated and require no operator interference. Chemical cleaning, normally performed as maintenance cleaning every 4–6 weeks, is being performed without removing the membrane modules from their positions. Just by isolating a stack or block from the main operation it can be drained easily due to its limit sludge content followed by any appropriate chemical cleaning action.

In conclusion, it can be stated that these combined conventional MBR systems offer a cost-effective solution for purification of municipal wastewater into high quality effluent suitable for safe discharge into the environment and for sustainable urban water chain management.

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