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Original Research

Comparison of Flat-Sheet and Hollow-Fiber Membrane Modules in Municipal Wastewater Treatment

I. Bodík*, A. Blšťáková, L. Dančová, S. Sedláček

Institute of Chemical and Environmental Engineering, Faculty of Chemical and Food Technology, Slovak University of Technology Bratislava, Radlinského 9, 812-37 Bratislava, Slovak Republic

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Abstract

The aim of this study was to test membrane modules immersed in pilot-scale domestic WWTP and in the aeration zone of the municipal WWTP Devínska Nová Ves - Bratislava. The first three phases were operated long-term without the employment of additional aeration. The fourth and fifth phases were operated with the employment of additional aeration applied as membrane cleaning in order to prevent the membrane from clogging. The operation of flat-sheet and hollow-fiber membrane modules showed similar results in permeate characteristics. Membrane modules were able to remove organic matter (as much as 92%) and more than 98% of NH_4-N in the long-term operation without activated sludge removal.

Keywords: additional aeration, domestic wastewater treatment plants, nitrogen removal, membrane clogging, long-term operation

Introduction

The membrane bioreactor (MBR) process with immersed membranes can be used for industrial as well as municipal wastewater treatment. Studies on MBRs have received considerable attention due to the deterioration of the water environment all over the world, and due to the advantages of MBRs compared with the conventional activated sludge (CAS) process. MBRs are operated at higher biomass concentrations with resulting high metabolic rates, MBRs produce a more hygienic effluent and since hydraulic and solid (biomass) retention times are independent of each other, MBRs offer an additional degree of freedom for process control. MBR process disadvantages include investment costs, complicated equipment and increased demands on quality maintenance and service.

*e-mail: igor.bodik@stuba.sk

The main limitation for the widespread application of MBRs lies in membrane fouling that reduces the filtration performance and thus increases investment and operating costs [1-3]. The MBR main power requirement comes from aeration, which is used for supply of dissolved oxygen and to maintain solids in suspension. The aeration in MBRs is generally provided by fine bubble aerators, used to keep the tank well mixed and provide oxygen to the biomass. In addition, in submerged MBRs, coarse bubble aerators situated under the membrane modules are used to scour and/or gently agitate the membranes in order to control membrane fouling. Fouling that cannot be removed or suppressed by air scouring or other physical means (such as backflushing of the membrane by reversing the flow of water through it to dislodge the fouling layer) demands chemical cleaning. This uses aggressive chemicals such as oxidants (usually hypochlorite) to remove organic matter, followed by organic acid (citric or organic acid) coupled with mineral acid to remove metal hydroxides. Membrane life data are limited, but anecdotal evidence suggests that membrane deterioration is accelerated by excessive cleaning with oxidative chemicals [4-5].

The use of membrane filtration has recently become more significant in the Slovak Republic. It is being mainly adopted in small-scale WWTPs (domestic WWTP). Czech and Slovak international cooperation coordinated by the ASIO company (CZ), together with the Slovak University of Technology Bratislava (SK) and the Institute of Chemical Technology Prague (CZ), has resulted in long-term pilot plant experiments with MBR. The results from the Prague experiments are reported in [6]. The purpose of the Slovak part of the study was to investigate the long-term operation of a domestic WWTP with immersed membrane modules without backwashing or chemical cleaning. The second purpose of this work was to monitor the effect of additional external aeration used in experiments carried out in a submerged membrane bioreactor (SMBR) immersed in domestic WWTP, and in the activated sludge tank of the municipal WWTP.

Experimental Procedure

Set-up

Operations of membrane modules were carried out in a pilot-scale domestic WWTP installed at the Devínska Nová Ves municipal WWTP, and in the activated sludge tank of Devínska Nová Ves municipal WWTP, which has ca 35,000 people equivalent (PE). The long-term operation of a domestic WWTP with immersed membrane module without backwashing or chemical cleaning was realized from February 2005 to September 2006. Operation of an SMBR immersed in domestic WWTP and in the activated sludge tank of the municipal WWTP with additional external aeration were realized between February and July 2007.

Description of Pilot-Scale Domestic WWTP with SMBR

The tested domestic WWTP (Fig. 1) consisted of a primary sedimentation tank and biological activated sludge tank. Row municipal wastewater, after passing through fine screens (6 mm) of municipal WWTP, was pumped as influent into the pilot plant. In the first phase of the plant (the primary sedimentation reactor), particular suspended solids settled and accumulated at the bottom of the sedimentation reactor. The pretreated wastewater (sedimentation tank output) flew into a biological activated sludge tank equipped with an immersed membrane module. Aeration was performed by an external aerator used for aerating the activated sludge, as well as for cleaning the membrane module. The air flow rate value was 60 L min^{-1}. The treated water was pumped through the membranes using a small (12 W with constant pressure less than 10 kPa) pump, which is activated (turn on) depending on the activated sludge-level in the activated sludge tank. Permeate flux (effluent from the activated sludge tank, i.e. treated water after membrane) was not constant during operation and its values are presented in this paper. After decreasing measured permeate flux rates below 10 L m^{-2} h^{-1}, the operation of tested modules was terminated.

Description of Municipal Wastewater Treatment Plant DNV with Membrane Filtration

The Bratislava-Devínska Nová Ves municipal WWTP (Fig. 2) (ca 35,000 PE), with one tested immersed membrane module in a biological activated sludge tank, was also used for this study. The technological line of municipal WWTP consisted of fine screens (6 mm), grid-chamber, primary sedimentation tank, biological activated sludge tank (with nitrification, denitrification and parallel with phosphorus-precipitation) and secondary sedimentation tank.

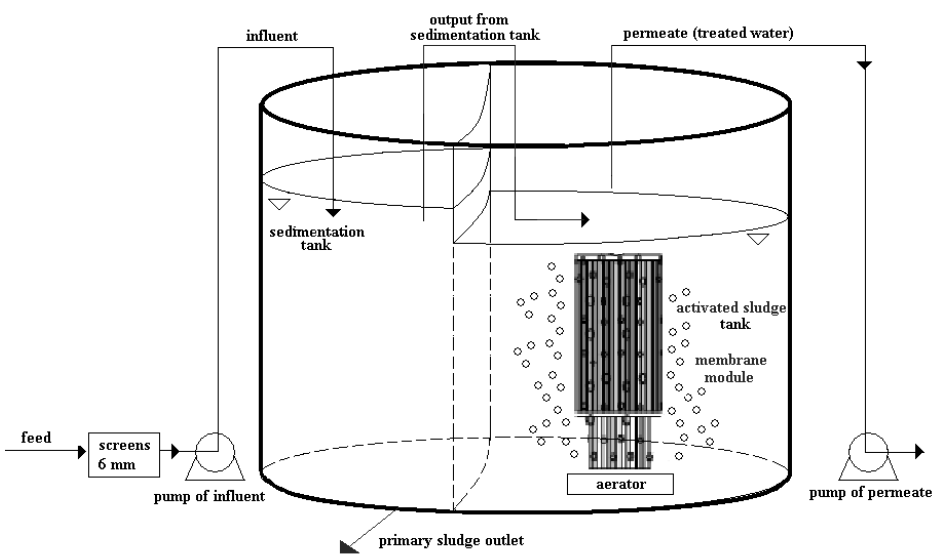

Fig. 1. Schematic diagram of domestic WWTP with immersed membrane module supplied by the ASIO Brno company (Czech Republic).

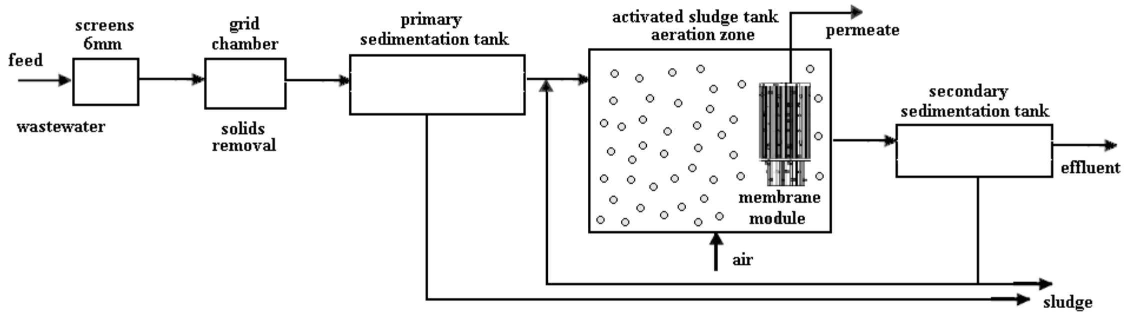

Fig. 2. Schematic diagram of municipal WWTP Devínska Nová Ves with immersed membrane module.

Table 1. Basic experimental conditions.

Phase	Time period	Main phase goal	Inflow rate [L d^{-1}]	HRT* [d]	Place of installed membrane	Used MM
First	Feb 05 – Jul 05	Start-up without seed sludge	360	1.87	AST of domestic WWTP	FS*
Second	Jul 05 – Sep 05 Sep 05 – Jan 06	Start-up with seed sludge, long-term operation, no cleaning	450 700	1.6 1.1	AST of domestic WWTP	FS
Third	Mar 06 – May 06 May 06 – Oct 06	Parallel operation of two different MMs, no cleaning	480 700	1.6 1.1	AST of domestic WWTP	FS parallel with HF
Fourth	Feb 07 – Jul 07	monitoring the effect of external injected air aeration	800	1.0	AST of domestic WWTP	HF*
Fifth	Feb 07 – May 07	monitoring the effect of external injected air aeration	7,000·10^3	0.5	AST of municipal WWTP	HF

*HRT – hydraulic retention time in activated sludge tank, MM – membrane module, AST – activated sludge tank, FS – flat-sheet, HF- hollow-fiber.

The depth of the activated sludge tank was 3.8 m. A membrane module was immersed into the activated sludge tank at a depth of 1.6 m up to the bottom. Aeration was performed by the aerators applied in the activated sludge tank.

Experimental Conditions

Basic experimental conditions are presented in Table 1. The first four phases of domestic WWTP were operated with the total working volume of 1,450-1,500 L, the primary sedimentation reactor with volume 730 L (fixed) and biological activated sludge reactor with volume 720-770 L. Feed was pumped into the pilot plant in the amount of 360-700 L d^{-1} (disconnectedly in eight time intervals per day with drowing of influent 3-5 minutes for each interval) during the first three phases and in the amount of 800 L d^{-1} during the fourth phase. In the first phase, with hydraulic retention time (HRT) = 1.87 d, the influent rate was 360 L d^{-1}. During the second phase, the influent rate increased from 360 L d^{-1} to 450 L d^{-1}, and then to 700 L d^{-1}, finally at the end of this phase, the influent rate again decreased to 450 L d^{-1}. The third phase started with an influent rate of 480 L d^{-1}, which then changed to 700 L d^{-1}. In the fifth phase (real municipal WWTP DNV) with HRT=0.5 d, the influent rate was 7,000·10^3 L d^{-1}. The treatment system was empty between tested phases. After the first, second and third phases the system was inoculated by activated sludge.

Membranes and Membrane Modules Characteristic

Organic polymer membranes, flat-sheet (Martin Systems - Germany) with average pore diameter of 0.04 µm and hollow-fiber microporous membrane (Anonym – Czech Republic) with pore diameter less than 0.10 µm were used for this study. During the first and second phase a flat-sheet membrane with surface area of membrane module 6 m^2 was used. In the third phase the same flat-sheet membrane parallel with hollow-fiber membrane with surface area of membrane module 4 m^2 (5 fiber bunches) were used. Operation of the fourth phase was realized with hollow-fiber membrane with a surface area of membrane module 8 m^2 (10 fiber bunches). From the first to fourth phase, membrane modules were immersed in the activated sludge tank of domestic WWTP. During the fifth phase a hollow-fiber membrane with a surface area of membrane module 48 m^2 (60 fiber bunches) was used and its operation was realized in the activated sludge tank of municipal WWTP. The photos of employed membranes and membrane modules are presented in Fig. 3.

Sampling and Analyses

Samples of influent, sedimentation tank output, permeate (effluent from membrane module - treated water) and activated sludge were taken regularly at eight o´clock in the

FS membrane (First and second phase)	FS and HF membrane (Third phase)	HF membrane (Fourth phase)	HF membrane (Fifth phase)

Fig. 3. Photos of employed membrane modules.

morning. Sampling was realized two times per week. Activated sludge samples were taken from activated sludge tank and analyzed (MLSS) in laboratory. During the experiments, the basic influent and effluent parameters – temperature, pH, COD, BOD_5, SS, NH_4-N, NO_3-N, PO_4-P, as well as activated sludge parameters (MLSS) were determined. All these parameters were analyzed using standard methods [7].

Results and Discussion

The First Phase (February 2005 – June 2005)

The first operation of domestic WWTP with an immersed flat-sheet membrane module (si Claro FM 611, Martin Systems, Fig. 3) was started on 14th February 2005. The goal of this experiment was to test and examine the applicability of the new membrane model without using an inoculum of sludge.

The first phase was characterized by numerous cloggings of the membrane module and also by some technical problems (ice-up of feeding pipes). Membrane module clogging was probably caused by free-swimming microscopic particles (colloid or high-molecular) which entered into the membrane pores and caused membrane fouling. The membrane module operation without membrane cleaning resulted in complete pore-blocking. If the free-swimming particles were in an environment with higher sludge concentration, physical or physicochemical reactions among the particles and the sludge flocks would occur and slow the membrane pore-blocking or completely reduce it. Because of experience from the first phase, it can be said that clogging of the membrane module could be limited with the sludge inoculation.

Besides technical problems, samples were analyzed throughout the whole first phase. The average COD value of permeate was 64.4 mg L^{-1}, which represents 85% efficiency of the process.

The Second Phase (July 2005 – January 2006)

At the end of the first phase, the flat-sheet membrane module was physically and chemically cleaned and regenerated. The second phase of the domestic WWTP operation began by inserting a flat-sheet membrane module into the aeration tank (henceforth referred to as activated sludge tank) of domestic WWTP inoculated with activated sludge from the activated sludge tank of the municipal WWTP in the amount of ca 100 L of sludge with MLSS 7-8 g L^{-1}. The start-up of MLSS was 0.6 g L^{-1} (Fig. 4). Biomass growth and suspended solids accumulation during this phase led to an almost constant sludge concentration of 3.0-3.5 g L^{-1}. Because of a relatively stable sludge concentration in the activated sludge tank, for a new experiment the influent was increased from 450 L d^{-1} to 700 L d^{-1} (September 2005). An increase of inflow rate, as well as summer temperature and higher amount of settled sludge in sedimentation tank caused disturbance of suspended solids in the sedimentation tank and resulted in a higher MLSS concentration (0.5-1 g L^{-1}) at the output of

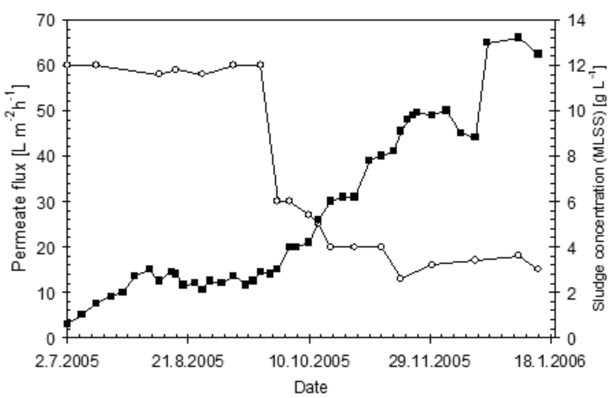

Fig. 4. Sludge concentration in activated sludge tank and permeate flux (effluent of treated water from flat-sheet membrane module) – the second phase.
□ permeate flux (plate membrane module),
■ sludge concentration.

the sedimentation tank for a short time, and slow but continual increase of the sludge concentration in the activated sludge tank up to 12-13 g L^{-1}. The permeate flux did not change during the first two months of operation and showed a relatively stable value of 60 L m^{-2} h^{-1}. The permeate flux decreased significantly when the influent of wastewater was increased. This change in flux was probably caused by a significant fraction of the primary sludge entered into the activated sludge tank. This sludge consistence was too sticky for membrane filtration. In order to avoid the aforementioned operation problem, in the next experimental phases, the digested sludge was regularly drawn from the primary sedimentation tank. The end of the flat-sheet membrane module operation, as well as the end of the second phase, were dated 13th January 2006 because of low values (10-15 L m^2 h^{-1}) of permeate flux.

Table 2. Water characteristics of the influent, sedimentation tank output, permeate – the second phase.

Parameter	Influent [mg L^{-1}]		Sedimentation tank output [mg L^{-1}]		Permeate [mg L^{-1}]		
	average	scope	average	scope	average	scope	η [%]
COD	787.8	502.7 – 1419	157.6	145.6 – 663.7	45.6	12.4 – 86.9	94.2
BOD_5	327.4	227.2 – 420.1	188.5	80.5 – 333.7	5.8	2.8 – 12.2	98.2
SS	383.1	60 – 976.7	120.2	83.0 – 203.3	< 3	-	≈100.0
NH_4-N	68.6	33.5 – 134.1	77.1	42.3 – 164.3	1.5	0.2 – 14.1	97.1
NO_3-N	1.4	0.5 – 3.1	0.8	0.5 – 2.5	21.2	6.8 – 34.4	-
N_{total}	156.7	91.5 – 259.5	158.5	88.5 – 291.2	29.0	2.4 – 46.0	81.4
PO_4-P	1.5	0.6 – 2.2	1.4	0.2 – 3.0	1.3	0.2 – 2.1	-

Table 3. Water characteristics of the influent, sedimentation tank output – the third phase.

Parameter	Influent wastewater [mg L^{-1}]		Sedimentation tank output [mg L^{-1}]	
	average	scope	average	scope
COD	644.4	247.9 – 1163.9	347.8	156.5 – 617.3
BOD_5	239.4	110.0 – 450.0	88.3	35.0 – 180.0
SS	247.5	100.0 – 480.0	104.4	10.0 – 321.4
NH_4-N	67.5	28.8 – 147.6	58.6	28.1 – 102.9
NO_3-N	1.3	0.4 – 3.1	0.7	0.4 – 2.4
N_{total}	149.1	88.8 – 268.2	119.6	75.5 – 177.3
PO_4-P	2.1	0.7 – 4.7	2.6	0.8 – 4.9

Table 4. Water characteristics of permeate (the effluent of treated wastewater: plate membrane module and hollow-fiber membrane module) – the third phase.

Parameter	Permeate (effluent: plate membrane module) [mg L^{-1}]			Permeate (effluent: hollow-fiber membrane module) [mg L^{-1}]		
	average	scope	η [%]	average	scope	η [%]
COD	56.3	14.9 – 109.9	91.3	51.6	17.8 – 118.6	91.9
BOD_5	3.1	0.8 – 8.4	98.7	4.1	0.8 – 8.8	98.3
SS		< 3	≈ 100.0		< 3	≈100.0
NH_4-N	0.9	0.1 – 4.5	98.7	1.1	0.3 – 3.6	98.4
NO_3-N	34.5	18.9 – 61.8	-	33.4	19.0 – 63.5	-
N_{total}	30.8	10.4 – 66.7	79.3	31.9	12.9 – 71.1	78.6
PO_4-P	2.0	0.3 – 4.8	-	2.1	0.5 – 5.1	-

During the whole second phase the samples were analyzed and the main characteristic parameters of the influent, sedimentation tank output and permeate are summarized in Table 2.

During the entire second phase, relatively high N_{total} concentrations (average 156.7 mg L^{-1}) in influent (raw municipal wastewater) were measured (see Tables 2, 3 and 5). These high values were caused by grab sampling and by high morning urea concentrations in wastewater. A relatively high efficiency in the parameter N_{total} was observed. Despite the high NH_4-N concentrations in the influent, NH_4-N concentrations in the effluent were relatively low. The nitrification process proceeded without any problems. The efficiency of ammonium removal was 97.1%. Some characteristic parameters (COD, BOD) in permeate were relatively high compared to literature statements [8-9]. The reason could be that no excess activated sludge was removed from the system during the whole second phase, resulting in the cumulation of the soluble parts of the decayed sludge. These parts could slightly increase the values of some effluent parameters.

The Third Phase
(March 2006 – September 2006)

The third phase was characterized by parallel operation of the flat-sheet and hollow-fiber membrane module immersed in the activated sludge tank of domestic WWTP. The system was inoculated by activated sludge in the same way as in the second phase. At the beginning of the third phase the sludge concentration was 0.6 g L^{-1}. During the operation, sludge concentration continually increased to 12 g L^{-1} (Fig. 5). The permeate flux was measured in both membrane modules. For the flat-sheet membrane module, the initial value of permeate flux was 60 L m^{-2} h^{-1} and for hollow-fiber it was 40 L m^{-2} h^{-1}. During the whole sixth months of the operation, relatively stationary fluxes of 40 L m^{-2} $h^{-1}$for the flat-sheet, and 30 L m^{-2} h^{-1} for the hollow-fiber membrane were observed. Because of a significant decrease of the flux at the beginning of August 2006, the hollow-fiber membrane was cleaned by a back-flush of air (Fig. 5). The end of the third phase as well as the end of the operation was caused by a significant fall of the flux in both membranes due to the digested primary sludge, which entered into the activated sludge tank (analogous to the second phase).

The water characteristics of the influent, sedimentation tank output and permeate are presented in Tables 3 and 4.

The average value of COD in the influent was 644.4 mg L^{-1}. The effluent concentration of COD from the plate membrane and the hollow-fiber membrane was 56.3 mg L^{-1} and 51.6 mg L^{-1}, respectively. The effluent COD concentration and the efficiency of the removal of organic matter were approximately identical in both membrane modules. The NH_4-N values of the effluent (Fig. 6) in both membrane modules were in the range of 0.9-1.1 mg L^{-1}. After the start-up phase and during the stabilized period of operation, NH_4-N concentrations were measured below 1 mg L^{-1} (Fig. 6). Until the first membrane clogging (on 3rd August 2006), the NH_4-N removal efficiency was 98%. In the period when the primary sludge started to overflow (after 18th July 2006), NH_4-N concentrations of about 2.5 mg L^{-1} were measured. Pilot plant nitrification occurred without problems. Effluent NO_3-N concentrations were relatively high because the pilot plant was not well adapted to denitrification. During operation, the NO_3-N concentration gradually increased, and after some time, stable concentrations at about 30 mg L^{-1} were observed (Fig. 6). From the nitrogen balance (Table 4), we concluded that N_{total} removal efficiency was relatively high and obtained 70% efficiency.

Parallel operation of the plate and frame membrane modules and of the hollow-fiber membrane module reached similar results in wastewater treatment. According to the permeate concentrations, the water characteristics from both membranes were very similar. We could confirm

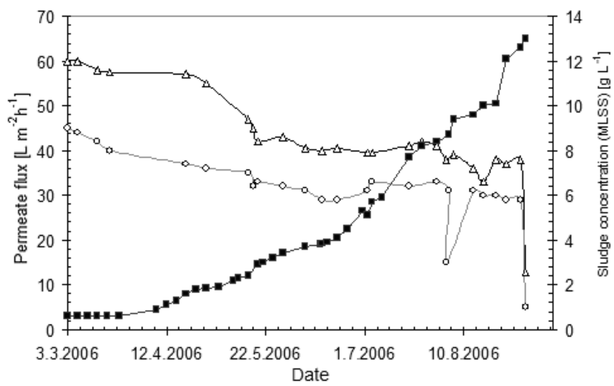

Fig. 5. Sludge concentration in activated sludge tank and permeate flux during the third phase.
■ sludge concentration,
○ permeate flux - hollow-fiber membrane module,
Δ permeate flux – flat-sheet membrane module.

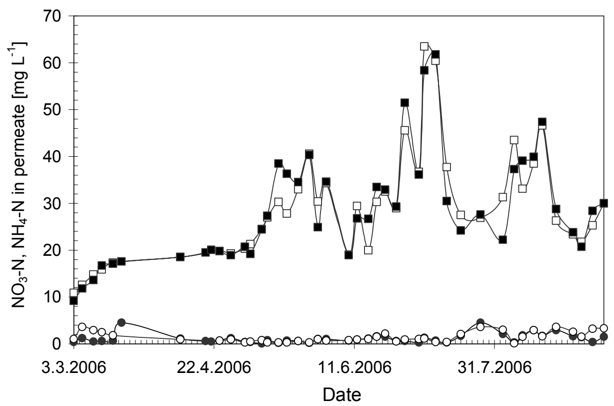

Fig. 6. NO_3-N and NH_4-N concentration in permeate during the third phase.
□ NO_3-N – hollow-fiber membrane module,
■ NO_3-N – flat-sheet membrane module,
○ NH_4-N – hollow-fiber membrane module,
● NH_4-N – flat-sheet membrane module.

Table 5. Water characteristics of the influent and the permeate of hollow-fiber membrane module for domestic WWTP during the fourth phase.

Parameter	Influent		Permeate		
	average [mg L^{-1}]	scope [mg L^{-1}]	average [mg L^{-1}]	scope [mg L^{-1}]	efficiency [%]
COD	595.9	248.7 – 1037.9	46.9	14.9 – 78.2	92
BOD_5	291.6	255 – 330	3.6	2.9 – 8.6	99
pH	8.1	7.5 – 8.5	7.4	6.9 – 7.7	1
SS	500	160 – 530	< 3	-	≈100.0
NH_4-N	54.1	23.2 – 76.6	1.5	0.4 – 2.6	97
NO_3-N	1.4	0.6 – 2.9	29.6	21.2 – 38.9	-
N_{total}	139.5	114.3 – 200	32	20.8 – 40.4	77
PO_4-P	4.0	2.9 – 6.4	3.7	2.3 – 5.6	-

Table 6. Water characteristics of the influent and the permeate of hollow-fiber membrane module during the operation of municipal WWTP - the fifth phase.

	Influent		Permeate		
Parameter	average [mg L^{-1}]	scope [mg L^{-1}]	average [mg L^{-1}]	scope [mg L^{-1}]	efficiency [%]
COD	595.9	248.7 – 1037.9	44.9	29.3 – 66.7	92
BOD_5	291.6	255 – 330	4.2	3.1 – 8.9	99
pH	8.1	7.5 – 8.5	7.3	6.9 – 7.8	1
SS	500	160 – 530	< 3	-	≈100.0
NH_4-N	54.1	23.2 – 76.6	1.2	0.5 – 1.9	98
NO_3-N	1.4	0.6 – 2.9	27.3	13.1 – 56.2	-
N_{total}	139.5	114.3 – 200	29.5	11.2 – 62.1	79
PO_4-P	4.0	2.9 – 6.4	2.2	1.5 – 2.9	-

that the plate membrane separation in long-term operation showed relatively higher values of flux, which shows its good operational parameters. During the six-month phase, different requirements of both membrane systems on cleaning were observed. In case of the hollow-fiber membrane, it was necessary to clean the membrane after four months from the start, while the plate membrane worked without cleaning for the whole term of the operation.

The Fourth Phase (February 2007 – July 2007)

The operation of domestic WWTP with the immersed hollow-fiber membrane module began on 28th February 2007. The pilot plant was inoculated by activated sludge in the same way as in the second and third phases. The starting sludge concentration in the activated sludge tank was nearly 3.2 g L^{-1}. For demands of increased membrane cleaning during operation, a compressor for additional aeration was installed. At the start of the operation a compressor with compressed air was not used, and the hollow-fiber membrane module was not subjected to additional (supplemental) aeration (only to aeration by the standard diffuser placed besides the hollow-fiber membrane module). The compressed air cleaning of the membrane was first used in the second half of the operation (the first membrane clogging was on 26th March 2007).

After start-up, the permeate flux was 20 L m^{-2} h^{-1}. Gradually the permeate flux decreased to the minimal value 0.4 L m^{-2} h^{-1} at the end of March (Fig. 7). On 26th March 2007 the membrane module was completely clogged and the activated sludge overflowed the pilot plant. The membrane was subsequently cleaned and regenerated only by backwashing with dilute NaOCl and by blowing. After cleaning the membrane, additional injected air aeration of the membrane was installed into the module with a cycling-time of ten seconds at ten-minute intervals. The module with additional injected air aeration was repeatedly started-up and the permeate flux was held at stabilized values about 20 L m^{-2} h^{-1} until the end of the experiment.

The decreased permeate flux gradually increased the sludge concentration to a maximum value of 8.4 g L^{-1} (Fig. 7) at the time of total membrane clogging. After membrane regeneration, sludge concentrations were stabilized. By the end of the operation (last month), sludge concentration did not change significantly. The average sludge concentration value was about 6 g L^{-1}.

Despite the high age of activated sludge, its organic portion generated an average of 70% of suspended solids. The sludge index values during the entire operation were about 70 mL g^{-1}.

On 12th July, after three months of stable measured values for the key parameters, the operation of module measurement ended together with operation of the domestic WWTP.

The water characteristics of the influent and permeate for domestic WWTP during the fourth phase are presented in Table 5.

The efficiency of the removal of organic matter was similar to the second and third phases, up to 92%. Pilot plant nitrification occurred without problems. During the stabilized period of operation, NH_4-N concentrations were measured about 1.5 mg L^{-1}. The permeate NO_3-N concentrations (Fig. 8) were relatively high because the pilot plant was not well adapted to denitrification. During operation, the NO_3-N concentrations changed and at the end of operation, NO_3-N concentrations were in interval from 21-31 mg L^{-1} and average value was about 29.6 mg L^{-1}.

From the nitrogen balance (Table 5), we concluded that N_{total} removal efficiency was relatively high and obtained 77% efficiency. For a short period after high COD influent was pumped into the pilot plant, the oxygen concentration sharply decreased to below 1 mg L^{-1} in summer season and 3 mg L^{-1} in winter season (Fig. 9). This caused a partial reduction of NO_3-N in the activated sludge tank during the summer season.

The Fifth Phase – Municipal WWTP (February 2007 – May 2007)

On 23rd February 2007, the operation of the membrane module started with the installation of the hollow-fiber membrane module into the activated sludge tank (with fine bubble aeration) of the real WWTP in Bratislava - DNV. Because it was anticipated that the membrane would be

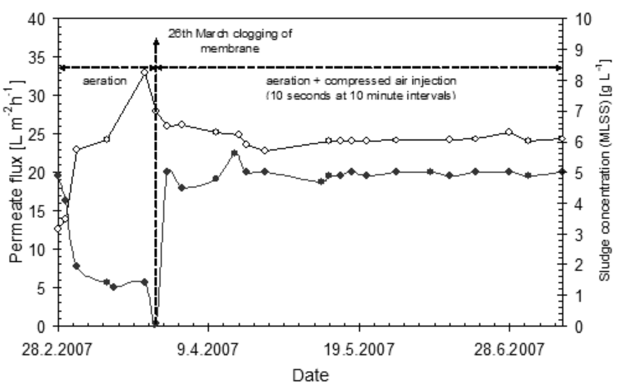

Fig. 7. Sludge concentration and flux hollow-fiber membrane module during the fourth phase.
● permeate flux of hollow-fiber membrane module,
○ sludge concentration).

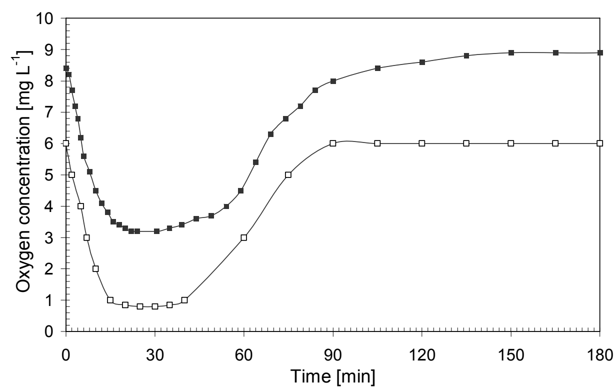

Fig. 9. Oxygen concentration during the three-hour cycle pumping the influent for domestic WWTP operation (□ summer season, ■ winter season).

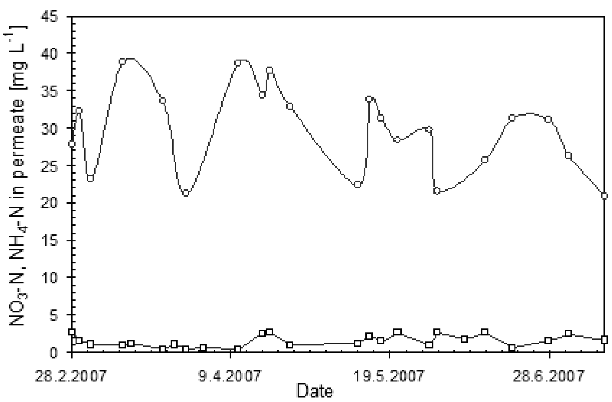

Fig. 8. NO_3-N and NH_4-N concentration in permeate during the fourth phase,
○ NO_3-N and □ NH_4-N– hollow-fiber membrane module.

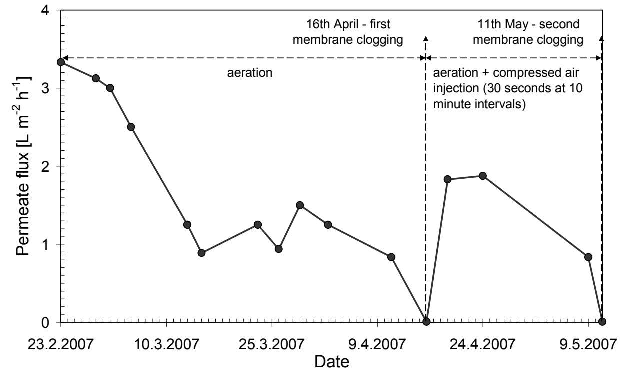

Fig. 10. The permeate flux of hollow-fiber membrane module during the operation of municipal WWTP - the fifth phase.

insufficiently cleaned by fine bubble aeration from activated sludge tank, supplemental aeration by injection of compressed air (analogous to the operation of domestic WWTP) was prepared for use as needed. In the start-up of the operation, the hollow-fiber membrane module worked without supplemental cleaning by compressed air until the first membrane clogged (16th April 2007).

The permeate flux during the first month of operation gradually decreased from 3.5 L m^{-2} h^{-1} to 1 L m^{-2} h^{-1}, but stabilized during the next month (see Fig. 10). However, on 16th April 2007 total membrane clogging was observed. The membrane was consequently cleaned and on 25th April 2007 the operation started again. To prevent membrane clogging, the hollow-fiber membrane module was subjected to supplemental compressed air injection for thirty seconds at ten-minute intervals. On 11th May the membrane clogged again and its operation ended.

Because of the relatively high surface area of the hollow-fiber membrane module, the supplemental compressed air injection during the test period was inadequate to prevent clogging. The flux values were too low and it is concluded that the MBR process needs advanced efficiency aeration to clean the membrane modules to inhibit clogging.

Table 6 shows the water characteristics of the influent and the permeate of hollow-fiber membrane module installed into the activated sludge tank of WWTP DNV during the fifth phase.

Besides technical problems, samples were analyzed throughout the whole fifth phase. The average COD value of permeate was 44.9 mg L^{-1}, which represents 92% efficiency of the process. A relatively high efficiency in the parameter N_{total} was observed. The nitrification process proceeded without any problems. The efficiency of ammonium removal was 98%.

Conclusions

The purpose of this study was to investigate the long-term operation of a domestic WWTP with immersed membrane modules without backwashing or chemical cleaning. The second purpose was to monitor the effect of additional external aeration used in experiments carried out in a submerged membrane bioreactor immersed in domestic WWTP and in the activated sludge tank of the municipal WWTP. Based on data from experiences, the conclusions are:

- The first phase: pilot plant needs activated sludge inoculation, because a membrane module without inoculation becomes clogged in a short time.
- The second and third phase: Experimental testing of membrane modules during pilot plant operations for several months without external cleaning showed that measured water quality parameters and fluxes were satisfactory. The flat-sheet membrane module was operated without external cleaning for 6 months with flux of 20-60 L m^{-2} h^{-1}. The operation of hollow-fiber membrane module was operated for 4 months without external cleaning with flux of 20-45 L m^{-2} h^{-1}.
- The fourth phase: short duration, short interval, external cleaning of hollow-fiber membrane by an adequate quantity of compressed air was demonstrated. The permeate flux in the module with additional injected air aeration was held at stabilised values about 20 L m^{-2} h^{-1} until the end of the experiment.
- The fifth phase: depends on surface area of membrane module, the supplemental compressed air injection during the test period was inadequate to prevent membrane clogging.
- Long-term operation of the activated sludge tank without excess sludge drawing off occurred due to an effective pre-treatment phase (high HRT in the sedimentation tank).

Results of water quality analyses illustrated that the membrane technologies can be used to treat raw municipal wastewater to produce high-quality water. Organic matter removal in this system was stable and efficient (up to 92%). Under these conditions, more than 97% of NH_4-N was removed, and effluent NH_4-N concentration was less than 1.5 mg L^{-1} during long-term measurement. Nitrogen removal via denitrification was observed during the short periods with low oxygen concentration. Parameters such as *Escherichia coli* were 0 CPU/ 10 mL of the MBR effluent sample.

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Abbreviations

AST	activated sludge tank	
BOD_5	biological oxygen demand	[mg L^{-1}]
COD	chemical oxygen demand	[mg L^{-1}]
FS	flat-sheet	
HF	hollow-fiber	
HRT	hydraulic retention time	[d]
MBR	membrane bioreactor	
MLSS	mixed liquid suspended solids or sludge concentration	[g L^{-1}]
MM	membrane module	
N_{total}	total nitrogen	[mg L^{-1}]
NH_4-N	ammonium nitrogen	[mg L^{-1}]
NO_3-N	nitrate nitrogen	[mg L^{-1}]
PE	people equivalent	
PO_4-P	phosphate phosphorus	[mg L^{-1}]
SMBR	submerged membrane bioreactor	
SS	suspended solids	[mg L^{-1}]
WWTP	wastewater treatment plant	

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