SLOVAK JOURNAL OF CIVIL ENGINEERING

Vol. XX, 2012, No. 2, 28 – 36

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TWO YEARS OF THE OPERATION OF A DOMESTIC MBR WASTEWATER TREATMENT PLANT

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ABSTRACT

The paper evaluates the results of data obtained from two years of observing an actual domestic wastewater treatment plant (WWTP) with an immersed membrane module. The domestic MBR (membrane bioreactor) WWTP was linked to a dwelling with four residents. Two different commercial flat sheet membrane modules were investigated. The membrane modules, as well as the whole WWTP, were tested with different fluxes as well as the response of the membrane and activated sludge to different conditions, such as actual peak wastewater flows, extremes temperatures (a winter below 5 °C), and high pH values.

KEY WORDS

- *Domestic WWTP,*
- *Wastewater,*
- *Membrane module,*
- *Membrane flux,*
- *Membrane fouling.*

INTRODUCTION

Decentralised wastewater treatment is used to treat and dispose of relatively small volumes of wastewater, which generally originate from groups of dwellings and businesses that are located relatively close together, but are not attached to a central sewer system that collects the wastewater down to a WWTP [1]. Increasing water scarcity coupled with stringent regulations has meant that a single-domestic MBR, with the effluent being recycled for nonhuman contact applications such as irrigation, washing and toilet flushing, is potentially economically viable. However, a single-domestic MBR is believed to be costly compared with an established freshwater supply and effluent discharge [2]. The MBR technology integrates the biological degradation of wastewater pollutants with membrane filtration, ensuring the effective removal of organic and inorganic contaminants and biological material from domestic and/or industrial wastewaters [3].
In this study the treatment plant was fed by actual domestic wastewater. In contrast to most other investigations of small-scale WWTPs, the wastewater did not originate from a sewer system. Several difficulties had to therefore be overcome: this wastewater was not diluted by rainwater or infiltrated groundwater; it contained hair and particles; the water flow and pollutant load to the plant fluctuated greatly and was not controllable; and neither the wastewater composition nor the concentrations in the raw influent could be measured [4].

MATERIALS AND METHODS

Pilot domestic MBR WWTP

The domestic MBR WWTP (Figure 1) tested was installed in the garden of a four-person house. All the wastewater produced in the house flowed to the treatment plant. The plant had no possibilities of bypass or emergency overflows. The effluent was stored in an effluent tank and could be reused for irrigating lawns and gardens or cleaning floors, etc.

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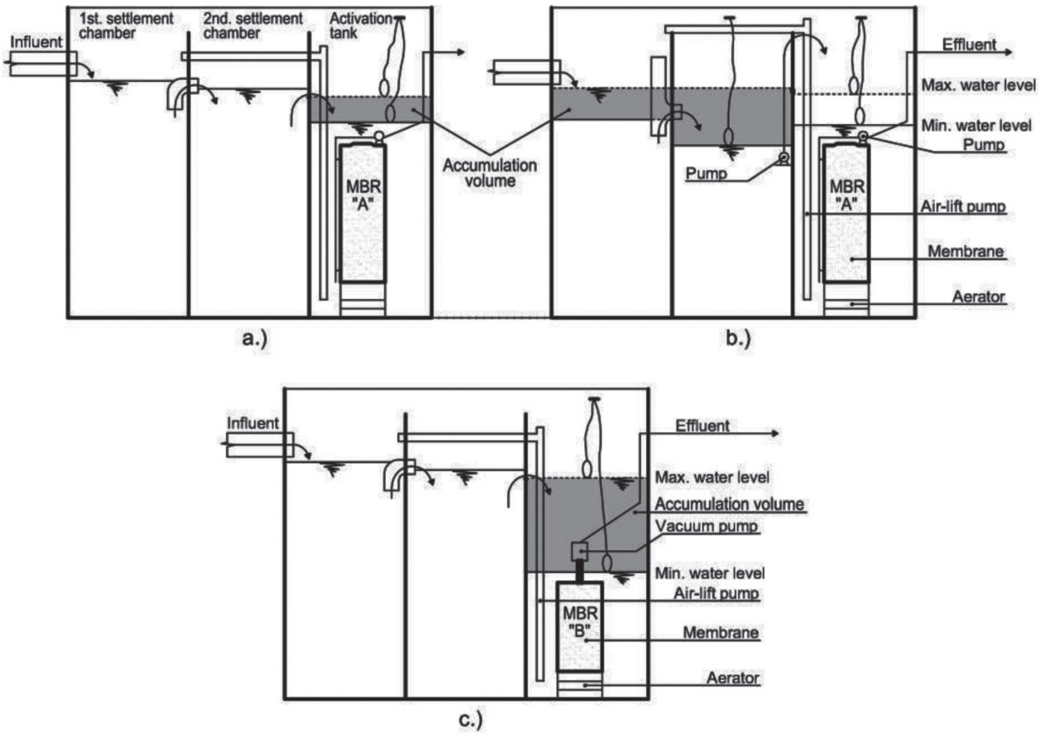

Fig. 1 *Scheme of domestic MBR WWTP*
a) membrane module "A" - concept 1 applied in the 1st and 2nd phases, b) membrane module "A" - concept 2 applied in the 3rd phase, c) membrane module "B".

The pilot-scale MBR plant consisted of three chambers in a series; the volume of each was approximately 0.58 m^3. The first two chambers were used as a preliminary treatment stage. In these settlement chambers the majority of the solids were removed from the raw wastewater by sedimentation. The pretreated wastewater (from the settlement chambers) flowed into the biological activated sludge reactor, which was equipped with an immersed membrane module.

During the experiment two flat sheet membrane modules from two different commercial suppliers were tested. The parameters are shown in Table 1. Aeration was provided by an aerator placed under the membrane module. The aeration provided aerated the activated sludge as well as the mechanical cleaning of the membranes. The water level in the plant was controlled by water-level floats.

The hydraulic retention time (HRT) in the entire domestic MBR plant was 7.2 days; the HRT in the preliminary stage was 4.8 days; and the HRT in the biological reactor was 2.4 days. The volumetric loading was approximately 0.35 kg COD.m^{-3}.d^{-1}.

Each membrane module was surveyed for one year. At that time the research was divided into three phases, depending on the necessity

Tab. 1 *Parameters of the observed membrane modules given by the suppliers.*

Parameter	Unit	Membrane module "A"	Membrane module "B"
Membrane parameters	mm	185 x 1090 x 316	207 x 207 x 492
Membrane area	m^2	6.7	3.5
Pore size	μm	0.1	0.05
Pressure	bar	0.02-0.4	0.1-0.15
Max. flux	L.m^{-2}.h^{-1}	50	50
Average flux	L.m^{-2}.h^{-1}	15-30	15-30
Membrane material		PVDF (polyvinylidene difluoride)	PES (polyethylsulphone)
Max. inflow	m^3.d^{-1}	0.6	0.6
Pump		submersible pump	vacuum pump

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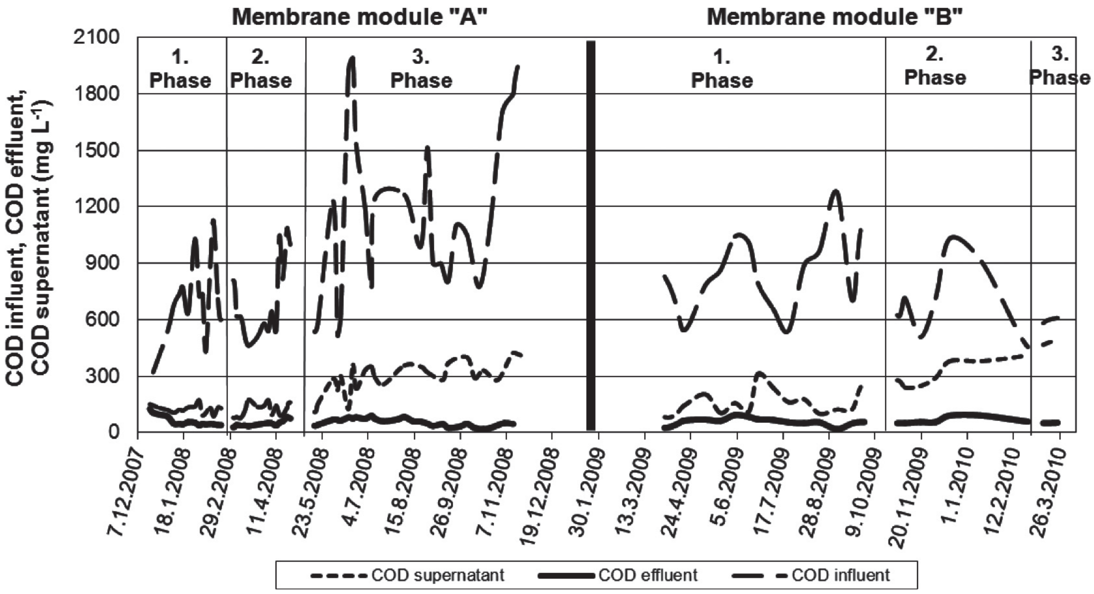

Fig. 2 *Comparison of COD values (influent, supernatant, effluent).*

of regenerating the membrane or technical changes. The major differences between the compared membrane modules were the membrane area, the membrane pump and the technical arrangement of the WWTP.

RESULTS

The quality of the raw wastewater and effluent

During the entire experiment the chemical parameters of the raw water (influent) as well as the effluent were monitored. As seen in Figure 2, the concentrations of COD in the influent and supernatant fluctuated quite a bit during each period. The COD of the permeate had a relatively sustained value, and the average value during the monitored season of membrane module "A" was 53.4 mg.L^{-1} and 57.6 mg.L^{-1} of membrane module "B".

The BOD_5 concentrations in the effluent varied from 0.2 to 8 mg.L^{-1} in the entire experiment; the removal efficiency was approximately 99.5 %. Although the initial effluent values of the COD (125 mg.L^{-1}) and BOD_5 (8 mg.L^{-1}) were relatively higher, they fulfilled the legislative demands without any problems for the SR and ČR for the domestic WWTP during the entire experiment (BOD_5 = 40 mg.L^{-1} for the discharge to surface water, BOD_5 = 20 mg.L^{-1} for the discharge to underground water) [5, 6] – Table 2.

Tab. 2 *The average values of the raw wastewater (influent) and effluent from the domestic WWTP.*

Parameter	Membrane module "A"		Membrane module "B"	
	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})
COD	917.6	53.4	720.7	57.6
BOD_5	593.8	2.3	504.5	2.5
NH_4-N	151.8	44.9	145.3	61.8
N_{tot}	213.8	137.1	203.0	145.7
P_{tot}	18.7	11.7	22.2	15.0

However, it is necessary to refer to the high concentration of N_{tot} in the influent (Table 2, Figure 3). N_{tot} is usually higher in concentrated domestic wastewater and can have a negative influence on nitrification. The high concentration of N_{tot} in the influent incurred a higher pH (during colder periods normally above 9 ^{o}C); thus in the activation tank the substrate's inhibition was achieved (inhibition with an undissociated NH_3) [7]. During the low liquid temperature (during colder periods mainly of less than 11^{o}C; winter weeks of less than 7^{o}C), it was logical that the nitrification was not complete. In the domestic WWTP the nitrification only started when the temperature was above 8-9 ^{o}C, despite the sufficient age of the sludge (above 70 days); the high sludge concentration and high

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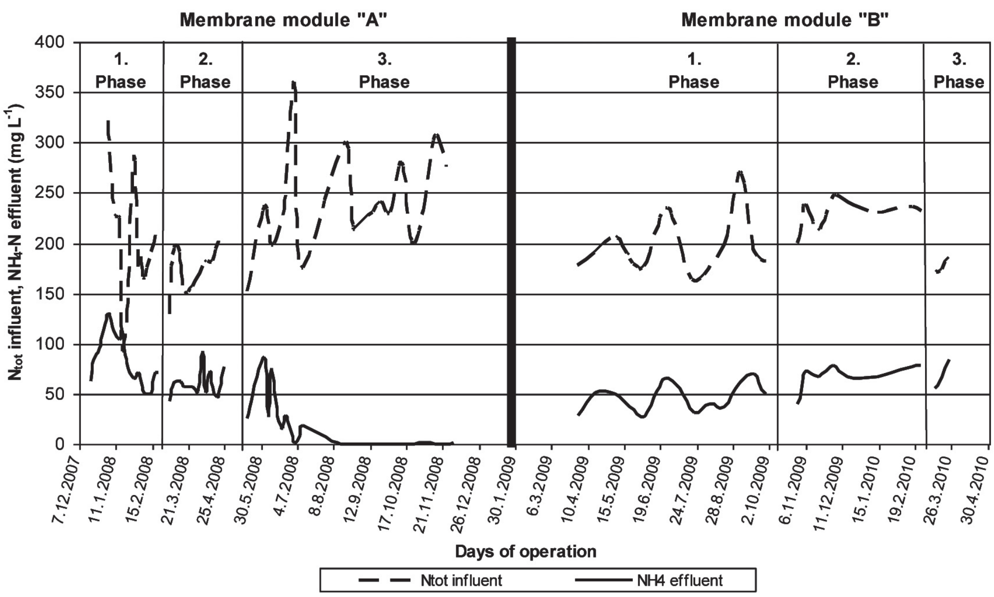

Fig. 3 *N_{tot} influent and NH_4-N effluent concentrations.*

concentration of dissolved oxygen (constantly over 5-6 mg $O_2.L^{-1}$). European standard EN 12566-3 [8] establishes the conditions for testing domestic WWTPs, after which they may receive a CE marking. CE marking provides the opportunity to sell these products on the European market. For tests of domestic WWTP the standard is recommended in raw wastewater, besides other values like COD, BOD_5, SS and P_{tot}, the values of KN = 25 - 100 $mg.L^{-1}$ and NH_4-N = 22 – 80 $mg.L^{-1}$. According to our experience and also measurements (Table 2, Figure 3), these values are very low and unrealistic for an actual domestic WWTP.

Quality of the activated sludge and its parameters

Sludge sedimentation properties were also observed in the activation tank. The sedimentation was verified during each period of the research. Figure 4 shows an evaluation of the Sludge Volume Index (SVI) and the Mixed Liquor Suspended Solids (MLSS). During the first two periods of the first year (MBR "A") the domestic MBR WWTP was inoculated with activated sludge from the municipal WWTP with a worse level of SVI. At the beginning of the first period (the SVI of the inoculum was 210 $mL.g^{-1}$). The SVI decreased, but after approximately one month, the sedimentation rapidly got worse. Subsequently, the SVI gradually decreased, but mainly as a consequence of the increased MLSS concentration. During the second period, the inoculum was even more bulky (SVI 461 $mL.g^{-1}$) [9]. The SVI gradually decreased in the same way. The actual 30 minute sediments were so high that it was not possible to separate the supernatant; and the zone of free liquid above the sludge layer was minimal.

The dominant filamentous bacteria were Microthrix Parvicella - the amount was 5 out of 6 according to the Jenkins method [10]. In this situation of massive sludge bulking, the domestic MBR plant offered an advantage over the conventional WWTP by preventing the failure of the biological system due to the loss of biomass. The membrane is a physical barrier, and this implies that all the suspended solids had been retained in the system. In the third period, the inoculum was from another municipal WWTP and did not contain filamentous bacteria in such a high amount (an SVI of less than 100 $mL.g^{-1}$). Even though in the third period after 1.5 months the SVI increased above 250 $mL.g^{-1}$, it subsequently gradually decreased, and the separation of the clean water was achievable by settling.

The inoculum from the same municipal WWTP as in the third period of the investigation of MBR "A" was used in the second year of research (MBR "B"). Even though the inoculum did not contain filamentous bacteria, they appeared and overgrew in the biological reactor in every period. A similar situation with a spontaneous overgrowth of filamentous bacteria appeared in Jakubcova, et al. [11]. From the results it can be seen that in domestic WWTPs, sludge bulking may be a real problem (and if an inoculum with filamentous

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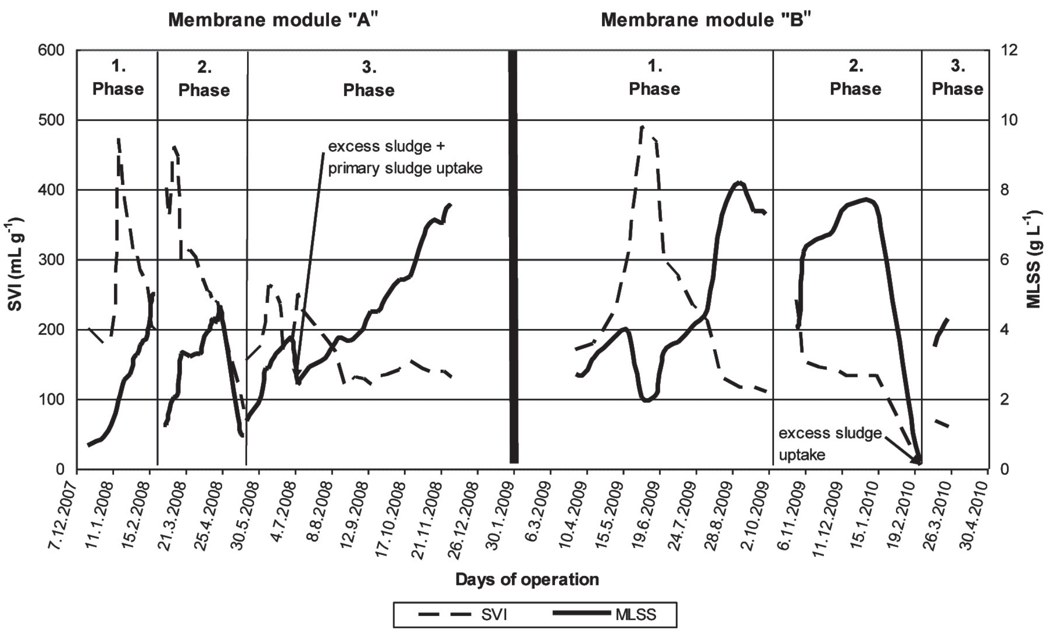

Fig. 4 *Progress of SVI and MLSS concentration during the entire experiment.*

bacteria is used, this problem is much more accentuated). In a conventional activated sludge system (without membrane filtration), such bulking sludge will leak out in the outflow.

EVALUATION OF THE MEMBRANE FLUX

Membrane module "A"

Special attention was paid to the flux. The filtration in the first period started without any regulation of the flux or transmembrane pressure. It was assumed that the majority of the owners and users of a domestic WWTP would not be wastewater treatment experts and would not pay attention to the flux or pressure regulation. The initial flux was 45 $L.m^{-2}.h^{-1}$, and we did not change the system. The flux decreased from a value of 45 $L.m^{-2}.h^{-1}$ below 10 $L.m^{-2}.h^{-1}$ after approximately three months (it corresponded to 22 m^3 or 3.2 $m^3.m^{-2}$ of the filtered wastewater through the membrane) [9].

The membrane module was changed for a new one and was started in the second period. Because of the possibility of flux regulation, a throttle at the effluent conduit was installed. At the start-up, the membrane module was operated under a flux of 13 $L.m^{-2}.h^{-1}$ for three days; then the flux was set at 20 $L.m^{-2}.h^{-1}$. After three months, the flux rapidly decreased to 6 $L.m^{-2}.h^{-1}$ again. Through the membrane module 12.1 m^3 or 1.8 $m^3.m^{-2}$ of the treated wastewater was filtered [9].

The membrane was regenerated by a 0.5 % solution of acetic acid before the start of the third period. The membrane module was operated at a low flux below 10 $L.m^{-2}.h^{-1}$ and lower transmembrane pressure approximately below 0.1 bars in the third period [9]. The operation of the membrane module at this value of the lower flux appeared to be steady and suitable – after 184 days of operation the flux started to decrease. The membrane regeneration was necessary after seven months (a flow of 45.1 m^3 or 6.7 $m^3.m^{-2}$ of the filtered wastewater through the membrane).

When the lower filtration flux is used, it is necessary to pay attention to the volume of the accumulation in the biological reactor. This volume of the accumulation should be as big as possible due to the peak wastewater flow, but it also depends on the height of the membrane module. In this case, the height of the biological reactor was 1.6 m, and the height of the membrane module with its facilities (the aerator and pump, which had to be submerged) was 1.44 m; accordingly, the volume of the accumulation was just 60 L (Figure 1 a.).

The flux of 15-25 $L.m^{-2}.h^{-1}$ (common values given by manufacturers of flat sheet membrane modules) was calculated when this domestic MBR WWTP was designed, but with regard to the third period, which was operated at the relatively lower flux, the biological

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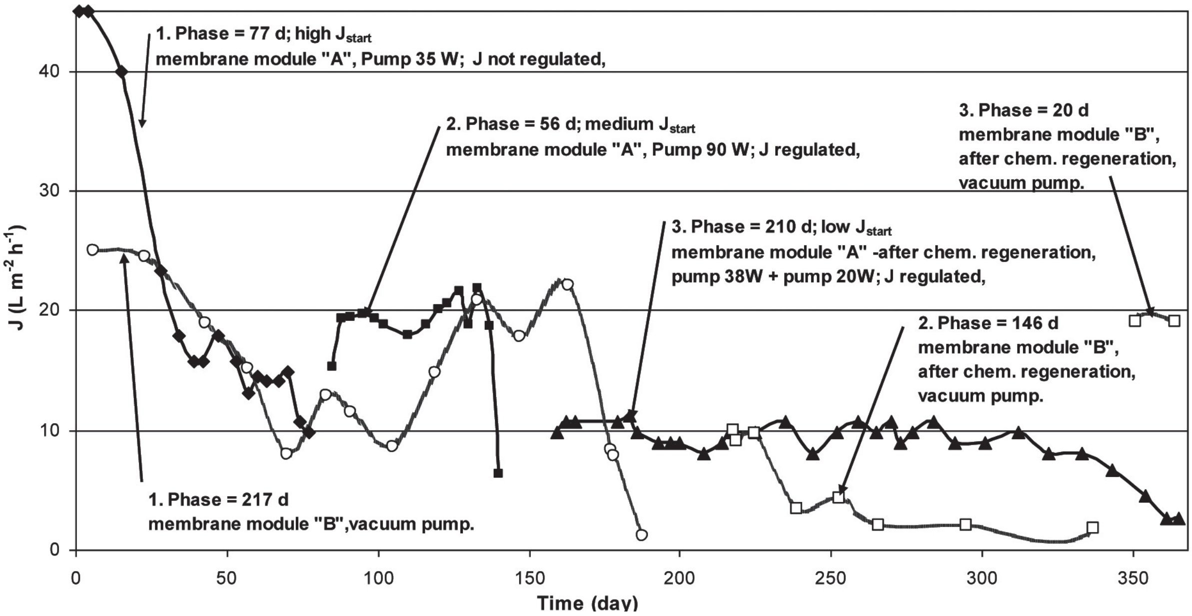

Fig. 4a *Flux evaluations of two different membrane modules during the experiment.*

reactor was flooded (the flux through the installed membrane was so low that it could not rise to occasional peak wastewater flow). This is a particularity of the membrane, which must not be omitted by the designer. Therefore, the gravity inflow from the second settlement tank was changed to a pumped inflow. The first and second settlement chambers were then used as accumulation (buffer) tanks with an accumulation volume of 200 L (Figure 1 b.). However, this was not a convenient solution, because it was another device which could break down; therefore, a different membrane module was used in the second year of the research.

Membrane module "B"

The "B" membrane module offered a greater accumulation volume in the biological reactor because its height was considerably smaller compared to the membrane module "A". The concept behind the gravity flow of the wastewater among the chambers was restored (Figure 1 c.).
The initial membrane flux was predetermined by the membrane producer at a value of 25 $L.m^{-2}.h^{-1}$ at the transmembrane pressure of 0.1 bars. The flux fluctuated from 25 $L.m^{-2}.h^{-1}$ to 9 $L.m^{-2}.h^{-1}$ during the 6 months of operation and then suddenly decreased to 1.1 $L.m^{-2}.h^{-1}$ due to the membrane clogging. Through the membrane module, 35.6 m^3 or 10.2 $m^3.m^{-2}$ of the treated wastewater was filtered. The mechanical cleaning and regeneration by citric acid with a pH = 3 and then by sodium hypochlorite (pH = 11) was performed. During the mechanical cleaning large pieces of sludge cake appeared, the thickness of which was approximately 3 mm. Between particular sheets a continual layer of the dewatered sludge cake was created, which caused the blocking of an entire membrane, thereby resulting in the dysfunction of the whole system. Therefore, it can be considered to be a big risk of flat sheet membrane modules.
In the second phase, the membrane module "B" was observed at a lower flux of about 10 $L.m^{-2}.h^{-1}$. However after one month, the flux decreased and held around a value of 5 $L.m^{-2}.h^{-1}$. The transmembrane pressure fluctuated between the 0.12 – 0.20 bars. The flux decreased below 2 $L.m^{-2}.h^{-1}$ after 5 months, and the membrane module had to be repeatedly regenerated.
The regeneration was made by citric acid with HCl to reduce the pH (pH = 2) and then by NaClO with NaOH (pH = 11). After the regeneration the flux was 19 $L.m^{-2}.h^{-1}$. The flux remained at this value until the end of the research, which means one month. In domestic WWTP conditions, the need to regenerate the membrane even more than two times per year was confirmed, whereby it is necessary to expect that the membrane would have to be exchanged after half a year.
During the entire experiment the flux fluctuated as can be seen in Figure 4. After this experience, it is possible to assert that, despite

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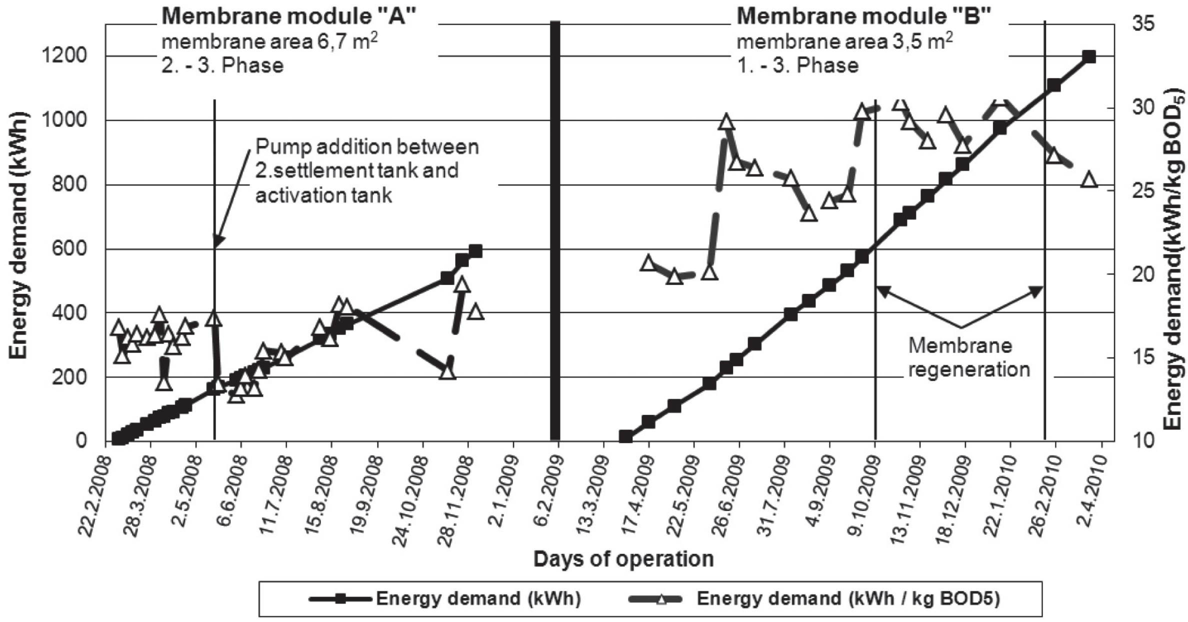

Fig. 5 *Evaluations of the energy demands of two different membrane modules during the experiment.*

the manufacturer's recommendations, the flux decreases spontaneously and that the common proposed flux with a regeneration demand of 2 or 3 times per year is at a level of 10 $L.m^{-2}.h^{-1}$. The membrane manufacturers and suppliers normally recommend a flux of 15 - 20 $L.m^{-2}.h^{-1}$; nevertheless; after two years of research this value is considered by us to be dangerous and irresponsible.

The membrane fouling was probably contributed to by additional factors:

- high flux, mainly in the first days after the start up,
- low temperatures, normally below 10 °C in the winter season. Temperature impacts on membrane filtration through its influence on the viscosity of the permeate fluid. The low temperature also resulted in incomplete nitrification, which started when the temperature was above 10 °C,
- the high concentration of N_{tot} (Figure 2) in the concentrated domestic wastewater resulted in higher pH levels and the precipitation of phosphates PO_4-P. Incipient precipitation may foul the membrane. In the winter this problem was even more striking, because the nitrification did not work in the biological reactor; thus, the pH level did not decrease [8],
- sludge bulking. In the domestic WWTP a problem with sludge bulking occurred (the dominant filamentous bacteria was Microthrix Parvicella), which had a tendency to flotation and foaming during the whole experiment. The overgrowth of filamentous bacteria could result in a much higher release of extracellular polymeric substances (EPS), which would correlate to the membrane fouling and could result in great harm to the membrane permeation [12, 13].

The significant impact of the temperature on the MBR fouling suggests that winter is a critical time for the membrane's operation. To control the possible intensification of membrane fouling under winter conditions, it is suggested that the MBR be run at a lower filtration flux, if possible (in a domestic WWTP, below 15 $L.m^{-2}.h^{-1}$), and that the coarse bubble aeration be intensified [13] (continuous aeration, if possible, or a very small pause in aeration of 1 max. 2 minutes off and more than 5 minutes on).

Evaluation of energy consumption

For a domestic MBR WWTP operation it is also important to know the energy consumption. During the experiment with the membrane module "A" in the second and third phases, the energy demand was 2.1 $kWh.d^{-1}$, which is equal to 10.4 $kWh.m^{-3}$ (1 m^3 of filtrated water), and the price for electricity was approximately 4.9 € per month or approximately 58.8 € per year. It is necessary to take into consideration that during the operation energy needed for the second

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Tab. 3 *Comparison of investment and operating cost.*

Parameter	WWTP (4EO)	MBR WWTP (4PE)	Cesspool 10m^3	Tariff of sewage (4PE)
Investment cost - €	2000	3800	2100	
Operating costs electricity consumption - €/year	50	70		
Regeneration - 2 x year		100		
Disposal of primary sludge to WWTP < 30 km	100 (2xyear)	100 (2x year)	750 (15x year)	
Total costs €/ 1year	**150**	**270**	**750**	**165**[b]
Total costs €/ 5 year	750 + 200[a] = **950**	1350 + 200[a] = **1550**	**3750**	**825**
Total costs €/ 10 year	1500 + 400[a] = **1900**	2700 + 400[a] = **3100**	**7500**	**1650**

Note: a – exchange of aeration components approximately every 5 years,
b – assumed wastewater production = 100 L.inhabitant^{-1}.d^{-1}, price 1,13 €/m^3

pump's operation was also added (the pump between the second settlement chamber and the biological reactor), which partly led to the increased energy demands.

The energy demands of the membrane module "B", which was furnished with a vacuum pump and membrane area of 3.5 m^2, was approximately 3.4 kWh.d^{-1} and 17.4 kWh.m^{-3} during the entire investigation. The cost of the energy demand was approximately 6.5 € per month, i. e., 78 € per year.

In terms of the quality of the effluent (particularly for the area where the treated water was reused), these values are not especially expensive. The difference in energy consumption between the two tested models can be seen; however, the difference is not so high, and each model has its own advantages as well as disadvantages. For example, the membrane module "B" is smaller and thereby offers the advantage of a larger accumulation volume in the biological reactor and also fewer complications with the pump system. An evaluation of the energy demands of the two different membrane modules during the experiment is shown in Figure 5.

Besides the energy demands the operating expenses also include membrane regeneration (2 regenerations per year = approximately 100 €) and maintenance (disposal of primary sludge twice per year to the WWTP at a distance of no more than 30 km = 100 €).

The investment and operating costs of a conventional domestic WWTP, MBR WWTP, cesspool and sewage tariff over 1, 5, and 10 years are compared in Table 3.

CONCLUSION

The paper refers to the results obtained from an investigation of a domestic MBR WWTP placed in actual conditions and with actual wastewater. The task was to compare and evaluate two commercial membrane modules.

Both of the observed membrane modules offered excellent effluent parameters, because under the actual conditions, it would be impossible for sludge to separate by settling in a clarifier in a conventional WWTP because of massive sludge bulking. Only the installed membrane module guaranteed the perfect effluent quality.

The average value of COD during the monitored season of membrane module "A" was 53.4 mg.L^{-1} and 57.6 mg.L^{-1} of membrane module "B". The average value of the BOD_5 of membrane module "A" was 2.3 mg.L^{-1} and 2.5 mg.L^{-1} of membrane module "B".

Membrane module "A" was furnished with a submersible permeate pump which turned out to be problematic due to its breaking down frequently. When the flux decreased below 10 L m^{-2} h^{-1}, the WWTP started to flood during situations of peak inflows, because the activation tank had an accumulation volume of only 60 L. The installation of another pump between the second settlement chamber and the activation tank was necessary. Later, the first and second settlement chambers were used as the accumulation (buffer) tanks.

The membrane module "B" was furnished with a vacuum pump, which was trouble free and therefore was a very advantageous solution. The membrane module did have a smaller membrane area of 3.5 m^2, which ensured an adequate accumulation volume, and the gravity flow through the WWTP was possible.

Acknowledgements

This work was undertaken as a project of the MBR-TRAIN 8th Framework Programme (MEST-CT-2005-021050). I would also like to thank Envi-pur, s.r.o., for its technical support.

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