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Slow Sand Filtration of Treated Domestic Wastewater as a Pre-treatment to Ultrafiltration: Effects of Operation Conditions on Pilot Scale

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Abstract

The present study investigates the effects of biologically active slow sand filtration (SSF) as a pre-treatment process prior to a pressurized ultrafiltration (UF) on a pilot-scale. The investigations were conducted with secondary effluent of the Berlin sewage treatment plant Ruhleben. A series of filtration experiments under various operating conditions were conducted to investigate the subsequent performance of the UF. Trans-membrane pressure (TMP) development of the UF unit shows that SSF reduces the foulant concentration in treated wastewater and causes much slower TMP increase versus run time compared with no pre-treatment. Experiments under different operating conditions show that applied filtrating flux and backwash interval (BWI) influence the performance of UF process to a large extend. Under certain presented operating condition sustainable operation of UF is achievable. In a further approach fouling critical operating conditions at high permeate fluxes and long BWI were applied. Three kinds of chemicals were added into the backwash permeate to compare the effect of enhanced backwash. The results demonstrate that by using hydrogen peroxides (H_2O_2 20 mg/L) or sodium hypochlorite (active chlorine 8-10 mg/L) in backwash process, the TMP was efficiently controlled during long operation time. Sodium hydroxide (pH 12) was not suitable as backwash reagent because of serious inorganic scaling under the conditions of Berlin secondary effluents.

Keywords: secondary effluent, slow sand filtration, fouling, ultrafiltration, operating condition, enhanced backwash

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1 Introduction

In wastewater reclamation, low pressure membrane filtration has been recognized as a promising treatment option to produce hygienically safe and particle free water. However, membrane fouling seriously limits the application of this technique: without suitable pre-treatment, optimized operating condition or effective cleaning in place (CIP) / enhanced back wash, the treatment costs for low-pressure membrane filtration systems can be unreasonable high (Xie and Gomez et al., 2006).
The influence of operating condition on the performance of low pressure membrane process applied in secondary effluent treatment has been well documented in previous studies (Decarolis and Hong et al., 2001; Teodosiu and Kennedy et al., 1999). The results show that flux and BWI (backwash intervals) play important role in fouling control. With higher flux or longer BWI, TMP increases much faster because of more irreversible fouling arising either from changing of fouling structure or higher concentrations of foulants cumulating on the membranes surface.
To reduce foulants concentration prior to membrane process, different pre-treatment measures can be applied (Downing and Bracco et al., 2002; Shon and Vigneswaran et al., 2004; Thiruvenkatachari and Shim et al., Basu and Huck 2005; Wang and Wang, L. et al., 2007). Next to a suitable pre-treatment, in practice the operation of the low pressure membrane system must be optimized by an additional cleaning strategy. In general it is necessary to dose chemicals into backwash water to remove irreversible fouling and disinfect the membrane module. Relying on the chemical characteristics of fouling oxidants, bases and acids can be used individual or combined (Yamamura and Kimura et al., 2007).
In present work, SSF is applied as pre-treatment process prior to UF pilot plant for potential domestic wastewater reclamation. As fouling potential was largely reduced, slow sand filtrate was delivered directly to a UF pilot plant. The effect of operating conditions on fouling development is tested. Under critical operating conditions, different chemicals were added into back wash permeate and the fouling control effect is then compared.

2 Material and Methods

2.1 Slow sand filtration

A slow sand filter is operated continuously since Sept. 2006 to filtrate tertiary effluent which is secondary effluent from the WWTP Ruhleben Berlin after sieve filtration (pore size 100 µm). The filter is operated in down flow mode using filtration rates 0.2-0.25 m/h with filtration area 2 m^2 to deliver influent to a UF pilot plant. Prior to the sand filter the effluent is aerated. The sand layer in the filter is around 0.8 m in heights, filled with silica sand, particle size 1 to 2 mm (Sand-Schulz GmbH, Germany). The height of supernatant water is 0.55 m. From time to time, the upper 5 cm sand layer was removed manually and new sand was added to reduce the head loss in the filter.

2.2 UF pilot plant and membrane productivity

A UF pilot plant (W.E.T, Germany) with hydrophilized poly ethersulfone (PES) membrane (Dizzer 450, INGE, Germany) was used to perform all the experiments in this study. The membrane module has a filtration area of 4.5m^2 and the molecule weight cut off is 100 K Dalton. It operates in dead-end filtration mode and with inside-out flow configuration. The specific permeability of the membrane at 20°C is about 530 $Lm^2h{\cdot}bar$ (tested with tap water). The membrane has specific properties enabling it for water reclamation: the ability to withstand pH range 1-13 and a high tolerance to free chlorine (200ppm) and hydrogen peroxide (500ppm), the arrangement of seven capillaries in one fiber result in high mechanical strength against fiber breaking during intensive hydraulic backwash (Panglisch and Loi-Bruegger et. al., 2007). The pilot plant can be operated automatically or manually as demanded. During operation the module can be backwashed either with permeate or chemicals injected into permeate to conduct enhanced backwash.

In each experiment, the pilot plant was operated until the TMP reached to 700-800 mbar or to a given operation time. After that, the module was cleaned with different chemicals until the specific water flux (tested with tap water) was recovered to more than 90% of the initial flux and then was applied to next experiment. The time the plant operated between two chemical cleaning evens is defined as run time (hours), the TMP data used in present work is the TMP value after 5 minutes filtration in each filtration cycle with unit mbar.

During each experiment the membrane productivity was evaluated with the decline of specific flux (Kw) with respect to run time. The Kw was determined with the following equation.

$$Kw = \frac{Fw_{20}}{\Delta P} \tag{1}$$

where Kw is the specific flux of the membrane module, ΔP is the trans-membrane pressure, Fw_{20} is the flux normalized to 20 °C and calculated with equation (2) (Roorda, 2004).

$$Fw_{20} = \frac{Fw \cdot 494}{(T + 42.5)^{1.5}} \tag{2}$$

where Fw is the flux and T is the water temperature.

2.3 Water quality Analysis

During the experiments, DOC (Elementar Analysensysteme GmbH, Germany), turbidity (Hach 2100N, HACH), pH (pH 537, WTW, Germany), UV_{254} (Perkin-Elmer GmbH, Germany) and the concentration of biopolymers (the first peak in a size exclusion chromatogram) (Haberkamp et al., 2007) (DOC-LABOR Dr. Huber, Germany) were measured weekly.

3 Results and discussion

3.1 Water quality improvement through SSF and effect on the performance of UF

After installation the slow sand filter was operated for about two months with secondary effluent to stabilize its bacterial community and ensure constant removal rates for organic compounds. Since November 2006 the filtration treatment process can be considered constant in DOC removal and water quality. Table 1 summarizes the average values after stabilization.

Table 1: Water quality of tertiary effluent and slow sand filtrate (n=30)

Water sample	**Turbidity**	**DO**	**pH**	**Biopolymer**	**DOC**	**UV_{254}**	**SUVA**
	NTU	**mg/L**		**mgC/L**	**mg/L**	**cm^{-1}**	**$Lm^{-1}mg^{-1}$**
Tertiary effluent	1.7±1	6.5±2	7.19±0.5	0.4±0.2	11.7±3.5	0.27±0.02	2.3 ±0.1
SSF 0.25 m/h	0.26±0.1	0.2±0.2	7.10±0.1	0.15±0.1	10.5±3	0.26±0.02	2.5±0.1

For turbidity, the removal rate is always around 85%. The concentration of biopolymers which have been identified as major dissolved organic foulants for UF in former studies (Jarusutthirak et al., 2002; Laabs et al., 2006; Sperlich et al., 2007) is removed through SSF around 60% and hold stable around 0.15mgC/L. The pH of slow sand filtrate is lower than that of the secondary effluent because of degradation of DOC and the resulting production of organic acids. Dissolved oxygen (DO) concentration shows that most of the detectable oxygen is consumed during biological filtration process. The DOC and UV_{254} removal through SSF is around 10% and 6% respectively, specific UV absorption (SUVA) shows that the proportion of aromatic structure substances improved slightly and the organic compounds in the water become less bio-available. The removal of either particle or dissolved foulants improved the performance of UF. As shown in Fig.1, the TMP increased much slower after filtrating slow sand filtrate than secondary effluent under the same operating condition.

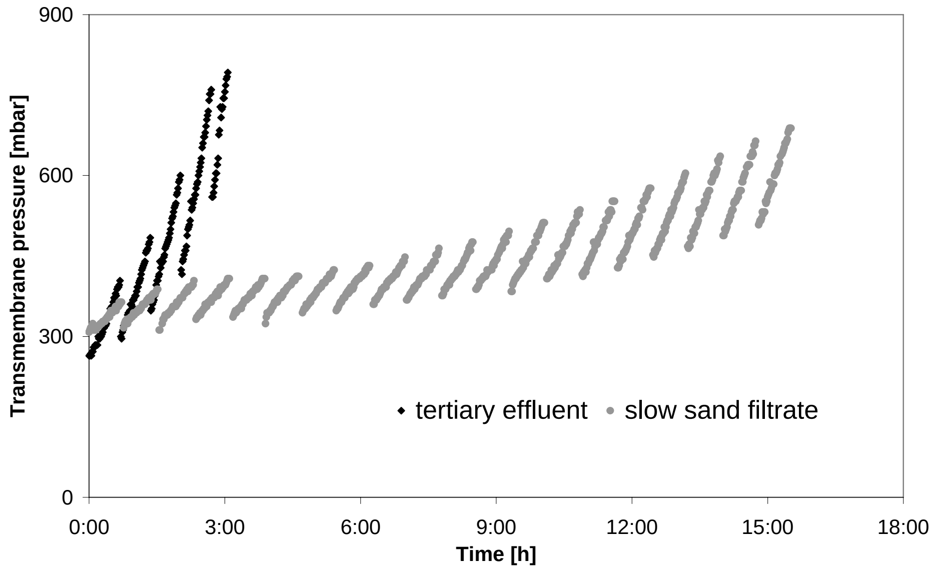

Figure 1: TMP development filtrating tertiary effluent and slow sand filtrate

3.2 Influence of operating conditions on the performance of UF

Although in the slow sand filtrate the concentration of biopolymer compounds (large organic foulants) are lower compared to that in secondary effluent, under higher permeate flux and longer BWI (critical filtration operating condition), e.g. flux 89 lmh ($lm^{-2}h^{-1}$), BWI 40 minutes and BWT (backwash time) 50 seconds, the TMP increased to 400 mbar within 16 hours (Fig.1). Lower flux or shorter BWI were then tested to operate the plant aiming at controlling TMP improvement with permeate backwash.

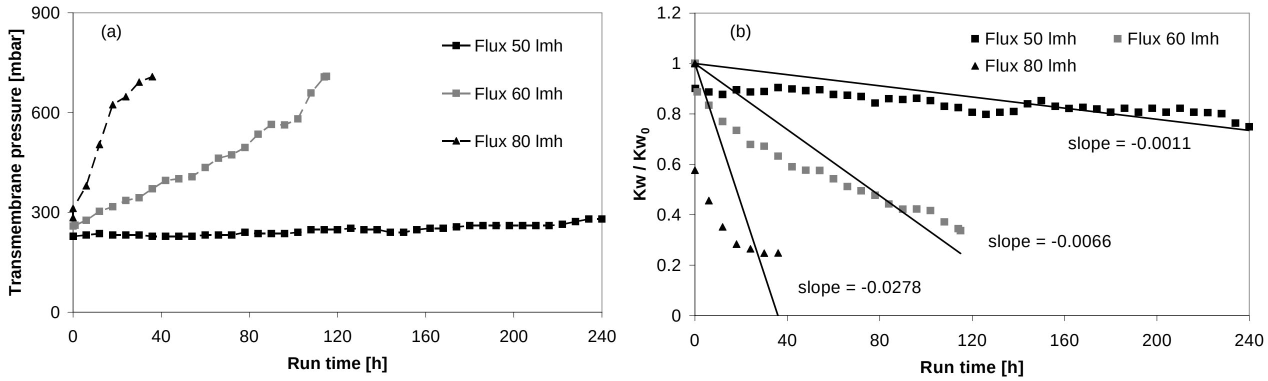

Figure 2: (a) TMP development vs. run time at different fluxes (b) Kw/Kw_0 vs. run time at different fluxes. Other operating parameters were identical: BWI 10 minutes and BWT 20 seconds

Influence of flux

The effect of operating flux was investigated by conducting experiments at 50, 60 and 80 lmh. Each experiment was performed with BWI 10 minutes and BWT 20 seconds, the specific permeability of the membrane in each experiment was around 260 $Lm^2h\cdot bar$ (tested with tap water, at 20°C), lower than a new one because it was used before. Fig.2 (a) shows the result of TMP development with respect to run time at different fluxes. At 80 lmh TMP increased from 250 to 800 mbar within 40 hours, at 60 lmh the run time was extended to more than 120 hours. When the flux was reduced to 50 lmh the TMP increased in 240 hours only 50 mbar. The comparison indicates that under each flux the fouling increased over run time, but at lower flux the formed fouling can be effectively removed by backwash and the TMP was effectively controlled within the given operating time. The normalized productivity development is shown in Fig.2 (b) and reflects the same trend. The decrease of the Kw/Kw_0 rate with time at each operating flux indicates that the membrane productivity was reduced because of the increase of fouling resistance. The lower the operating flux, the gentler the magnitude of the productivity decline demonstrates that the formed fouling at lower flux shows higher reversibility than that formed at higher fluxes, the initial flux can be efficiently recovered using permeate backwash.

Influence of BWI

The influence of BWI on TMP development was tested at flux 50 lmh at BWI 10, 20 and 40 minutes, the specific permeability was also around 260 $Lm^2h\cdot bar$ (tested with tap water, at 20°C). As shown in Fig.3 (a), TMP increased more quickly when BWI is extended. Comparing at BWI 10 minutes the TMP increased 50 mbar in 240 hours, TMP raised about 600 mbar in 210 hours and 40 hours at BWI 20 and 40 minutes respectively. The slopes of Kw/Kw0 in Fig.3 (b) shows also that extended operating time leads to sharper productivity reduction. The results indicate that with the extension of operating time, more foulants can be delivered to the membrane and cumulate on it, this enhances the irreversibility of the formed fouling layer and reduces the productivity.

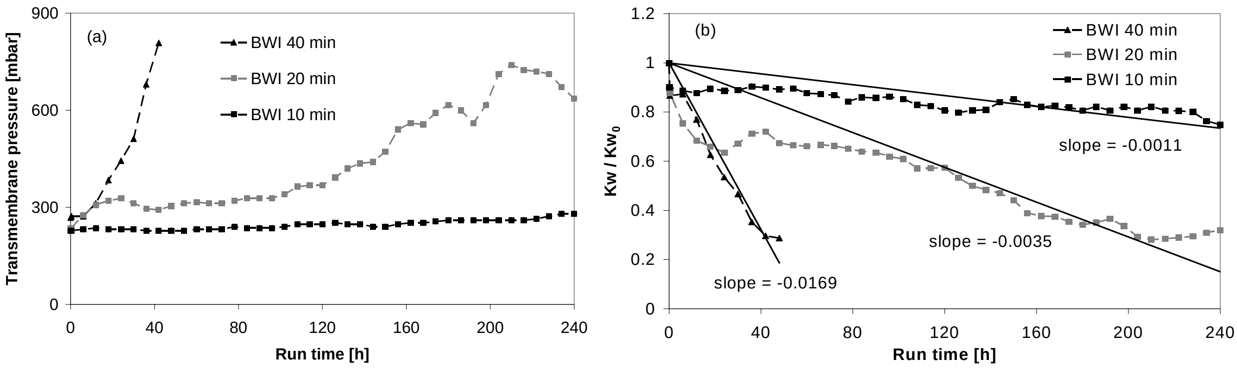

Figure 3: (a) TMP development vs. run time at different BWI (b) Kw/Kw_0 vs. run time at different BWT. Other operating parameters were identical: flux 50 lmh, BWT 20 seconds

Comparison of the significance of flux and BWI on fouling development

Since flux and BWI are considered as dominant operating factors affecting fouling development, significance of the two factors affecting productivity is compared using Kw/Kw_0 plotted against total permeate volume. Sharper slopes were expected when more foulants was delivered to the membrane assuming stable feed water quality and similar backwash strength. However as presented in Fig.4, although between two back washes the delivered foulants to membrane under flux 50 lmh, BWI 20 minutes should be more than under flux 60 or 80 lmh, BWI 10 minutes, the slope of normalized productivity under former condition is gentler than that under latter conditions. Similar result was found comparing the slope of at 50 lmh, BWI 40 minutes and at 80 lmh, BWI 10 minutes. An explanation of this phenomenon can be attributed to the structural characteristic of irreversible fouling under different operating conditions. At higher filtration rates, the foulants delivered rate to the membranes surface is higher than that at lower fluxes, foulants can then cumulate on membrane surface with higher concentration and aggregate to more compact fouling layer under increased pressure. With the same backwash strength, the compact fouling layer is more irreversible than that formed at lower fluxes and leads to higher hydraulic resistance during filtration.

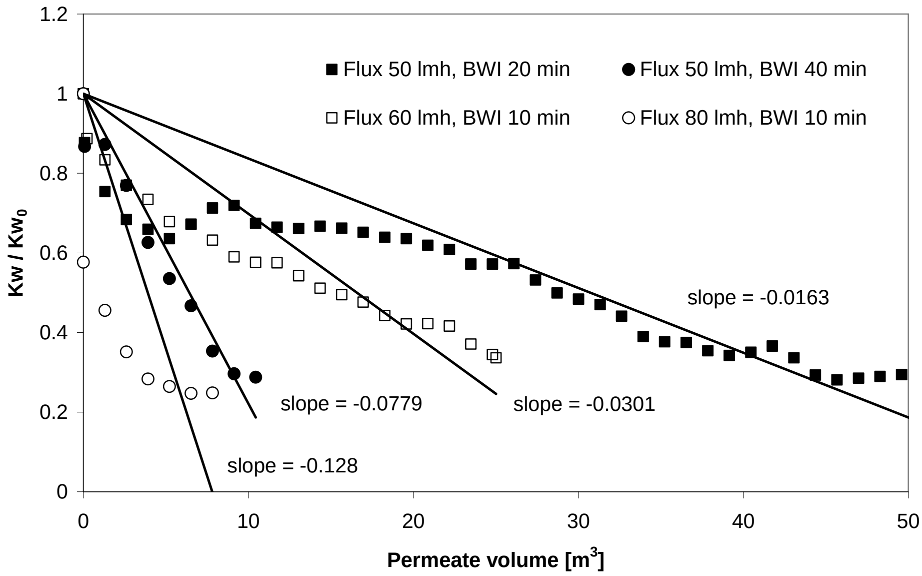

Figure 4: Significance of flux and BWI on membrane productivity reduction

3.3 Effect of enhanced back wash with different reagents on the performance of UF

As membrane filtration is often operated under critical operating conditions aiming to decrease investment and improve productivity, chemical enhanced backwash is necessary to stabilize the performance. Depending on chemical character of fouling and feed water quality, different enhanced backwash reagents can be used. In present experiment the UF pilot plant filtrated slow sand filtrate at flux 89 lmh, a filtration cycle consisted of filtration 40 minutes, chemical backwash 50 seconds and subsequent disinfection 5 minutes in still. During chemical enhanced backwash and disinfection process sodium hydroxide, hydrogen peroxide and sodium hydrochloride were tested individually as enhanced backwash reagents. The dosage was controlled in each backwash process either keeping the backwash permeate at pH 12 or holding the concentration of H_2O_2 around 20 mg/L or active chlorine about 8-10 mg/L in backwash permeate. Each experiment was conducted till the TMP increased to 700 mbar or to a given run time. New membrane module was used in the experiment using H_2O_2 or NaClO and the average TMP was around 200 mbar after first 5 minutes filtration; after these experiments the module was chemically cleaned and applied in the experiment using permeate backwash or NaOH enhanced backwash, the average TMP after first 5 minutes filtration was around 300 mbar, the specific permeability was around 70% of the new ones because of serious chemical irreversible fouling.

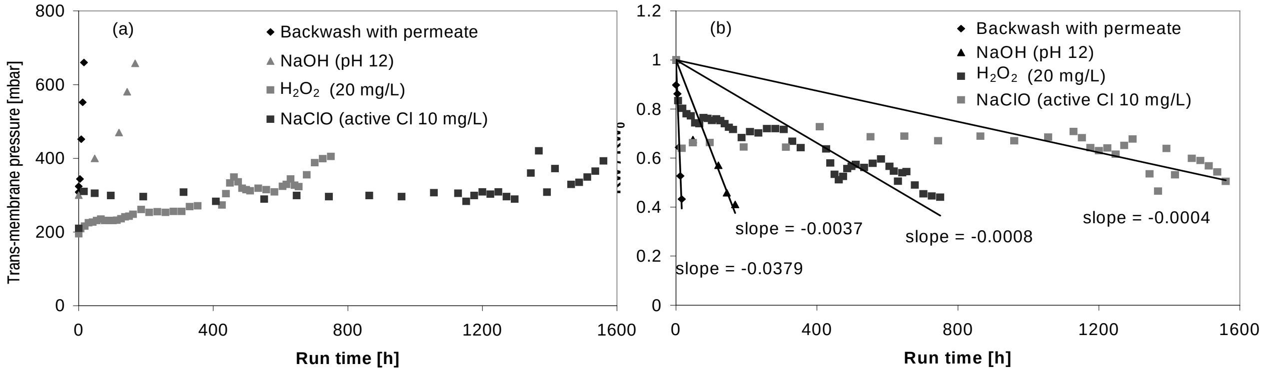

Figure 5: (a) TMP development vs. run time using permeate backwash and enhanced backwash reagents (b) Kw/Kw_0 vs. run time using permeate backwash and enhanced backwash reagents

TMP control results are shown in Fig.5 (a). The dosage of backwash reagent extended the run time of the pilot plant in different manners. Within the same TMP increase, the usage of NaOH extended the run time from 16 hours to around 150 hours in comparison with applying only permeate backwash. The dosage of NaOH shows that hydraulic irreversible fouling can be more removed with basic reagent. But after the experiment the module was out of operation because of serious fouling and scaling in the in-/outside of the membrane. The inorganic precipitates scaled the outside of the membrane surface so seriously that the whole system was stopped due to high pressure losses in the modules. Best TMP control was achieved by the application of NaClO, the TMP raised from 200 to 450 mbar after 1600 hours operation. Dosing H_2O_2 was identified also as an effective fouling control method, within TMP increase from 200 to 500 mbar, the run time was about 800 hours. Normalized permeate productivity versus time (Fig.5 (b)) shows that the usage of NaClO leads to the flattest productivity reduction comparing with other enhanced backwash reagents. Although using H_2O_2 shows sharper productivity decrease, it is presented as a reliable chlorine-free fouling control reagent comparing with the usage of chlorine which causes disinfection by-product (Hua and Reckhow, 2007) problems in water treatment.

4 Conclusions

The following conclusions can be derived from the present results.

- Slow sand filtration can remove turbidity and dissolved organic foulants in treated domestic wastewater and improve the performance of a subsequent ultrafiltration process substantially.
- Operating conditions are influencing the overall performance of UF to a large extend. Using slow sand filtrate as feed water irreversible fouling can be effectively controlled with permeate backwash under certain operating conditions. Higher flux and longer BWI cause more irreversible fouling and lead to sharper TMP increase and membrane productivity reduction. Comparing with BWI, applied flux has more significant influence on TMP increase under similar delivered foulants amount to membrane.
- Under critical operating conditions chemical enhanced backwash is necessary to control irreversible fouling in UF process. Suitable enhanced backwash reagents can extend the run time greatly. Hydrogen peroxide is proved to be an effective and suitable enhanced backwash

reagent in present work. Further research on the dosage and corresponding operating optimization is necessary and in progress.

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