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APPLICATION OF MEMBRANE TECHNIQUES FOR MUNICIPAL WASTEWATER TREATMENT AND REUSE

Abstract. State-of-the-art chemical, physical and biological water treatment techniques do not always properly remove some biogenic elements (nitrates, ammonia and phosphates) to reuse or reclaim wastewater. Modern membrane techniques provide high efficiency in removal of suspended and colloidal matter, bacteria and viruses, organic compounds as well as dissolved ions. For wastewater reuse and reclamation application of reverse osmosis provides reduction of BOD, phosphates and ammonia without application of biological treatment.

To successfully apply reverse osmosis to treat wastewater, adequate pretreatment is required. Often pretreatment costs even exceed reverse osmosis facilities costs. Long research in fouling and scaling mechanisms revealed that fouling rates are dependent not only on hydrodynamic factors, but on membrane properties and channel configuration as well. Therefore, development of a new type of membrane channel with improved hydraulic and fouling characteristics enabled us to present efficient water treatment techniques for wastewater treatment and reclamation. Schematic flow diagrams are presented for different wastewater treatment cases, such as car washing and laundry effluent as well as domestic wastewater treatment and reuse.

Keywords: membrane fouling; nanofiltration; open-channel module; reclamation; recovery; reverse osmosis; sludge dewatering; spiral wound module; domestic waste water; urban surface water.

INTRODUCTION

Protection of water resources from pollution is considered as important ecological problem that becomes more and more complicated with urban growth and development of industrial and agricultural water consumption. The use of different chemicals for industrial, agricultural and domestic purposes tend to constant degradation of water quality, accumulation of detergents, oil products as well as biological nutrients. Rational use of water resources to reduce their contamination should be introduced into practice as well as measures should be undertaken to transform sewage into a new source of raw water that could be used by communities for agricultural and technical purposes. To improve quality of wastewater new techniques that should be developed as conventional water treatment methods (coagulation, filtration, sorption, bioreactor etc.) do little to efficiently remove dissolved contaminants and maintain operational costs within reasonable limits.

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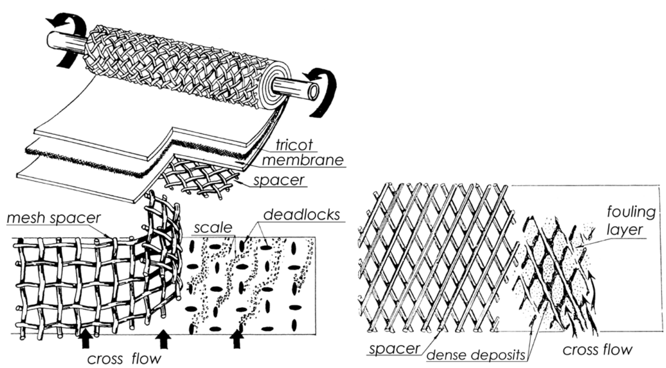
Modern membrane techniques (UF, NF, RO) have demonstrated high efficiency in removal of suspended matter, bacterial, as well as organic and mineral ingredients. Meanwhile, certain problems of membrane fouling arise, resulting in shortening of membrane life and product flow decrease. To prevent formation of fouling layers on membrane surface and cake resistance increase, a number of measures are applied, such as backflushes, chemical cleanings, pretreatment. Despite these measures applied, fouling remains a major factor that determines operational costs.

Successful RO and NF operation depends on pretreatment quality that could be obtained through introduction either of conventional sedimentation/coagulation and filtration process [1] or continuous microfiltration (CMF) techniques [2]. Adequate pretreatment involves the use of different types of equipment that is difficult to implement due to unstable operation and high capital/operational costs. Long research devoted to investigation of membrane fouling mechanisms has revealed that fouling process depend mainly on the membrane material properties and channel configuration as well [3, 4]. The existing spiral wound module configuration used for RO, NF and UF applications is very susceptible to fouling that makes it useless to treat wastewater containing high organics, bacteria and suspended matter. Main disadvantages of spiral wound modules are attributed to presence of separation spacer mesh in the channel that traps fouling particles and increase delta pressure (Fig. 1). Elimination of the mesh provides an open-channel configuration thus enabling us to increase flow velocities and to assure foulant particles shear effect. Introduction of new RO open channel modules offers certain perspectives for direct treatment of municipal effluents without a fear to suffer fouling problems during long period of stable operation.

Main considerations of a new membrane channel concept as well as fouling problem solutions are presented below. Examples of new process applications to treat well/surface water and reclaim domestic, laundry and car-wash effluents demonstrate efficient performance of RO and NF.



a) b)

Fig. 1. Fouling / scaling control: formation of fouling layers: a) formation of scale crystals; b) membrane surface with fouling layer

MODULE DESIGN CONSIDERATIONS

The idea of possible membrane module modification and its further safe operation without pretreatment was already proposed and discussed in early 1990-s [3]. The results of different fouling mechanism investigations drew to the conclusion that membrane fouling is dependent not only on hydraulic factors but on membrane channel configuration as well. This statement could be confirmed by latest attempts to introduce UF/RO processes into direct treatment of industrial effluents and high turbidity surface water as well. The process efficiency and reliability is mainly attributed to hydraulic flow conditions in tubular and capillary modules that provide high cross-flow velocities and shear force for suspended particles not to foul membranes.

Spiral wound configuration is recognized as optimum as it provides highest flat sheet membrane filtration surface with minimum of module volume at significantly low costs. The presence of a spacer mesh provides high flow resistance that often dramatically increase during membrane operation and results in product flow reduction. Elimination of the mesh and creating and creating an open channel configuration could provide excellent flow conditions to escape fouling.

We have worked-out another approach to eliminate mesh from spiral wound membrane channel and reduce fouling potential. To provide separation of opposite membrane surfaces in membrane envelope, we use thin “ledges” glued to membrane surface. The “ledges” are parallel and are glued on the opposite membrane surfaces in the opposite directions. When spiral wound channel is formed during envelopes wrapping, “ledges” provide membrane separation and flow turbulating effect. Elimination of mesh eliminates reasons for crystal formation that provides scale control tools. Also application of described “ledges” could decrease turbulation effect compared to conventionally used spacers.

Higher cross-flow velocities provide lower foulant accumulation rates and facilitate flushing thus making cross-flow UF process more safe than dead-end filtration [3]. The results of research conducted by the authors suggest different solutions to provide an open-channel [4, 5]. Several concepts are already patented and further research is going on.

To confirm a new concept for direct use of RO and NF to treat high turbidity effluents, a research was conducted to investigate mechanisms of different foulants formation and its influence on membrane behavior as well as ways to control it.

To provide theoretical and experimental basis for novel process optimization, experimental research program was conducted that provided comparison of conventional type and open-channel module behavior and outlined operational guidelines to control fouling.

EXPERIMENTAL PROCEDURE AND RESULTS

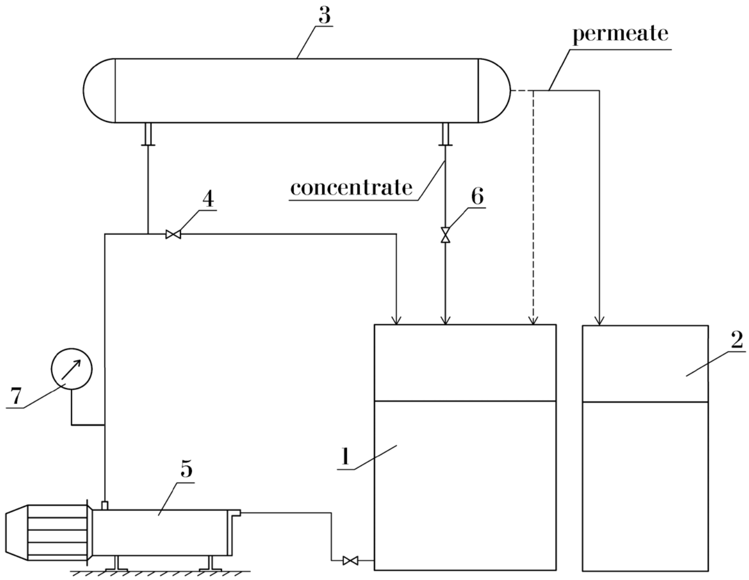


Fig. 2. Schematic diagram for RO/NF test unit: 1 – feedwater tank; 2 – product tank; 3 – membrane module; 4 – by-pass valve; 5 – high pressure pump; 6 – concentrate line valve; 7 – pressure gauge

Previously we have reported results of particulate, organic and biological fouling mechanisms investigation [4 – 6]. The influence of flow, pressure, recovery as well as membrane material and module configuration on membrane fouling was investigated. The test procedure was conducted in circulation and circulation modes whereby reject flow (concentrate) is returned to the feed tank and product is either returned to the feed tank or collected in separate tank (Fig. 2). Determination of concentration values in brine tank and in product tank enable us to calculate the amount of foulant accumulated on membrane surface throughout experiment duration and to evaluate fouling rates. Delta pressure increase is also determined and presented as a function of foulant amount (Fig. 3). Membrane elements of 1812 size standard were manufactured and tested. The experimentally obtained relationships are presented on Fig. 4. Results of particulate and organic fouling rates evaluation demonstrate their dependence on the cross-flow velocity values.

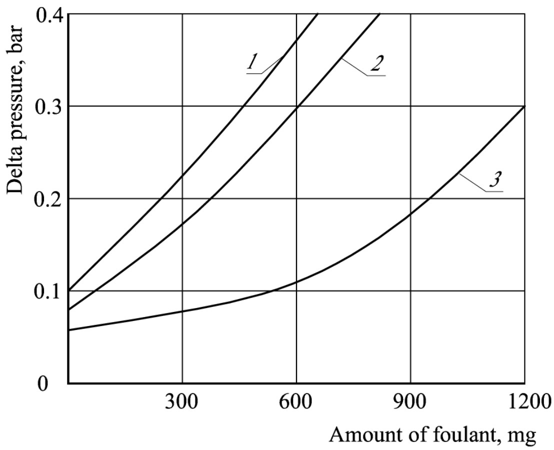


Fig. 3. Dependencies of delta pressure increase versus cross-flow and amount of accumulated foulant amount. Cross-flow: 1 – 360 l/h; 2 – 100 l/h; 3 – 25 l/h

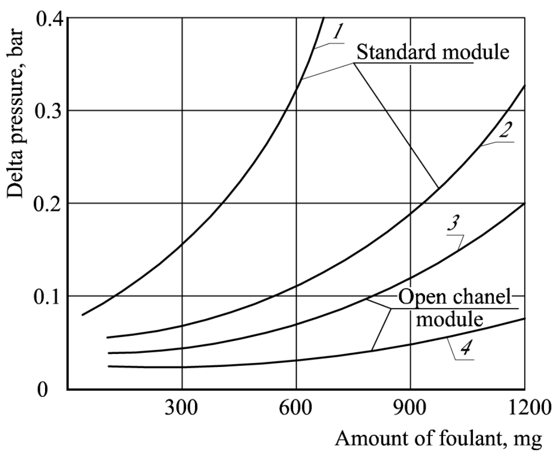


Fig. 4. Determination of delta pressure increase during foulant accumulation. Cross-flow: 1, 3 – 100 l/h; 2, 4 – 50 l/h

Application of hydraulic flushes destroys fouling layers and withdraw accumulated foulants from membrane surface due to cross-flow velocity increase and water-hammer process initiation. Flushing modes (intervals between flushes and their duration) are very important to maintain fouling control and product flow values on the desired level. Suspended solids concentration, colour, TDS, recovery, pressure, cross-flow velocities, membrane material and module design are factors that influence operational and flushing mode selection. During fouling layer formation coagulation of particles, organic compounds and bacterial cells occur, and the coagulated flocs that are being withdrawn from membrane surface throughout flush cycle possess good sedimentation characteristics.

Biofouling is considered as a very serious problem when domestic wastewater is treated by membranes. These waters contain very high bacterial count and high TDS content, as well as high concentrations of biological nutrients that cause rapid colonization and bacterial growth. As it was reported, the biofilm formation process consists mainly of two phases, which are adhesion and growth [6]. Bacteria adhesion rates were evaluated through the course of circulation experiments. Bacteria concentrations were determined by the total bacterial count, assuming that 109 bacteria provide 1 mg of dry weight. The results of adhesion rates evaluation are presented on figure 5. To accelerate growth of bacteria on the membrane surface, enriched medium (nutrient substrate) circulation experiments were performed. During circulation samples of substrate were collected and TOC measurements were performed. TOC reduction versus time provides an indirect estimate of biofilm growth rate.

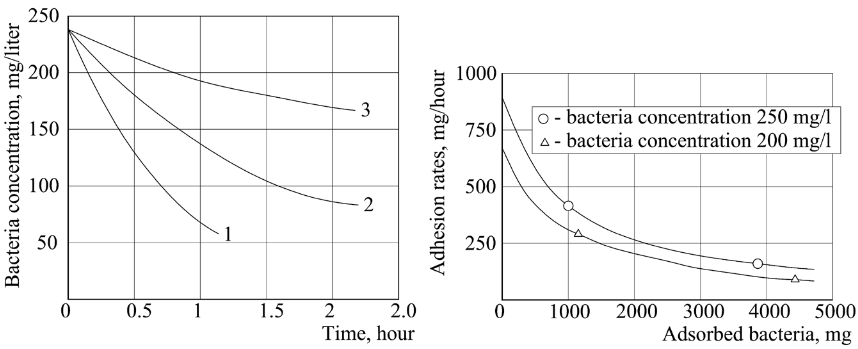


Fig. 5. Experimental determination of adhesion rates: a) biomass amount versus time: 1 – at the beginning; 2 – after accumulation at 1000 mg; 3 – after accumulation at 4000 mg; b) adhesion rate versus biomass amount

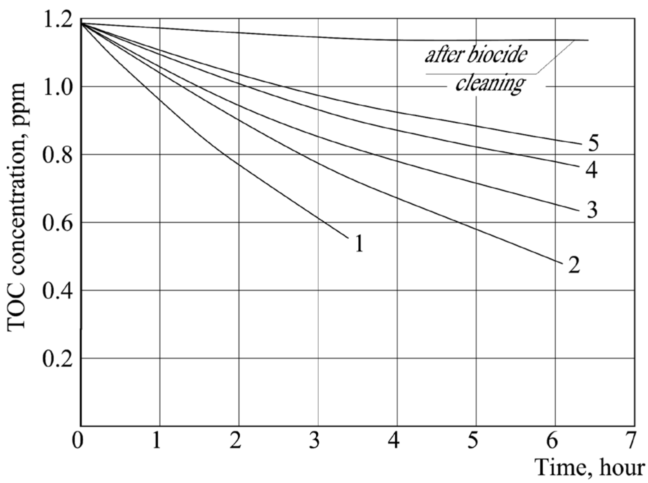


Fig. 6. TOC reduction with time during biomass growth: 1-5 – experimental number

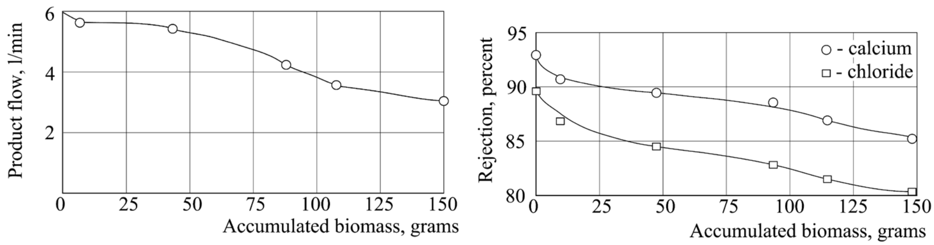


Fig. 7. Deterioration of membrane performance with biomass accumulation: a) product flow decline versus biomass amount; b) rejection decline versus biomass amount

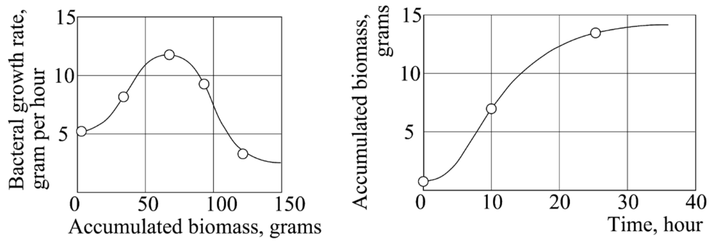


Fig. 8. Prognosis of biomass growth: a) bacterial growth rate versus biomass; b) biomass growth with time (predicted)

The amount of biofilm accumulated with time in membrane module could be thus predicted. The amount of accumulated bacterial material was calculated using TOC consumption data and biofilm growth prognosis was performed, as shown on figure 6. The dependencies of membrane flux and rejection on the amount of biomass accumulated in RO module during biogrowth experiments are shown on figure 7. Figure 8 shows the results of calculation of biomass at different stages of bacterial growth.

The developed techniques could be successfully applied when treating municipal sewage, i.e. domestic effluents, laundries effluents, car-washing wastewater and other cases. For all cases the use of RO and NF membranes provide high quality water that could be efficiently reused or supplemented to natural water sources.

DOMESTIC WASTEWATER TREATMENT

Membranes have become attractive to replace conventional wastewater treatment techniques due to low costs, high efficiencies and low reagent consumption. Depending on water composition and class of contaminants required to be removed, ultra filtration, nanofiltration or reverse osmosis techniques could be improved into waste treatment practice to improve quality and to reuse treated effluents for agricultural, industrial and domestic applications.

At early stages of membrane use, their role was to “support” conventional biological treatment process to reduce suspended matter, BOD etc. Meanwhile, high rejection qualities of membranes enable us to treat sewage directly without biological treatment process to obtain high quality water. Such approach to use membranes substantially reduces costs and simplifies treatment techniques.

Membrane bioreactor (MBR) is becoming popular and efficient tool to reduce volume of water treatment plant and provide better quality of treated water with lower BOD, complete nitrification and partial denitrification [7]. Today submerged membranes (flat sheet or capillary) are mainly used at MBR applications and provide stable operation due to application of backwashes and chemical cleanings. Initially MBR process used cross flow membrane operational mode where high velocities reduced concentration polarization and fouling [8, 9]. High cross flow velocities require higher energy consumption than dead-end filtration mode used in submerged MBR process. Biological treatment process does not provide required removal level for major contaminants to reclaim municipal effluents, thus RO desalination techniques could be successfully applied to post-treat biologically treated wastewater. The concept of converting wastewater into a new raw water supply for further treatment to potable standards is called "indirect potable reuse" that has been practiced in US since 1970-s [10].

As membranes demonstrate high rejection characteristics for different contaminants, the idea to use membranes [1, 11] and other techniques [2] for direct treatment of domestic and urban effluents promise to significantly reduce costs and simplify treatment. Table 1 demonstrates RO rejection characteristics for main municipal wastewater ingredients.

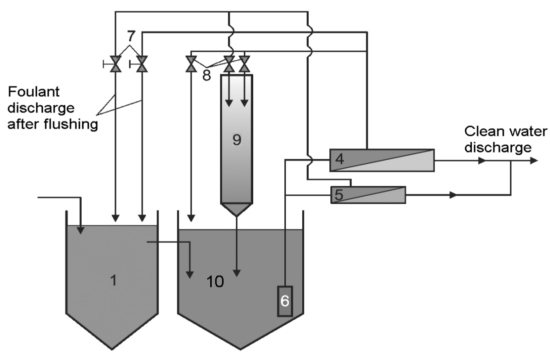
Table 1. Municipal wastewater treatment with different RO pretreatment stages

Parameters	Direct RO treatment microfiltration pretreatment			Direct RO treatment sand filter pretreatment			RO treatment after MBR		
	waste-water	Effluent MF pre-treatment	Direct RO	Effluent	After sand filter	After RO	Feed	MBR	RO
pH	–	5.4	5	7.06	6.99	5.92	7.4	7.27	6.01
Total dissolved solids, mg/l	2030	2030	99	994	968	12.78	1100	999	51
Turbidity, NTU	15	< 1	0	23.54	7.33	0.14	–	0.18	0.07
Ammonia (NH_4), mg/l	–	38	3,6	18.78	18.19	1.55	27	0.11	–
Nitrates (NO_3), mg/l	40	39	7,1	3.47	2.42	1.08	–	–	–
Phosphates (PO_4), mg/l	56	54	3,8	7.97	6.08	0.67	24	1.46	–
Total coliforms (colonies/100 ml)	$3.5 \cdot 10^6$	absence	absence	700	200	–	–	–	–
BOD5, mg/l	32	3	< 0.5	9.3	3,2	1.2	268	1.05	–
COD, mg/l	118	74	15	42.73	26.07	13.47	530	14.5	–
TOC, mg/l	30	21	1.9	–	–	–	–	6.18	<0.5

Development of advanced techniques that combines bioreactor and RO process could provide high quality effluent water after direct treatment and significantly reduce biological treatment costs (treating only RO concentrate) – Fig. 9. In the first case (Fig. 9a) membrane treatment is implemented in circulation mode, whereby concentrate solution is circulated through biofilter. After concentrate BOD has reached required level, it is treated by UF membranes to remove suspended matter. Then two streams (RO and UF products) are mixed, the required quality of treated water is reached, also material salt balance is maintained between TDS of wastewater at the inlet and discharged treated water. The suspended matter that foul membrane surface is removed from membrane modules during membrane "flushings" and directed to sludge sedimentation tank.

In the second case, when bioreactor is used (Fig. 9b), application of RO or nanofiltration membranes corresponds to the principle of MBR. Ultrafiltration membranes are also used, but their role is to withdraw excessive TDS from the circulating RO concentrate flow. High product water quality is reached due to application of RO or nanofiltration membranes that remove nitrates, ammonia, phosphates and organic compounds that form BOD values.

a)



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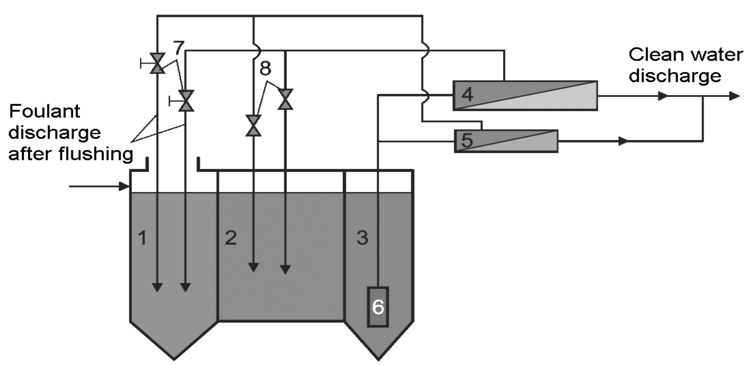

Fig. 9. Schematic diagram of waste water treatment system combined conventional biological treatment (a – biofilter, b – bioreactor) and membranes: 1 – inlet chamber (former first stage sedimentation tank); 2 – bioreactor; 3 – sedimentation section (former second stage sedimentation tank); 4 – NF module; 5 – UF module; 6 – submerged pump; 7 – solenoid valve for water flushing; 8 – control valve; 9 – biofilter; 10 – clean water tank

In a number of cases (private housing, small enterprise) it looks very efficient to decrease tap water consumption and domestic wastewater discharge in municipal sewer.

Membrane units could be used to treat wastewater and provide high product water quality to use it for technical and agricultural purposes. Figure 10 shows schematic flow diagram of RO unit for wastewater reuse. Wastewater is taken directly from the sewer, then feedwater passes through miller pump (that mills large size impurities, such as paper etc.) and then is forwarded to the screen that is automatically flushed to remove foulants and direct them back into a drain. Wastewater is then treated by RO membranes. The foulants that are accumulated on membrane surface are periodically flushed from membrane surface into a drain. The membrane unit is operated in circulation mode that ensures high concentrate flow velocities that provide a "shear force" for suspended particles to prevent their sedimentation and fouling of membrane surface.

Fig. 11 show 600 liter per hour membrane unit operated at "Electric and mechanic plant" (Lermontov, Russia) to decrease and reuse domestic wastewater (with water intake directly from the sewer standpipe).

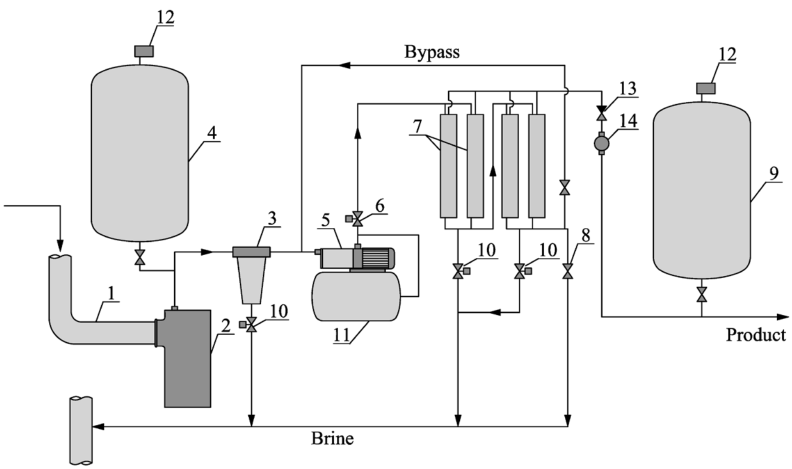

Fig. 10. Schematic flow diagram of RO unit to treat and reuse domestic wastewater taken directly from the sewer: 1 – sewer; 2 – waste miller pump; 3 – flushable screen; 4 – feedwater pressure tank; 5 – centrifugal pump; 6 – solenoid valve at the inlet of the unit; 7 – membrane module; 8 – pressure regulation valve; 9 – product water pressure tank; 10 – flushing solenoid valves; 11 – flushing water pressure tank; 12 – pressure switch; 13 – check-valve; 14 – water counter

Fig. 11. A 600 liter per hour unit operated at "Electrical and mechanical plant" (Lermontov, Russia) to treat and reuse domestic wastewater with water intake directly from the sewer

APPLICATIONS OF RO TO RECLAIM WASTEWATER

Contamination of water sources by oil products and detergents is considered as a serious environmental problem. Car-washing centers and gas station grounds are mainly responsible for pollution. Conventional treatment facilities (using coagulation-sedimentation-filtration techniques) remove contaminants to a level that meets required standards to add it to domestic sewer. Membrane application (RO and NF) provides efficient removal of organic and inorganic compounds that ensures water quality sufficient to reuse it for different technical purposes. Figure 12 shows a schematic flow diagram of car-wash wastewater treatment and reuse. Concentrate volume is decreased by 50-100 timed and is being withdrawn from the unit together with the sludge. Similar techniques are applied to remove oil and detergents from rainwater and laundry effluents. Membrane treatment efficiencies are presented in Table 2.

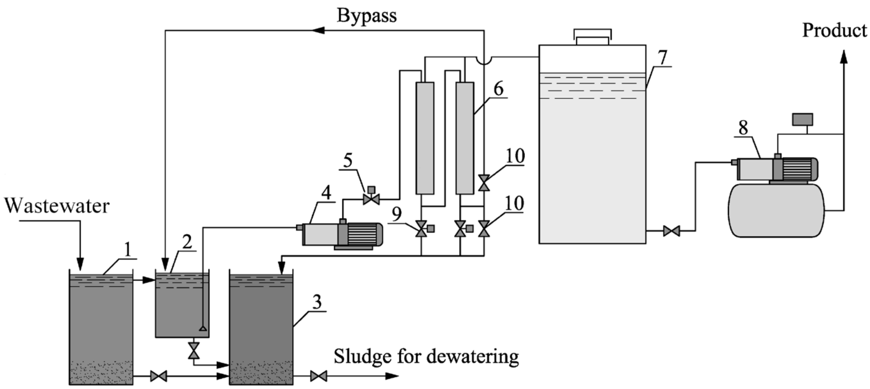

Fig. 12. Schematic flow diagram of membrane unit for car-wash wastewater treatment and reuse: 1 – wastewater collect sedimentation tank; 2 – circulation tank; 3 – sludge tank; 4 – centrifugal pump; 5 – solenoid valve; 6 – membrane modules; 7 – product water collect tank; 8 – pump station; 9 – flushing solenoid valves; 10 – pressure regulation valves

Table 2. Results of treatment of laundry and car wash effluents using NF and RO membranes

Quality characteristics	Car-wash influent	Effluent RO	Laundry influent	Effluent NF
pH	6.3	–	7.25	6.71
Colour, degree	11.9	–	–	–
Turbidity, mg/l	37.8	–	–	–
TDS, mg/l	511	35	710	76
Iron, mg/l	4.3	–	–	–
Phosphate, mg/l	0.54	–	19.3	0.09
Ammonia, mg/l	0.6	–	16.8	1.69
Nitrate, mg/l	< 0.5	–	–	–
Oil products, mg/l	9.4	0.15	–	–
Detergents, mg/l	–	–	16.9	0.96
Permanganate oxidability, mg/l	126	13	–	–
COD, mg/l	–	–	284	31

CONCLUSIONS

Long research devoted to membrane fouling has revealed that fouling mechanisms depend not only on hydrodynamic conditions in membrane channel, but on membrane material sorption characteristics and channel configuration as well. The existing spiral wound modules used in RO, NF and UF facilities are very susceptible to fouling that makes them useless for water treatment containing high organics, bacteria and suspended matter.

Main disadvantages of spiral wound modules are attributed to presence of spacer mesh in the channel that trap fouling particles and increase delta-pressure of the module.

Introduction of new open-channel modules suggests a new approach to treat wastewater with high fouling potential without a fear to suffer fouling problems throughout a long period of stable operation.

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ZASTOSOWANIE TECHNIK MEMBRANOWYCH DO OCZYSZCZANIA ŚCIEKÓW I ICH PONOWNEGO WYKORZYSTANIA

Streszczenie. Dostępne techniki chemicznego, fizycznego i biologicznego oczyszczania nie zawsze są w stanie efektywnie usuwać związki biogenne (azotany, azot amonowy, fosforany) w celu ponownego użycia oczyszczonych ścieków. Nowoczesne techniki membranowe zapewniają wysoką efektywność usuwania zawiesiny rozpuszczonej i koloidalnej, bakterii, wirusów, związków organicznych i rozpuszczonych jonów. Zastosowanie techniki membranowej w celu odzysku wody ze ścieków nie wymaga stosowania biologicznego oczyszczania ścieków. Efektywne zastosowanie procesów membranowych wymaga wstępnego oczyszczania ścieków, którego koszty mogą przewyższać te związane z eksploatacją membran.

Słowa kluczowe: ścieki bytowe, osad ściekowy, nanofiltracja, odwrócona osmoza, odzysk, regeneracja.