IOP Conference Series: Earth and Environmental Science

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To cite this article: D Barlokova *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **444** 012002

IOP Conf. Series: Earth and Environmental Science **444** (2020) 012002 doi:10.1088/1755-1315/444/1/012002

Drinking water treatment with membrane ultrafiltration

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Abstract. Ultrafiltration was investigated within the pilot-plant tests at the Rozgrund water treatment plant during the treatment of surface water originating from the Rozgrund reservoir. Fully automated ultrafiltration equipment with the membrane module UA-640 (Microdyn-Nadir) was used. On the base of filtration cycles, the effectiveness of membraned technology was evaluated. By the application of membrane technology used, the required quality of treated water has been achieved.

1. Introduction

The Rozgrund water treatment plant (WTP) was put into operation in 1997 for supplying part of Banská Štiavnica with water. Water reservoir Rozgrund, built in 1743-1744, is the source of water for the water treatment plant; it has been in operation since 1789. The dam (Rozgrund water reservoir) project was developed by Samuel Mikovíni in 1741. The dam has a crescent-shaped dam curved towards the valley immediately above the village. The Rozgrund reservoir held the world record for steepness of the dam for 111 years. It has been used as a source of drinking water since the early 20th century due to the purity of its water. Figure 1 shows the Rozgrund reservoir and the location of the WTP Rozgrund.

Figure 1. A view of the Rozgrund water reservoir and Rozgrund water treatment plant WTP (above the reservoir).

The Rozgrund water treatment plant serves for treatment and repumping of the treated water into the Červená Studňa water reservoir (volume is 650 m^3). The designed capacity of the water treatment plant is 14 L/s.

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The proposed modernisation of the water treatment plant is required to perform pilot experiments, to test various technologies, filtration materials, etc. and to adapt the technology to the water source quality. Ultrafiltration (UF) is a membrane separation process by which the particles of mechanical nature are removed from the water. Thanks to the pore diameter that are the order of tenths nm and the material, constructional and chemical properties of UF membranes, this technology represents the final solution for a secured protection against the turbidity that is caused by content of non-soluble and colloid particles of organic and inorganic origin, bacteria and the majority of viruses [1, 2].

Treatment of water from surface water sources that are polluted mechanically or biologically, pretreatment before the next technological step of water treatment are among the typical applications where the UF is used in. Effectiveness of ultrafiltration is increased by conventional methods such as coagulation, sedimentation and flotation [3].

Ultrafiltration represents a separation process that is powered by the pressure while the pressure impuls is caused by formation of vacuum or by the act of higher pressure from the outer side. The flow throughout the membrane ranges between 40-200 $L/m^2.h$. Asymmetric membranes are used in ultrafiltration and the separation process is also functional on the principle of sieve mechanism. Pore size of UF-membrane ranges from 0.01 to 0.1 µm and the difference in pressure is from 1-10 bar. Most frequently mentioned is the value for molecular weight cut off, MWCO, that ranges between 5 – 5000 kDa and indicates the lowest molecular weight of testing polymer that is 90% retained on the membrane. For a proper design it is essential to select a membrane with a lower MWCO than is the molecular weight of substances to be effectively removed. Shape of the molecule has a great impact on separation, as the linear molecules do pass the membrane through but the spheroidal molecules of the same size can be caught on it [4, 5, 6].

UF-modules are available in various constructional versions, e.g. of boards, framed, spiral winding and tubular. Each version is suitable to be used in different processes. Spiral winding modules are used for clean water, framed modules for high concentrated solutions and tubular modules are used in the treatment of drinking water [3, 7].

Membranes of an ultrafilter consist of a bunch of hollow fibres (Figure 2) where the functional surface represents an approximately 0,2 µm rough surface film of fiber hollows. Total filtration surface of one membrane standardly ranges between 40–60 m^2 in industrial modules. Fibers can be made of one or more hollows. Design and size of hollows is selected based on the level of pollution of the raw water. Hollows of larger diameter are preferred when the content of non-soluble substances is higher (> 50 mg/L), however the result of it is a smaller filtration surface of the membrane module [8, 9].

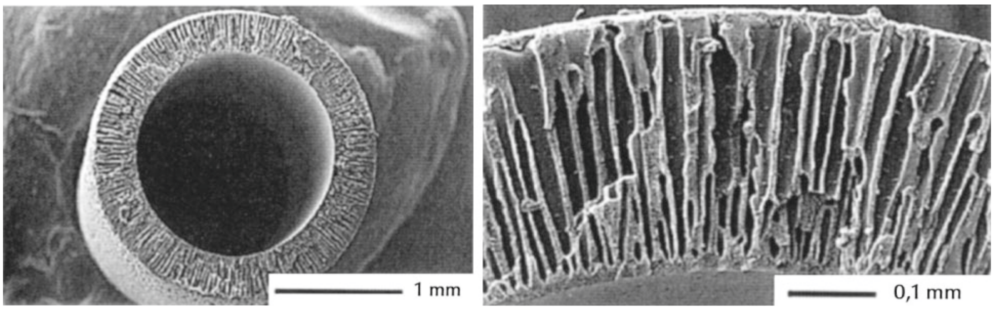

Figure 2. Microscopic zoom into the UF fiber, view of its structure and porous functional surface, functional surface of fibre is thinner from the inside than 1 µm. Flowing of water from the inside to the outside [9].

For manufacturing of the UF-membranes, materials of many kinds can be used, but when taking into account the mechanical and chemical durability, predisposition to siltation and the price the materials that were approved the most are polysulphone (PSO), polyethersulphone (PES), polyacrylnitrile (PAN), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), cellulose acetate (CA), polyamid (PA) and polypropylene (PP). Manufactured are also the more expensive ceramic UF-membranes (Al_2O_3, TiO_2, ZrO_2, SiO_2, SiC). However, these are rather used in microfiltration, or eventually in applications related with a need for thermic disinfection (food and pharmaceutical industry). Under the constant load on the membrane they are resistant to water with pH 3-10 and for a short term they resist the chemical washing of membrane at the pH ranging between 1-13. Membranes are resistant to the standardly used disinfectants (max. 20 mg/L NaClO) [8, 9].

Filtration cycle consists of filtration, forward-flush and upstream washing. Length of one cycle depends on the level of pollution of raw water. Usually, the phase of filtration takes 40-180 minutes and is followed by forward-flushing phase taking 30-50 seconds and upstream washing that takes 40-90 sec. Consumption of washing water ranges regularly between 2-4% from produced water, depending on the non-soluble substances content at the entry point [9].

Chocking of membranes can happen via the series of physico-chemical and biological mechanisms. Those mechanisms contribute to a higher accumulation of solid particles on the surface and within the membranes structure which results in that transmembrane pressure gets increased and the filtration velocity gets decreased. This leads to that the filtration cycle is shortened and the more frequent washing of membrane is needed [5].

We recognize external and internal clogging. External clogging on the membrane surface (scaling) causes the composition of the filtered medium from which the minerals on the membrane surface crystallize to form a filter cake and block the passage through the membrane. This kind of membrane fouling is temporary. External clogging can also cause so-called biofouling by forming biofilms or polymer layers on the membrane surface. The membranes so clogged are cleaned with oxidizing agents, weak sodium hypochlorite solutions are most commonly used. The fouling occurs in the pores of the membranes, representing the physical fouling of the pores by the pores where the pores are blocked and adsorbed, leading to a narrowing of the pores. This clogging is permanent.

2. Experimental part

This paper deals with the application of ultrafiltration and related operating experiences in the locality of Rozgrund.

2.1. Ultrafiltration module

A fully automated ultrafiltration facility with a UA-640 membrane module (Microdyn-Nadir) with a control system, measurement of trans-membrane pressure, backwashing of the membrane with water and air and the possibility of chemical washing was used within the experiments (Figure 3). The ultrafiltration module filtered water without the addition of a coagulant. Specifications of module UA-640 are listed in Table 1.

Figure 3. A view of the ultrafiltration device, the membrane module itself, the control system and the treated water storage tank.

Table 1. Specifications of UA-640 module.

Membrane type	Module with hollow fibres	Maximum discharge	to 1.3 m^3/h
Fibre diameter	OD/ID: 2.1 mm/1.1 mm	Maximum trans-membrane pressure	1 bar
Membrane material	PAN – polyacrylonitrile		
Pore size	0.025 µm	Max. module pressure	2 bars
Membrane area	16 m^2	Module diameter	168 mm
Filtration type	direct filtration	Module length	1210 mm
Regeneration	with water and air	Maximum turbidity	300 NTU

Altogether, 30 cycles were processed. Every third cycle was analysed. Each test lasted for 30 minutes. Samples were taken from the individual cycles as follows:
- filtered water (sample No. 1) – 15 seconds after washing;
- filtered water (sample No. 2) – 10 minutes after start of operation;
- filtered water (sample No. 3) – 20 minutes after start of operation;
- filtered water (sample No. 4) – 30 minutes after start of operation, or immediately before the next washing of the membrane.

Within each cycle, a sample of raw water was taken in advance of the membrane, of filtered water beyond the membrane and of the discharged wastewater after washing, wherein the washing cycle lasted only 10-12 seconds. An average sample of wastewater from three washings was used for the analysis.
The ultrafiltration experiment lasted for approximately 15 hours. The water flow rate through ultrafiltration was maintained at a value of 600 L/h. The following parameters were analysed in the samples: water temperature, pH, conductivity, acid neutralization capacity up to pH 4.5 ($ANC_{4,5}$), chemical oxygen demand (COD_{Mn}), total organic carbon (TOC), turbidity, colour, total dissolved solids (TDS) and undissolved solids (at 105°C).

2.2. The water quality

Table 2 shows the physical-chemical analysis of water on entry to the water treatment plant during the pilot tests.

Table 2. Water quality on entry to the Rozgrund water treatment plant during the experiments.

Parameter	Unit	Raw water sample	Parameter	Unit	Raw water sample
pH		7.69	chlorides	mg/L	8.01
conductivity	mS/m	15.3	nitrates	mg/L	3.12
COD_{Mn}	mg/L	2.4	sulphates	mg/L	34.61
TOC	mg/L	0.96	fluorides	mg/L	0.27
turbidity	NTU	2.94	phosphates	mg/L	0.06
colour	mg/L	11	iron	mg/L	0.03
$ANC_{4,5}$	mmol/L	0.922	manganese	mg/L	0.001
TDS	mg/L	120	ammonia	mg/L	0.02
Undissolved solids	mg/L	1.5	calcium	mg/L	27.72
Ca+Mg	mmol/L	0.922	magnesium	mg/L	5.6

From the long-term perspective, the water quality does not change very much, the water is of relatively high quality; without the impact of human activity, the pH of the water between 2012 and 2019 ranged from 6.97 to 8.23, the water temperature from 2.8 to 24.1°C. The water colour on the long-term average did not exceed 20 mg/L Pt. The year 2013 was an exception, as in March and April, 69 and 26 mg/L Pt, respectively, were measured. The water turbidity ranges from 1.0 to 3.0 NTU (nephelometric turbidity unit); in 2013, the turbidity measured in March and April was 5.8 to 3.3 NTU. COD_{Mn} on the long-term average achieves 1.4 to 2.9 mg/L, but in one case the value achieved 3.56 mg/L. With regard to the ageing of the reservoir and the eutrophication process, an increase of live organisms was determined from 150 up to 400 organisms/mL.

3. Results and discussion

Figure 4 shows the efficiency of ultrafiltration during treatment of water from the Rozgrund water reservoir. The figures give the concentrations of raw and filtered water (for 10 cycles). An average values of water samples determined before and after ultrafiltration and after backwashing in wastewater are listed in Table 3.

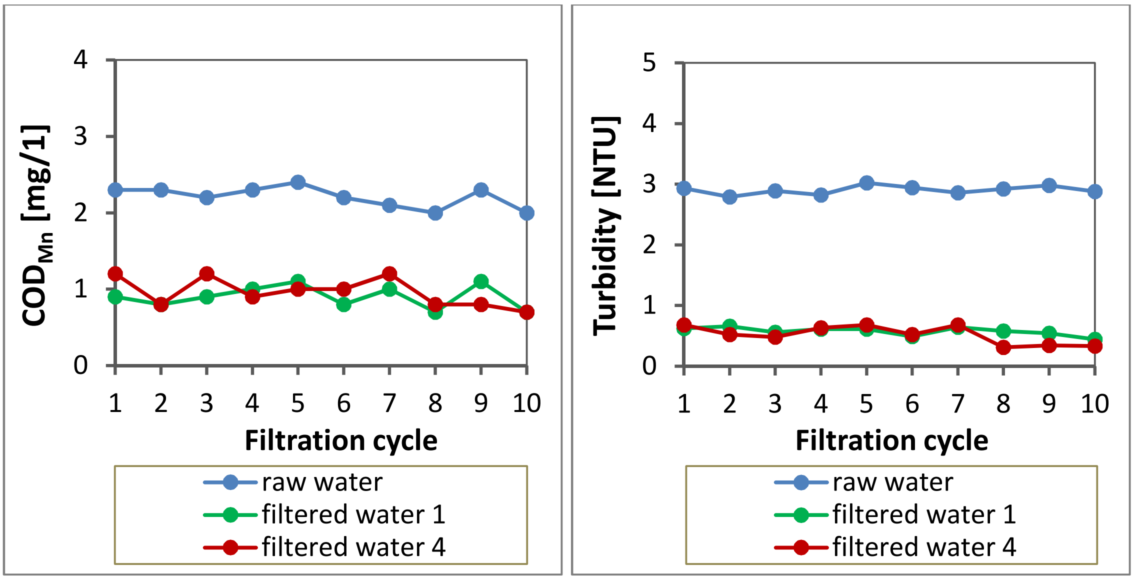

Figure 4. Concentration of COD_{Mn} (left) and turbidity (right) during 10 ultrafiltration cycles.

Table 3. The average values (altogether 10 cycles) determined before and after ultrafiltration.

Parameter	Unit	Raw water sample	Filtered Water 1 sample	Filtered Water 4 sample	Wastewater sample
pH		7.73	7.78	7.77	6.87
conductivity	mS/m	15.3	15.0	15.0	16.3
COD_{Mn}	mg/L	2.2	0.90	0.96	12.4
turbidity	NTU	2.89	0.57	0.51	25.3
colour	mg/L	11.7	0.5	0.8	65.6
$ANC_{4,5}$	mmol/L	0.973	0.940	0.947	1.069
TDS	mg/L	121	114	115	153
Undissolved solids	mg/L	1.5	0	0	10.3

Based on Table 3, it may be stated that ultrafiltration leads to a slight decrease in the conductivity, a slight increase in pH of the water, while the turbidity and water colour removal efficiency was 84.8% or 95%. The more than 52% COD_{Mn} reduction is an interesting result (without using of coagulation). This is thought to be due to the removal of humic acid from water as the pH decreased considerably (6.8–6.9) and the COD_{Mn} increased markedly (average value 12.4 mg/L) in the waste (washing) water. Monitoring the ultrafiltration efficiency over one cycle showed that there was no change in water quality after washing the membrane and starting a new cycle. Also, before the end of the cycle, no deterioration in the quality of the treated water was detected.

Compared to raw water in advance of the ultrafiltration membrane and scrubbing wastewater, there is an increase in solutes, a significant increase in insoluble matter, COD_{Mn}, color and turbidity. Therefore, it is necessary to solve what to do with wastewater after backwashing of membrane.

4. Conclusion
Based on pilot tests, ultrafiltration will be designed as one of the alternatives to the overall WTP Rozgrund modernization.
Advantages of ultrafiltration over conventional water treatments:
- perfect barrier against microorganisms (viruses, bacteria) with an efficiency of 99.9999%,
- the quality of the filtrate does not depend on the quality of the raw water,
- removal of pathogenic organisms resistant to chlorine,
- lower chemical consumption and production of sludge,
- compact design and smaller built-up area,
- simple control and automation.

Due to the fall in the price of the basic ultrafiltration components, with the global expansion of membrane module production, ultrafiltration is becoming an investment-friendly alternative to conventional multi-stage water treatment.

Acknowledgements
The technological experiments were performed with the financial support of the APVV-18-0205 and VEGA 01/0737/19 projects.

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