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Ultrafiltration used as pre-treatment for SWRO desalination: dynamic coagulant control under extreme conditions

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ABSTRACT

The increasing global needs of individuals, communities, industries and countries cause a worldwide stressed water infrastructure. The new AquaFlex ultrafiltration (UF) technology addresses these emerging circumstances by delivering a water purification technology for municipalities and industries worldwide to secure their future potable and process water requirements. The concept is specifically designed for the treatment of seawater, surface water and polishing of effluents. The newly upgraded AquaFlex UF system combines the vertical design of Pentair X-Flow's AquaFlex inside-out technology with the advantages of a minor bleed flow across the membrane surface as well as a module with a larger surface area. This allows your system to be designed with higher flux rates and a reduced footprint, thus providing the flexibility to treat a broader range of feed water qualities. In order to achieve a stable operation of the UF process in-line coagulation is often used. The application of in-line coagulation, however, increases the operating costs due to chemicals consumption and the increased disposal costs of the concentrate stream. Hence, it is desirable to develop a good dosing strategy, which applies the minimum addition at which the UF process still shows the desired performance. In this study, a dynamic control algorithm is proposed which enables to control the coagulant dosing, thus minimizing the coagulant consumption without destabilizing the filtration process. The dosing strategy for in-line coagulation was tested successfully at full pilot scale (with 8-inch Pentair X-Flow UF membrane modules). Experiments were carried out for both surface water from a canal in The Netherlands and seawater with strongly changing characteristics during the season. Compared to the current coagulant dosing strategy, a large reduction in coagulant consumption was achieved; in average up to 75%!

Keywords: Ultrafiltration; In-line coagulation; Dynamic control and optimization; Surface water; Seawater; Pre-treatment

1. Introduction

In the 1980s, it became clear that if ultrafiltration (UF) has to become a leading water treatment technology for large applications, energy consumption had to be cut. Therefore, several membrane manufacturers have developed energy-efficient UF systems, known as dead-end or semi dead-end systems. During the filtration mode, all the solids in suspension retain on the

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membrane surface. These retained solids are generally referred to as "fouling", which is an incorrect term, since the retaining of these solids is inherent to the process. The filtration process cannot be maintained indefinitely, due to the fact that the driving force across the membrane has to be increased constantly to keep the flow through the membrane constant. Hence, the system is backwashed (BW) by reversing the flow direction through the filter at regular intervals, hence the name 'semi' dead-end filtration. The solids are washed away to drain and the whole process repeats itself. While backwashing can remove most of the solids from the system, chemical cleaning methods have to be applied to clean the membrane completely.

Some substances tend to adhere to the membrane surface so they cannot be removed by mechanical force alone. These substances, often of organic and microbial origin, tend to slowly but surely block the membrane. This blocking of the membrane is what ought to be called fouling since the removal of these particular substances is most often not the main purpose of the process. They are sometimes in solution (small organic compounds) and would pass through the membrane, if not for their strong tendency to adhere to the surface. They could also constitute micro-organisms that are removed by the membrane, but start producing extra-cellular substances once they have settled onto the membrane surface. The majority of this type of fouling is chemically removable through a chemically enhanced backwash (CEB) or a cleaning-in-place procedure (CIP).

Pentair has developed two concepts for dead-end UF in order to cover the complete water market depending on the total suspended solid contents of the feed water sources:

Pentair XIGA™	Low suspended solids (0–50 mg/l)
Pentair AquaFlex™	Medium suspended solids (0–200 mg/l)

This XIGA™ concept is the main choice for large-scale water treatment processes. It is used when the suspended solids content of the feed is relatively low, typically below 50 mg/l as suspended solids. For the majority of large-scale water treatment processes this is the case. The XIGA™ processing is a typical process as described above. Recently, a dedicated version of this process named SEAGUARD has been introduced especially tuned for UF pre-treatment before reverse osmosis (RO) spiral wound elements for desalination of seawater (Fig. 1) [1].

This AquaFlex™ concept is typically suited for treating water with a suspended solids content of the feed water up to 200 mg/l. In this concept, the modules are mounted individually in a vertical configuration (Fig. 2). Because the modules are mounted vertically, this concept does not only provide backwashing and chemical cleaning to clean the membranes. Two extra steps for cleaning are introduced: Forward Flush and AirFlush®. The amount of cleaning chemicals for UF water applications can be significantly reduced by washing the membranes in forward flush with a mixture of air and feed water. In this feed-side cleaning procedure, air bubbles increase the shear forces on the membrane surface. The cake layer formed during the dead-end filtration mode is destabilized and washed out very effectively.

For some decades now, Spiral Wound RO (SWRO) is used to produce freshwater from saline and brackish water sources. The promise of a low chemical and low energy consuming system with a long sustainable lifetime, however, has never been achieved completely caused by the inadequate operation of the conventional (granular media) pre-treatment systems. At the beginning of the millennium, UF was introduced as an alternative pre-treatment for SWRO. UF, unlike conventional pre-treatment technologies, provides a physical barrier to particulate and colloidal material (including bacteria) and ensures that SWRO plants

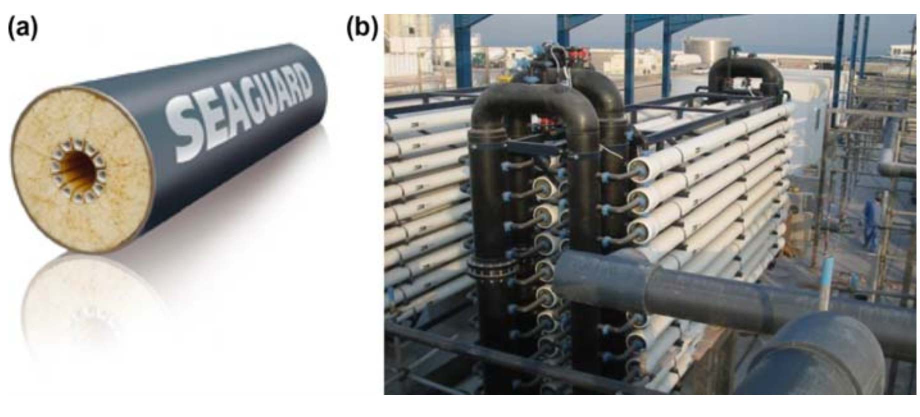

Fig. 1. XIGA™ concept based on 8-inch inserts: (a) 8-inch SXL225 element and (b) standard SEAQUARD skid.

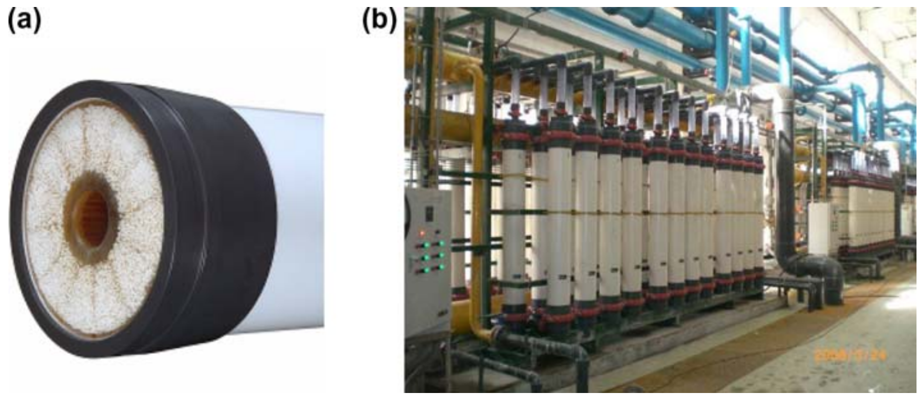

Fig. 2. AquaFlex™ concept based on 8-inch modules: (a) 8-inch SXL225 module and (b) typical full scale system (process water).

can operate on a continuous basis and at higher fluxes. UF/SWRO integration therefore seems an ideal solution, coping with the problems of existing traditional SWRO pre-treatment.

Although the SWRO part of these UF/SWRO systems shows significant performance improvements regarding fouling and lifetime, operational experience shows that chemical consumption for coagulation and chemical-enhanced backwashing of UF is still relatively high. Next to this, discharge of brine—as a byproduct from UF/SWRO-desalination—on the surface waters and especially its high iron content (originating from the coagulants used) is becoming a major concern for SWRO plants in operation. Therefore this study develops a dynamic dosing strategy enabling the dosing of the right amount of coagulants according to the current status of the system and avoiding under or overdosing.

2. Conceptual background

Consumption of coagulant and other chemicals is receiving increasing attention in the field of membrane filtration. This is motivated by both operating costs and environmental considerations. Although coagulant consumption can be reduced significantly by application of an advanced dosing strategy [2], it is not always possible to operate a dead-end UF plant without coagulant.

There are numerous forces acting on particles in the feed water, for example; viscous drag, double layer repulsion and Van der Waals attraction [3]. As a result, negatively charged and/or large particles tend to move away from the membrane. These are transported towards the end of the fibre. In dead-end filtration, however, it is inevitable that these particles accumulate on the membrane, where some particles will deposit near the end of the fibre [3,4]. These effects can be accounted to the low shear forces (no tangential flow) and the increased particle concentration.

By application of a small circulation flow (up to 15%), the particles that would otherwise deposit at the end of the fibres will be removed from the module. This operating strategy can be considered an intermediate between dead-end and cross-flow filtration (Fig. 3). Compared to dead-end filtration, this operational strategy has the advantage that membrane fouling is less severe, while compared to typical cross-flow filtration, this operating strategy consumes significantly less energy. As a result of the reduced fouling potential, the system can be operated at signif-

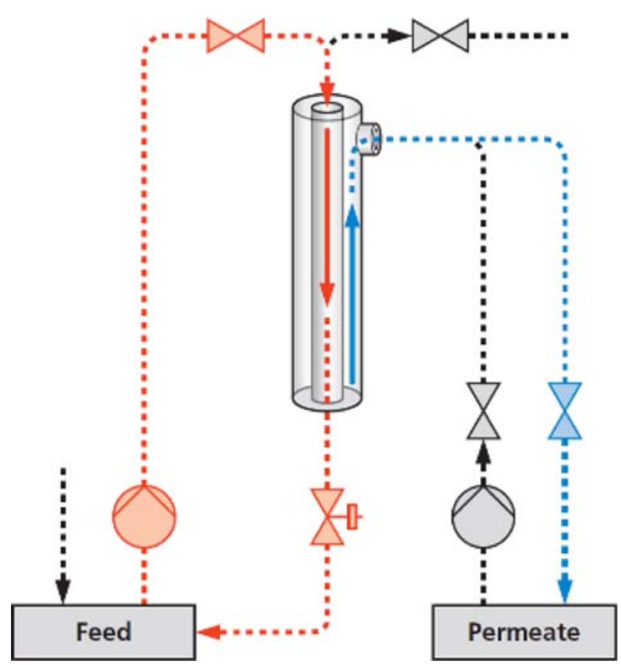

Fig. 3. AquaFlex™ processing: semi-dead-end with a small circulation flow.

icantly higher fluxes (in average 25%) without coagulant, longer filtration times, less membrane cleaning and higher recoveries, resulting in lower investment and operational costs.

The inside-out principle of membrane operation leads to high membrane performance in the most efficient manner. Inside-out operation provides an optimal flow profile within the cylindrical fibres over the full length of the membrane. This creates a well defined space and flow which helps prevent the buildup of solid on the membrane surface. The minor bleed flow of this process strengthens this effect even further.

By redesigning the well-known internal module design of our XIGA™ product line we were able to increase the membrane from 40 to 55 m^2 without leaving the 8-inch module diameter standard (Fig. 4). This decision will guarantee full backward compatibility for replacement and/or refurbishment of other vertical systems (Fig. 5).

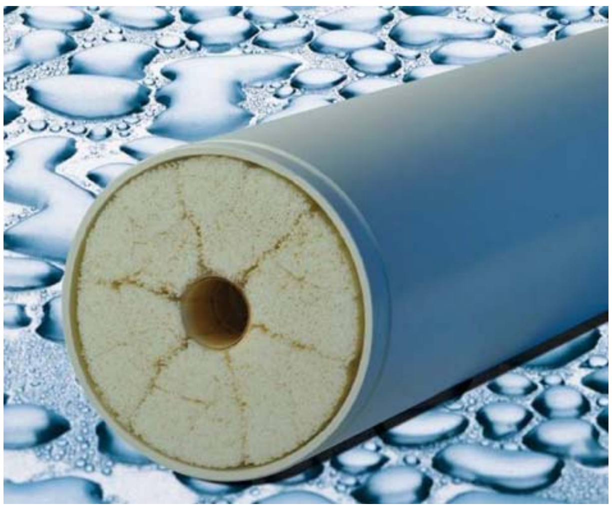

Fig. 4. The new 8-inch module with 55 m^2.

3. Experimental

For UF (irreversible) membrane fouling is a limitation in the application of this technology. The accumulation of the retained matter on the membrane surface leads to an increase in operating costs, due to increased energy consumption and the necessity of periodic cleaning. To reduce these operating costs, it is necessary to control the fouling behaviour.

This study uses in-line coagulation, which is the application of a coagulant before membrane filtration without a flotation/sedimentation or pre-filtration step. However, the application of in-line coagulation does have drawbacks. Firstly, it forms a large portion of the operating costs, due to chemical consumption and the increased disposal costs of the concentrate stream. Secondly, coagulant residuals in the permeate, caused by over dosing, reduce the product quality and can lead to issues in downstream processes, for example SWRO.

Fig. 5. The new skid with 25% reduction in footprint.

Hence, it is desirable to use a good dosing strategy, which applies the minimum addition at which the filtration process shows desired performance. This is different from the conventional optimal coagulant concentration, which is the concentration at which sedimentation yields good results.

Compared to the conventional optimum concentration, under-dosing leads to good filtration properties. If the dosing, however, is not continuously adapted to seasonal and long-term trends in the water composition, alteration of other operating settings and gradual changes in membrane properties, it can be expected that under or overdosing will occur.

UF is operated in dead-end mode consisting of a filtration step followed by a backwashing with permeate. After each backwash, the original membrane resistance is not always restored fully, so after 12–24 h, an additional chemical cleaning is required. The primary goal of in-line coagulation is stabilization of the filtration process between two chemical cleanings (Fig. 6). Hence, the amount of fouling that is allowed to accumulate between two chemical cleaning phases needs to be kept within certain bounds. This trajectory is indicated as the $R_0(n)$-function being the imaginative line through all the initial overall resistances after every backwash phase. The function of the control system is to follow this (ideal) trajectory as close as possible by changing the concentration of the coagulant after every backwash action.

It is known that the interaction between the physiochemical feed water properties and the fouling layer on the membrane surface under the influence of the coagulant dosing and other operating conditions is very complex. To eliminate the knowledge about the exact fouling process, a feedback controller is selected because feedback is able to deal with systems of which the behaviour is not exactly known.

Experiments were performed on two comparable full-scale pilot plants containing the 8-inch Pentair X-Flow SXL225 modules each with a filtration surface of 40 m^2. This module consists of capillary porous PES/PVP membranes with an internal diameter 0.8 mm and an effective length of approximately 1.5 m. The feed water was either surface water from the Twente canal (The Netherlands) or seawater obtained via an open water intake (China). In both cases, the feed water was pre-filtered (200 μm) to prevent too large particles from entering the system.

4. Results and discussion

The effect of the process mode on the backwash efficiency is evaluated. To compare different settings, the fouling remaining after a backwash is compared to the accumulation during a single filtration. Fig. 7 shows a typical performance of UF system operated in semi-dead on Twente canal water (The Netherlands) during an algae bloom, while operating under 15% cross-flow and no addition of coagulant. The slope of the all the initial resistances after a hydraulic backwash (and between two chemical cleanings) is defined as the fouling rate. Thus, the fouling rate parameter indicates the percentage of fouling that can be considered irreversible towards backwashing. This parameter is related with the consumption of cleaning chemicals and inversely related with the general robustness of the system.

4.1. Influence of filtration flux

A flux-step experiment was used to relate the fouling rate to the filtration flux. The result can be seen in Fig. 8. The figure shows a well-known phenomenon: with increasing flux the fouling rate progressively worsens. Thus, to increase the flux (reducing capital cost and footprint) it is needed to control the fouling rate.

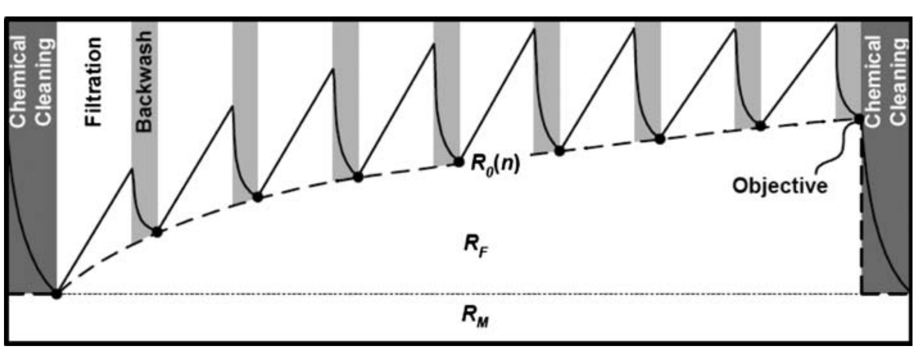

Fig. 6. Series of subsequent filtrations and backwashes between two chemical cleaning phases. The dashed line illustrates the development of the (ideal) resistance trajectory.

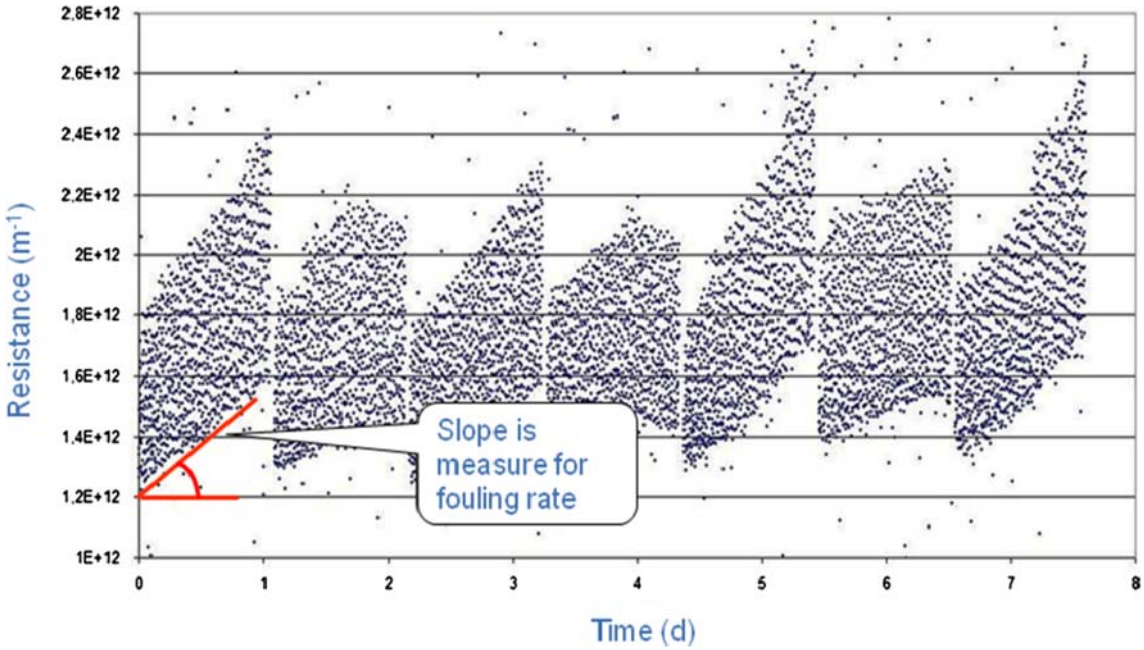

Fig. 7. Overall filtration resistance as a function of filtration time (Twente canal water (45–60 NTU), 15% circulation, no coagulant dosing).

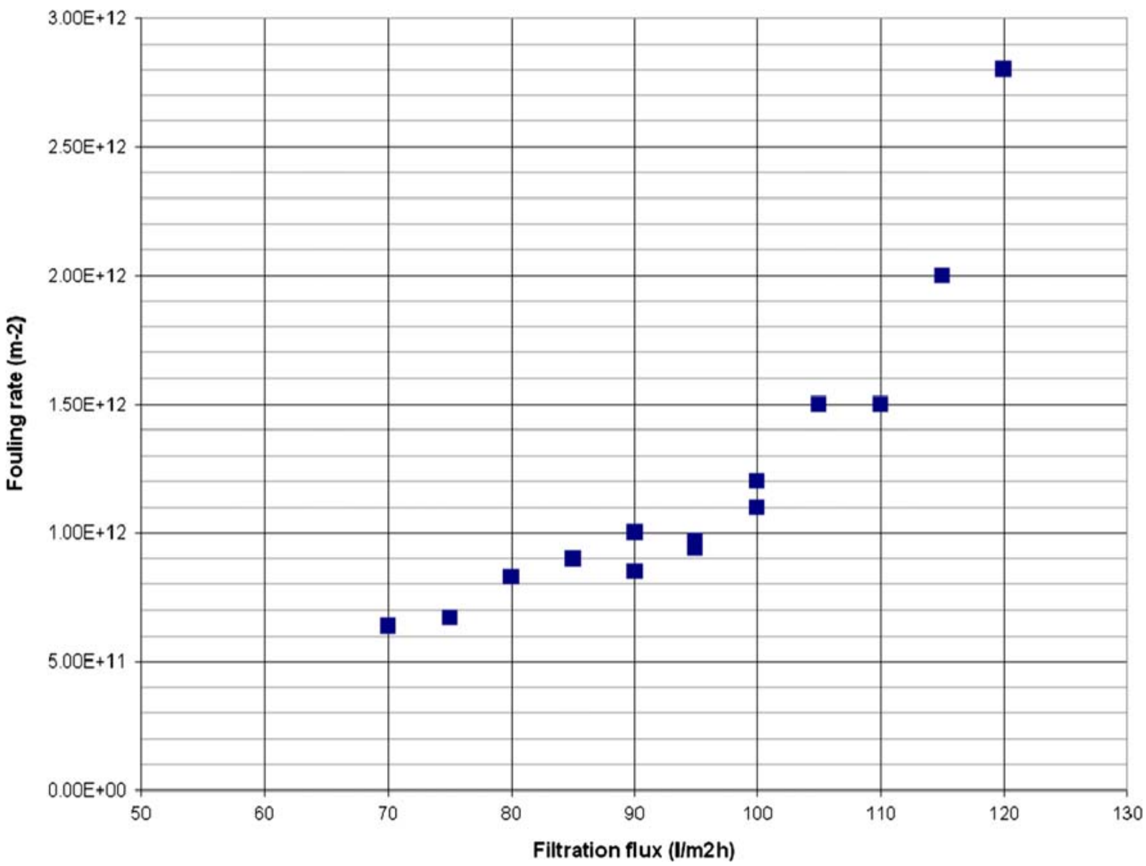

Fig. 8. Fouling rate as a function of filtration flux (Twente canal water (45–60 NTU), 15% circulation, no coagulant dosing).

4.2. Influence of recirculation

The application of a small circulation flow is one of the methods to control fouling. This can be effective when there is a high concentration of relatively large particles (e.g. algae). Fig. 9 shows the effect of changing the circulation on the fouling rate. It can be seen that the circulation flow significantly reduces the fouling rate.

4.3. Influence of coagulant dosing

Another means to control the fouling rate is the application of in-line coagulation. The effect of a constant coagulant dosing was evaluated (Fig. 10). It can be seen that going from 0 to 0.5 ppm gives a significant reduction in the fouling rate, while going from 0.5 to 1.0 ppm does not yield additional benefit.

4.4. Influence dynamic control

The new AquaFlex system integrates the Smart Technology, a newly developed automated intelligence algorithm that ensures maximum system performance and run-time while minimizing the energy and chemical usage. The system can respond in real-time to feed water quality and system changes by adjusting settings as needed. This eliminates energy and chemical waste when the system is set for the worst-case performance as well as downtime to make system adjustments. The Smart Technology optimizes automatically the actual performance of the installation in real-time.

Fig. 11 shows the transmembrane pressure and coagulant dosing during a typical operation of a pilot plant running at seawater during summer conditions (around 20°C). The pilot plant was operated at a constant flux of 100 l/m^2-h, with an internal recirculation of 15%, while the coagulant dosing was controlled dynamically. It is clear that when the fouling rate is low enough, no coagulant is dosed. Only when the fouling rate needs to be reduced, the controller doses coagulant. These results in an average dose of well below 0.1 ppm, while for seawater treatment coagulant values between 1 and 2 ppm are indicated generally.

5. Conclusions

A dosing strategy for in-line coagulation with UF was developed successfully. Compared to the current coagulant dosing strategy, a large reduction in coagulant consumption was achieved reducing the environmental burden of UF significantly (reduction between 75 and 90% compared to currently used values).

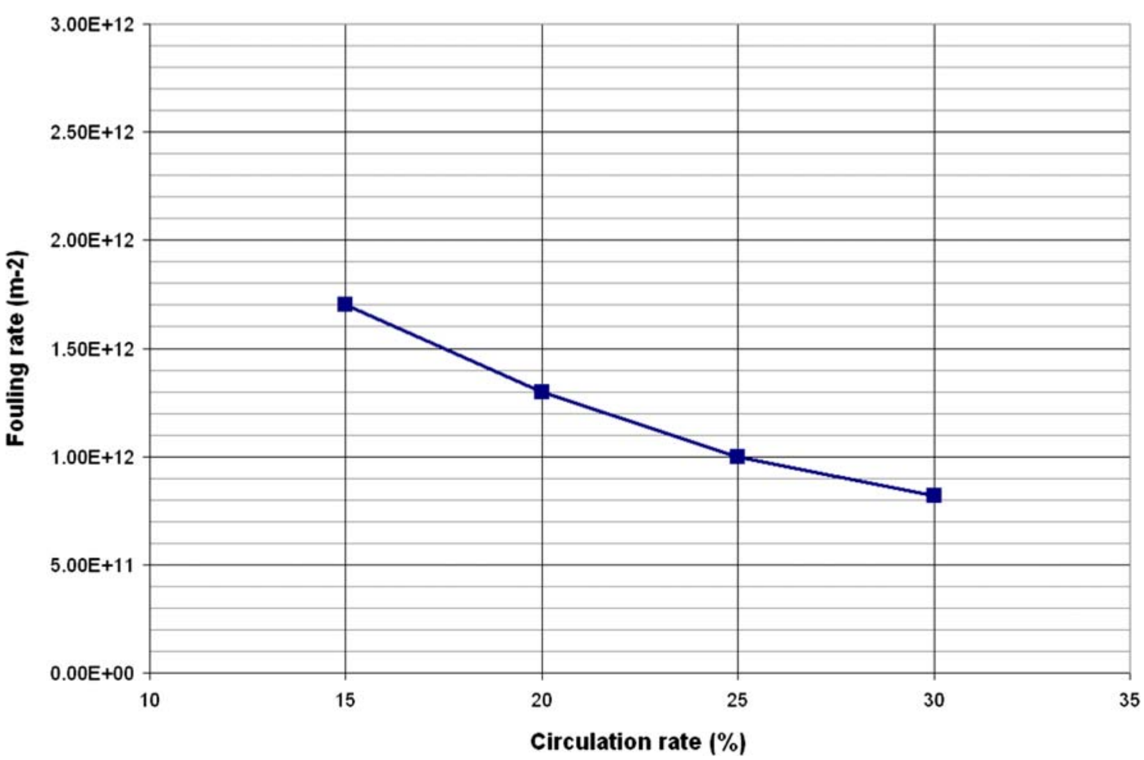

Fig. 9. Fouling rate as a function of recirculation rate (Twente canal water, during algae bloom 45–60 NTU, 100 l/m^2-h, no coagulant).

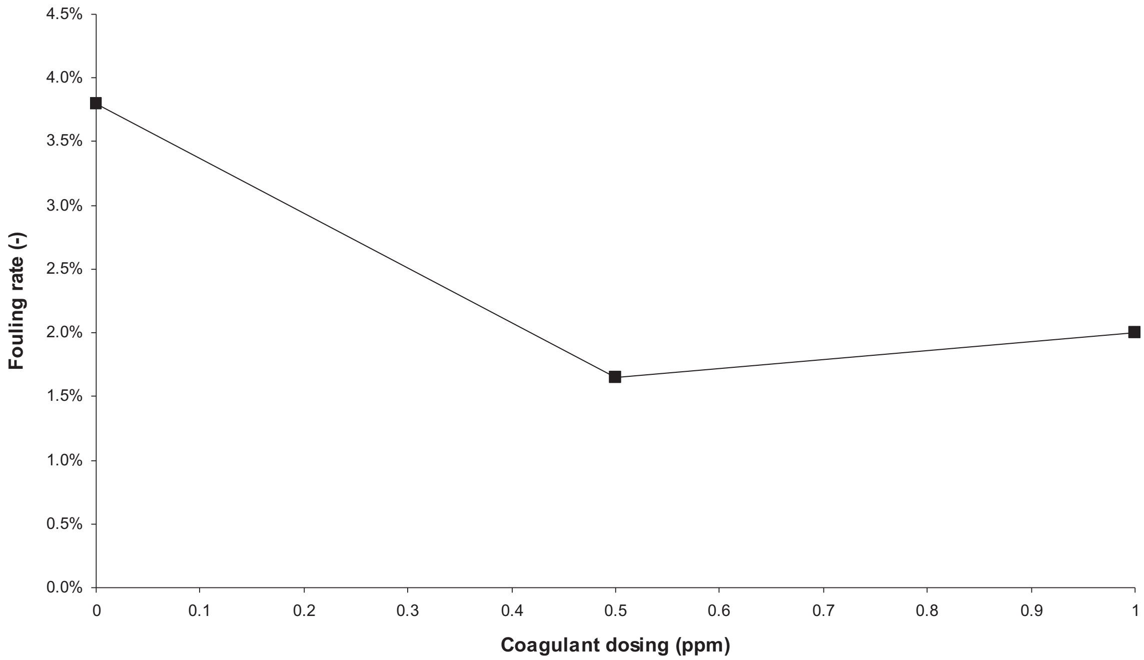

Fig. 10. Fouling rate as a function of coagulant dose (Twente canal water, $75\,l/m^2$-h).

The redesign of the well-known XIGA™ product line increases the membrane area from 40 to $55\,m^2$ without leaving the 8-inch module diameter standard enabling full backward compatibility for replacement and/or refurbishment of other vertical systems.

A plug-and-play vertically operated system applying inside-out fed ultrafiltration membranes and combining the power of a minor bleed flow across the membrane surface with a higher membrane area module showed through full-scale pilot experiments a significant flux increase; e.g. for surface water a maximum net-flux was found of approximately $90\,l/m^2$-h without using coagulant, while due to the high turbidity (45–60 NTU), this water would normally be filtered at a net-flux of $50\,l/m^2$-h and a coagulant dose of 2 ppm.

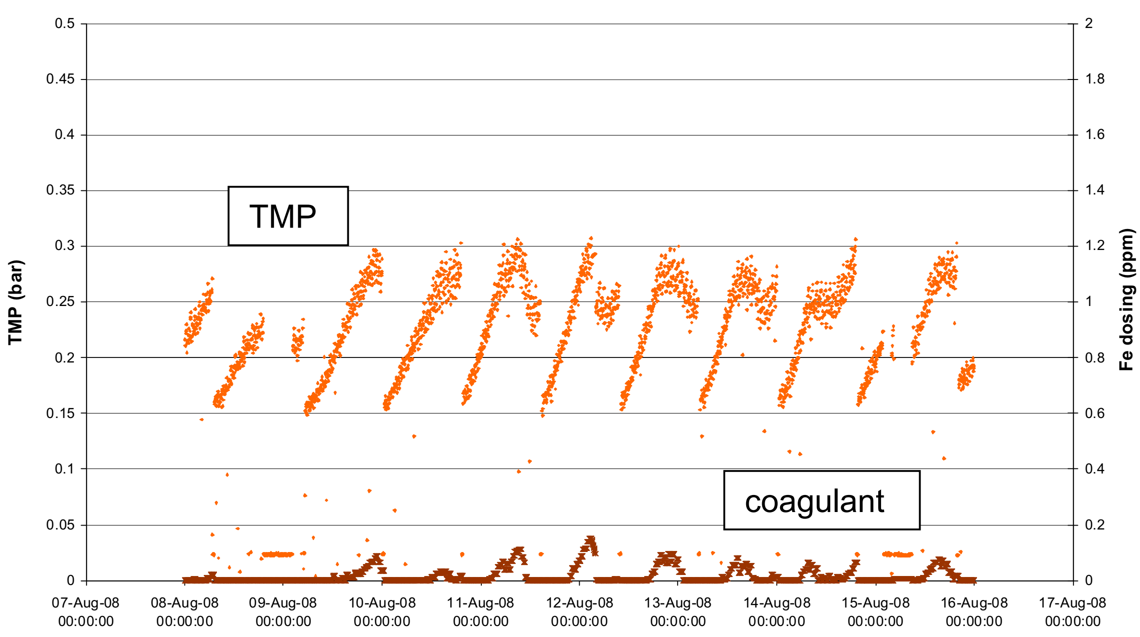

Fig. 11. Dynamic coagulant dosing in practice (seawater: flux is $100\,l/m^2$-h with an internal recirculation of 15%).

The newly developed automated intelligence algorithm ensures maximum system performance and uptime while minimizing the energy and chemical usage. The system is capable of responding in real-time to water quality changes by adjusting system settings as needed. Rather than setting the system at worst-case performance or turning the system off for needed adjustment, the algorithm automatically optimizes the actual performance of the process in real-time. Applying this algorithm during operation of a full-scale pilot under representative process conditions treating seawater obtained through an open water intake in summer time during an algae bloom showed a stable performance dosing a minor amount of coagulant.

All these improvements result in a strong reduction of the operational costs, a reduced proportional footprint and therefore a higher output of the installation per square meter footprint making UF very attractive as pretreatment for SWRO using surface water, secondary effluent or seawater as feed solutions.

Acknowledgement

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