Application of the membrane fouling simulator to determine biofouling potential of antiscalants in membrane filtration

Janneke Duiven, Bas Rietman and Wilbert van de Ven

ABSTRACT

In treatment of groundwater with reverse osmosis, the applied antiscalant can significantly contribute to the formation of biofouling, especially when legislation enforces the use of biodegradable, phosphorous-free products. As an alternative to extensive piloting, the use of the membrane fouling simulator (MFS) is proposed here to assess the biomass growth potential of different antiscalants. The biomass growth potential of two newly developed, phosphorous-free antiscalants was compared to a blank (no antiscalant) and a phosphorous-based antiscalant. The difference in biomass growth potential in the four experiments was significant, with the phosphorous-based antiscalant showing little biomass accumulation and strong and moderate biomass accumulation for the two newly developed phosphorous-free antiscalants. The results of visual observation and pressure measurements of the MFS were compared to the results of autopsy of the membrane sheets. Visual and pressure measurements were found to be a more reliable method to judge the biomass accumulation than membrane autopsy. In a comparison study of MFSs and test rigs with 4″ spiral-wound membrane modules, similar results were found, validating MFS use for simulating membrane modules.

Key words | antiscalant, biofouling, groundwater, membrane fouling simulator, nanofiltration, reverse osmosis

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INTRODUCTION

Membrane fouling, and in particular biofouling, will lead to a higher energy consumption, a higher cleaning frequency, shorter lifetime of the membranes and a decrease in permeate quality. This will lead to an unacceptable increase of the operational costs (Flemming 2002).

Drinking water company Vitens in the Netherlands has performed several pilot studies in the past before implementing membrane filtration in their existing drinking water treatment plants (DWTPs). From these pilot studies Vitens experienced that membrane fouling with membrane filtration of pre-treated groundwater can lead to unacceptable membrane fouling and, more specifically, biofouling. The conventional pre-treatment includes aeration and rapid sand filtration. Particularly the applied chemicals increase the biomass accumulation when used in combination with feed water that was aerated and filtrated in a preceding treatment step. Growth rate of the biofilm can be suppressed by operating membrane filtration directly with anaerobic groundwater (Hiemstra *et al.* 1999). Under anaerobic conditions this growth rate is acceptable, resulting in a limited chemical cleaning frequency.

Since 1999 Vitens successfully applies anaerobic membrane filtration in 11 different drinking water treatment plants to decrease the hardness and the degree of colour of the drinking water. The seven latest installations are based on the Optiflux® design that reduces energy consumption

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by 10–15% (van der Meer *et al.* 1998; van Paassen *et al.* 2005). In most membrane facilities, an antiscalant is dosed to the feed water to increase the recovery up to 80% without the occurrence of scaling. Vitens has permission from the water boards for disposal of the concentrate directly to the surface water as long as the discharge water meets strict regulations. The restrictions mainly focus on the iron and phosphate concentration in the concentrate. The total iron concentration must be smaller than either 2 or 5 $mg\,L^{-1}$ Fe (depending on the governing water board) while the phosphate concentration must be below 1 $mg\,L^{-1}$ (as phosphorous).

When membranes are operated directly with anaerobic groundwater the concentrate contains dissolved iron at concentrations up to 50 $mg\,L^{-1}$ and, as a result, the concentrate must be treated before the disposal. The treatment of concentrate for iron removal has the added benefit of simultaneous phosphate removal. Phosphate originates from both the groundwater itself as well as from the applied antiscalant, which is based on phosphorous as phosphonic acid. This specific antiscalant was selected based on its low contribution to the assimilable organic carbon (AOC) concentration in the feed water (Vrouwenvelder *et al.* 2000) and as a result shows low biofouling potential.

Recently, Vitens has begun applying membrane filtration at DWTPs where the groundwater is not strictly anaerobic. In these situations the groundwater needs to be pre-treated to avoid excessive fouling of the membranes due to iron hydroxides. In the pre-treatment the iron is removed to such an extent that concentrate treatment is no longer a necessity to meet iron discharge restrictions. The result is, however, that when the same phosphorous based antiscalant is used, the phosphate concentration in the concentrate will increase above the limit of 1 $mg\,L^{-1}$ (as phosphorous), and separate concentrate treatment would be necessary. This results in an undesired increase in investment and operational costs.

Concentrate treatment is not necessary when an antiscalant without phosphorous can be used instead. One additional limitation is important when selecting new auxiliary chemicals: The antiscalant must be biologically degradable. However, high biodegradability of these new antiscalants may result in biofouling on the membranes. The extent of biofouling depends on, among other things, the quality of the feed water and the quality of the chemicals that are used in the process.

To determine the biofouling potential different approaches are available. The AOC content of the feed water with the added chemicals should be determined and, depending on the results, (specific) pre-treatment can be selected. An AOC concentration below 10 $\mu g\,L^{-1}$ (as Ac-C) in the drinking water will reduce the regrowth of heterotrophic bacteria in the distribution system (van der Kooij 1992). The quality of chemicals can vary. If the AOC growth potential of an antiscalant is $\leq 0.1\,\mu g\,C\,mg^{-1}$ in aerobic feed water, the risk of biofouling resulting in a substantial deterioration of membrane performance is low (Vrouwenvelder *et al.* 2000). Determination of AOC is costly and time consuming. Since it only takes a snapshot of the water quality, multiple analyses must be performed. Finally, the measurement does not take the properties of the membrane element into account.

A second method is to perform long-term pilot tests. This will result in reliable information on the influence of the used chemical on the development of the biomass growth in combination with the feed water and membrane element. But piloting is time consuming and relatively expensive.

A new method uses a laboratory-size model of spiral-wound membrane elements: the membrane fouling simulator (MFS). The MFS was designed by Vitens, Kiwa Water Research and Technical University Delft (Vrouwenvelder *et al.* 2006). The MFS was proposed as a practical tool for fouling prediction and control. Among other purposes the MFS can be used to characterize the fouling potential of the feed water and the effect of a change in process conditions. As from experience biofouling and growth of biomass usually occur in the first element of a full-scale plant, the MFS was used to simulate the first element.

In this work the MFS was used to determine the contribution of different antiscalants to biofouling and biomass growth potential. In order to validate the performance of the MFS pilot tests were conducted in parallel to MFS and autopsies of the MFS cell membranes and pilot elements were performed. Ultimately, this research resulted in the selection of a phosphate-free antiscalant with a low contribution to biomass growth to be applied in reverse osmosis plants operating with aerobic groundwater.

MATERIALS AND METHODS

Feed water

Feed water for both the MFS and 4″ membrane module pilot tests was pre-treated river bank filtrated groundwater of DWTP Engelse Werk in the Netherlands. The pre-treatment on site consists of aeration, rapid sand filtration, re-aeration and a second rapid sand filtration step. A booster pump was used to increase the pressure towards the MFS cells and the pilot installations. The quality of the water was stable with a pH of 7.1 ± 0.2 and a temperature of 12.5 ± 0.5°C. Phosphorous was absent in the feed water ($< 0.016\,mg\,L^{-1}$ as P).

Antiscalants

The reference antiscalant, phosphorous based, currently used in the anaerobic full-scale installations within Vitens was 4Aqua-OSM92 ('OSM92', Aquacare Europe). The phosphorous concentration is 7.8 wt%. The two newly developed phosphorous-free (or lean) antiscalants that were used in the experiments were NovoPure 790 (Holland Novochem) and 4Aqua-BD25 ('BD25', Aquacare Europe). NovoPure 790 is based on unspecified biopolymers while BD25 is based on inulinase. The used concentration of antiscalants was determined in cooperation with the manufacturers and was $2.5\,mg\,L^{-1}$ in the case of OSM92 and NovoPure and $5\,mg\,L^{-1}$ for BD25. All chemicals were dissolved in ultrapure water and the pH of the solutions was adjusted with sodium hydroxide (pH ≥ 10) to meet manufacturers' standards.

Membrane fouling simulator (MFS)

To determine the contribution of the different antiscalants to biomass growth, four MFS cells were used in parallel. A flowsheet of the setup is given in Figure 1. The MFS cell was a small cell with dimensions of 0.07 × 0.30 × 0.04 m. The MFS cell was constructed of two linked stainless steel templates. Coupons of the membrane, feed spacer and permeate spacer of 0.20 × 0.04 m were placed in this cell. The heights of the feed spacer channel and the permeate spacer channel were 0.80 mm and 0.25 mm, respectively

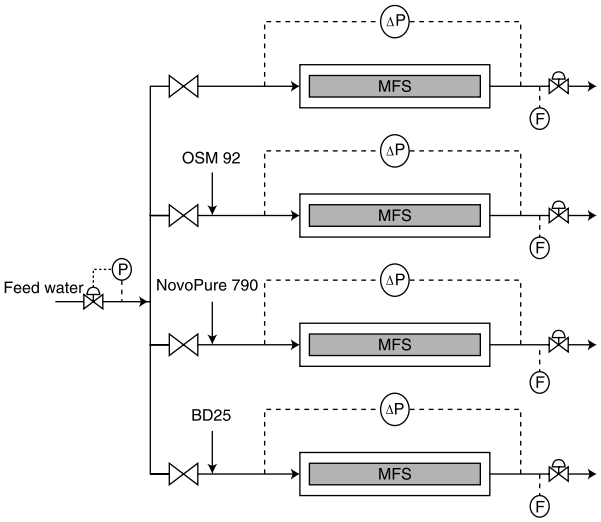

Figure 1 | Flowsheet of the four parallel MFS flowcells. All cells can be operated independently, but are fed by the same feed water at the same pressure. Flows (F) and pressure differences (ΔP) are measured and controlled for each cell.

(Vrouwenvelder *et al.* 2006). The membrane and spacer material originated from a Hydranautics ESPA4-4040 (composite polyamide) module.

The pressure of the feed flow was fixed at 1 bar. The pressure drop over the MFS cell ('axial pressure drop') was measured with a differential pressure transmitter (Deltabar S from Endress + Hauser). A feed flow of $16\,L\,h^{-1}$ was established through each MFS cell by means of manual flow controllers (Brooks) for each cell. This feed flow corresponds to a velocity of $0.16\,m\,s^{-1}$. To one of the cells no chemicals were dosed, and this MFS was used as a blank. To the three other cells, antiscalants were dosed with a special dosing pump (Stepdos 03, KNF Verder).

Three times a week the pressure drop over each MFS cell was measured, and the flow was determined and adjusted if necessary.

Pilot

Results from the MFS cells were compared to results of 4″ pilots testing. Two separate pilots were used to determine the biomass growth potential of the two phosphorous-free antiscalants in the modules. A simplified flowsheet of the two similar pilots is given in Figure 2. No additional pre-treatment of the feed water was performed. A feed flow

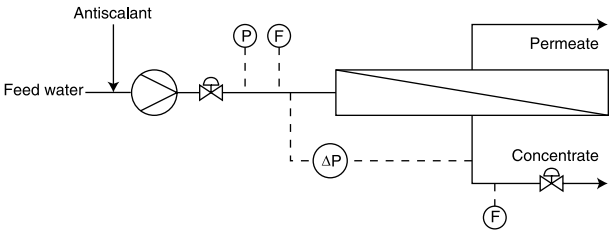

Figure 2 | Simplified flowsheet of one of the pilots used for the experiments with 4″ modules. Antiscalant was dosed to the feed water and a pump was used to pressurize the feed water. Feed pressure (P), flow (F) and pressure drop along the module (ΔP) were measured. The desired recovery of the system of 20% was set with control valves in the concentrate and feed lines.

rate of $1.0\,m^3\,h^{-1}$ was established by means of manual valves. The flow rate corresponds to a linear flow velocity of $0.11\,m\,s^{-1}$ through the membrane module. The recovery was manually fixed at 20%, which is typical for plants operated at Vitens, resulting in a flux of $21.6\,L\,m^{-2}\,h^{-1}$. To the feed water of one pilot $2.5\,mg\,L^{-1}$ antiscalant NovoPure 790 was dosed. To the other pilot $5\,mg\,L^{-1}$ 4Aqua-BD25 was dosed. Both pilots contained one Hydranautics ESPA4-4040 module.

Three times a week relevant process data were collected and the normalized flux, normalized axial pressure drop, recovery, retention and flux were calculated. The feed flow, concentrate flow and feed pressure were measured continuously.

Membrane autopsy

After the experiments, representative samples were obtained from the entrance, middle and exit of the membranes and spacers from the MFS and 4″ modules. The size of the membrane and corresponding spacer samples were measured and the surface area was calculated. For Al, Fe and Mn characterization, the membranes were submerged in nitric acid at low pH to redissolve the mineral deposits. The concentration of the metals was determined by ICP-MS and corrected for the surface area of the membrane samples. For TOC determination, the samples were submerged in concentrated sulfuric acid (pH < 2) and carbon content of the wash solution was determined. Biological activity was assessed by the R_2A bacterial colony count method after incubation for 10 days at 25°C and by analysis of the ATP content. The results were normalized for the surface area of the membrane sample. All analyses were performed at the laboratory of Vitens in Leeuwarden, except for the ATP measurements, which were performed by Waterlab Noord.

RESULTS AND DISCUSSION

In this section the effect of using different antiscalants on membrane fouling of reverse osmosis membranes is discussed. Two tools were used for the comparison: the membrane fouling simulator and 4″ membrane pilot setup. The applicability of both methods to assess membrane fouling will be demonstrated.

Membrane fouling simulator

The feed water for the MFS cell was pre-treated river bank filtrate produced at DWTP Engelse Werk, to which three different types of antiscalant were dosed. Since the MFS cells have a transparent top plate, visual inspection of the fouling state of the membrane can be performed during the test runs. In Figure 3, representative photographs from the four cells are depicted. Photographs were taken at the end of the experiments (after 63 days).

Visual observation of the sheets showed that some fouling was present in the cell used as a blank, which was most likely partly biofouling (brown threads) and partly particulate fouling. With the use of the phosphorous-based antiscalant (OSM92), no visual fouling of the membrane was observed. Use of the phosphorous-free antiscalants

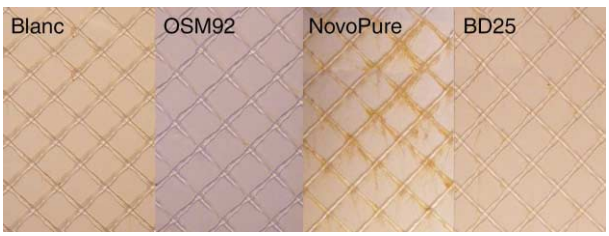

Figure 3 | Images of the membrane and spacer from the MFS cells after 63 days of operation while dosing different antiscalants. Differences in colours of the membranes were due to different lighting conditions. The blank and the membrane in the cell operated with BD25 showed minor mass accumulation. The MFS cell operated with NovoPure 790 showed severe mass accumulation. The cell operated with the standard antiscalant (OSM 92) showed negligible mass accumulation.

resulted in minor visual fouling for BD25 and considerably more visual fouling for NovoPure 790.

Regularly, the pressure difference over the length of the channel was determined for the cells operated with NovoPure, BD25 and a blank without added chemicals. In Figure 4 the pressure drop is given as a function of time. The observed increase in pressure drop for the cells showed the same results as the visual interpretation and is indicative for mass accumulation on the membranes and spacers. This method, when in the future extended with automatic logging of the data instead of manual measurements, can give a continuous indication for mass accumulation (or adsorptive of particulate fouling in other systems) and even membrane fouling.

The membrane and spacer were taken from each MFS cell after 63 days of operation and samples were taken from three areas of the membrane sheets and spacers, which allowed differentiation between fouling at the entrance and exit of the cell. The parts of the sheets from the entrance and exit were analysed for ATP concentration, bacterial colony count and deposited amounts of iron, manganese and aluminium. The middle sample was used to determine total organic content. The selection of the different analyses was based on the results of autopsy from modules from the anaerobic nanofiltration plant at DWTP Engelse Werk. The results from that autopsy showed that mainly biomass accumulation, as well as precipitation of iron and aluminium slats, occurred on the membrane and spacer.

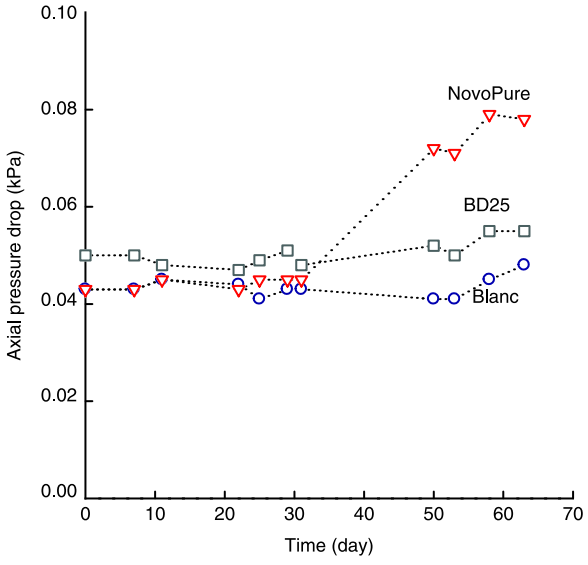

Figure 4 | Development of the axial pressure drop in three MFS cells operated for 63 days with two different antiscalants and a blank run with no added chemicals. The cell operated with NovoPure 790 (triangles) showed a strong increase in the axial pressure drop after 35–45 days of operation. The module operated with BD25 only showed a minor increase in axial pressure drop towards the end of the experiment, similar to the increase observed for the blank.

Values for ATP were not significantly different for the blank and the three tested antiscalants, with the exception of the significantly increased values found when dosing NovoPure. Together with the visual observations and the development of the pressure drop (Figure 4), this shows that the mass is mainly of biological origin and therefore indicated in the following as biomass. To further characterize the biomass techniques other than those used are necessary (Flemming *et al.* 2000). Colony counts varied widely among the measurements, which was largely due to the large experimental errors (which can be as high as 70%) that are characteristic for this method. Therefore colony counts were not used for further assessment. TOC values seem to be lower in the experiments with added antiscalant. This might further indicate increased biological activity when using antiscalants. The concentration of minerals did not significantly vary between the samples. This was expected, as there is no filtration in the MFS cells, and scaling therefore did not occur.

4″ membrane module pilot tests

Since the aim of the experiments was to find a suitable phosphate-free antiscalant for the reverse osmosis process that is planned for DWTP Engelse Werk, only NovoPure and BD25 were tested. Both of the 4″ pilot elements were operated under approximately the same conditions (feed test of $1\,m^3\,h^{-1}$, recovery of 20%, axial velocity of $0.11\,m\,s^{-1}$). A recovery of 20% for the lead elements and the axial velocity of $0.11\,m\,s^{-1}$ are typical for the Optiflux concept applied at Vitens. Since the module simulates a lead element, scaling and biofouling phenomena are decoupled and the results are indicative for process conditions in the first modules of a pressure vessel. At the start of the experiments, the feed pressure of the modules was 5.22 and 5.87 bar for the elements tested with NovoPure 790 and BD25, respectively. Over the same 63 days

of operation as for the MFS cells, the transmembrane pressure, flux and axial pressure drop over the length of the cell were recorded.

As (bio)fouling developed, the axial pressure drop over the membrane surface increased over time as feed test and overall recovery were kept constant. The axial pressure drop is given as a function of time in Figure 5. What becomes immediately apparent from the results is that the use of NovoPure 790 led to a much stronger development of the axial pressure drop than the use of BD25.

The increase in axial pressure drop did not lead to a noticeable decline in membrane filtration resistance. This is shown in Figure 6, where the filtration resistance is plotted vs. time. Over the entire duration of the experiments, the filtration resistance was in both cases fairly stable. A possible explanation can be given when matching the pilot results with the photographs from the MFS cells (Figure 3). The biomass was mainly attached to the mesh of the spacer. If the same occurred in the 4″ modules, this fouling of the feed spacer would increase the hydraulic resistance and as such

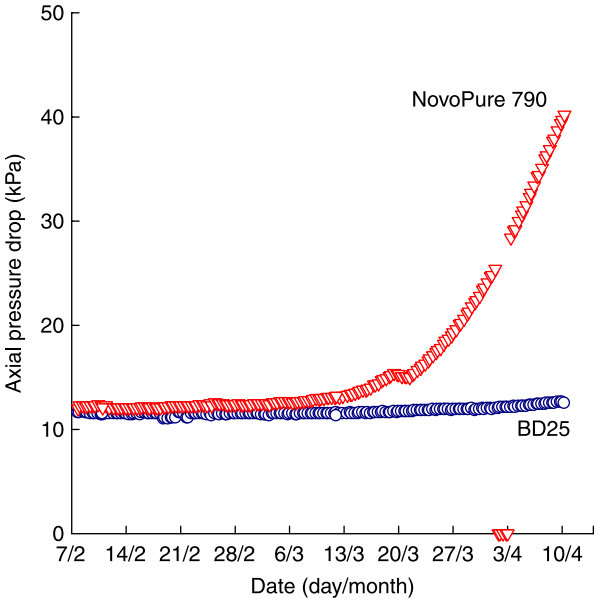

Figure 5 | Development of the axial pressure drop in the two 4″ test modules operated for 63 days with two different antiscalants. The module operated with NovoPure 790 (indicated with the triangles) showed a strong increase in the axial pressure drop starting at the beginning of March. The module operated with BD25 only showed a minor increase in axial pressure drop starting from the 13th of March. The NovoPure 790 dosage pump malfunctioned around the 20th of March, resulting in a decrease in the pressure drop. At the beginning of April, the axial pressure drop sensor was shortly disconnected.

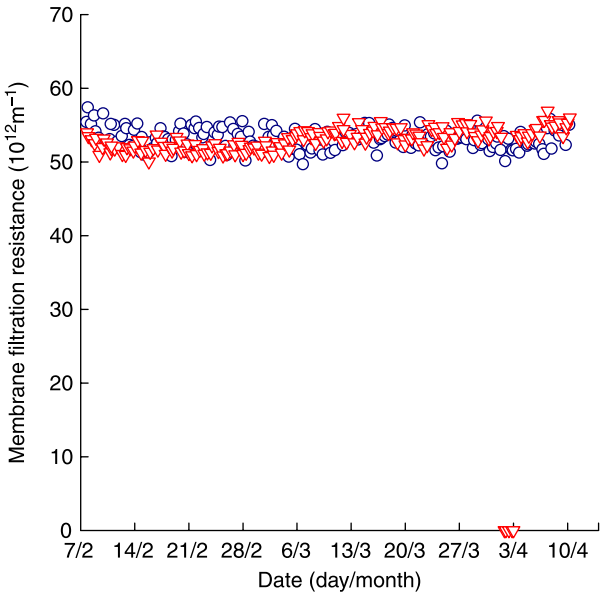

Figure 6 | Filtration resistance for the two 4″ pilot modules over the testing period of 63 days. No significant changes in membrane resistance were observed for the module operated with NovoPure 790 antiscalant (triangles) nor for the module operated with BD25 (circles).

the overall energy efficiency, but would not directly affect the permeability of the membrane. In a recent paper by Vrouwenvelder *et al.* (2009), the authors showed just that; in their work, the pressure drop in the channel was indeed mainly due to the accumulation of biomass on the mesh of the feed spacer and did not necessarily lead to a decline in membrane resistance. Another indication that the antiscalant itself had a strong influence on membrane fouling was the decrease in pressure drop after the antiscalant dosing pump of NovoPure 790 malfunctioned (around the 20th of March). The pressure drop decreased as the biology was no longer sustained by a steady food supply (see Table 1).

Autopsy of the 4″ modules

After the filtration experiments described in the previous section were finished, membrane autopsy was performed on the elements. After visual inspection, samples were cut from the entrance, middle and the exit of the element. The surfaces of these sheets and corresponding spacer samples were analysed for iron, manganese and aluminium deposition, and the colony count, TOC and ATP concentration were determined.

Table 1 | Analyses of the sheets and spacers obtained from the MFS cells

		Blank		OSM92		NovoPure 790		BD25	
		Begin	End	Begin	End	Begin	End	Begin	End
ATP	$ng\,cm^{-2}$	0.189	0.234	0.337	0.192	0.596	1.122	0.211	0.240
Colony count	$cfu\,cm^{-2}$	27×10^3	29×10^3	$>100 \times 10^3$	29×10^3	53×10^3	33×10^3	18×10^3	64×10^3
Al	$\mu g\,cm^{-2}$	0.379	0.551	0.512	0.359	0.349	0.419	0.326	0.418
Fe	$\mu g\,cm^{-2}$	1.1	0.8	0.4	0.4	1.4	2.4	1.2	1.6
Mn	$\mu g\,cm^{-2}$	<0.2	<0.1	<0.2	<0.1	<0.1	0.2	0.1	<0.1
TOC*	$\mu g\,cm^{-2}$	28		14		18		13.5	

*TOC samples were taken from the middle of the sheet and spacer.

Visual inspection of the modules showed a marked difference between the two elements (Figure 7). In the element that was operated with NovoPure 790, thick brown threadlike fouling was observed, mainly on the feed side of the element. The fouling was highly irregular over the membrane surface and attached to the feed spacer. The membrane itself was only lightly coloured. The element operated with BD25 showed a different picture. The whole membrane was coloured very evenly, but overall a much darker shade. The spacer itself was not found to be fouled during visual observations.

The results of the laboratory analyses of the membrane sheets are given in Table 2. When the numbers that indicate biofouling (ATP and colony count) were compared with the visual observation from the autopsy, the colony count results showed best agreement with the visual observations. For the module operated with NovoPure 790, colony count results followed the same trend (high at the entrance of the module, lower at the exit), while the numbers for the module operated with BD25 were fairly constant with respect to colony count results. The use of NovoPure 790 clearly led to increased values for both measurements compared to the use of BD25. With respect to the influence of both antiscalants on the scaling potential of the feed solution, the setup of the experiment could not give conclusive answers. This was due to the low recovery (20%) at which the experiments were performed. Even so, the results from the surface analyses of the used membranes suggested that both antiscalants were capable of keeping iron and manganese salts in solution, with BD25 showing somewhat lower numbers than NovoPure 790.

Figure 7 | Photographs from the membrane autopsies performed for the two elements. The left photo shows the element operated with BD25, the right photo shows the element operated with NovoPure 790. In the right photo, the feed water flowed from bottom to the top.

Since the membranes operated with the BD25 antiscalant were visually more and more evenly fouled than the membranes operated with NovoPure, higher numbers for TOC were expected for BD25; this was, however, not the case. The evenly distributed, coloured fouling layer that was the result of operation with BD25 is most likely due to adsorption of a very thin layer of antiscalant to the membrane. BD25 solutions had a dark brown colour.

One can speculate on the method of membrane autopsy and analysis of the fouling found on the surface of the membrane. Seemingly, both modules foul in a different manner, NovoPure 790 fouled the spacer more than the membrane itself, resulting in increased pressure drop and higher energy consumption, while BD25 adsorbed on the membrane. In both cases, membrane filtration resistance was not influenced. To distinguish between these two locations of the membrane fouling, in future research the biomass attached to the spacer should be analysed separately from the membrane.

Since the feed spacer was an important factor in the effect of biomass accumulation on the performance of the process, selection of the right spacer is essential in future

Table 2 | Results of the laboratory analysis of selected sheets of the membranes from the 4″ elements

		NovoPure 790			BD25		
		Begin	Middle	End	Begin	Middle	End
ATP	$ng\,cm^{-2}$	1.609	1.413	1.619	0.5913	1.045	0.5882
Colony count	$cfu\,cm^{-2}$	$>100 \times 10^3$	82×10^3	34×10^3	45×10^3	37×10^3	40×10^3
Al	$\mu g\,cm^{-2}$	0.050	0.060	0.062	0.064	0.063	0.066
Fe	$\mu g\,cm^{-2}$	5.2	6.1	5.0	4.3	4.1	3.9
Mn	$\mu g\,cm^{-2}$	0.7	0.3	0.2	0.1	0.1	0.1
TOC	$\mu g\,cm^{-2}$	<2.3	38.2	27.7	<2.4	41.8	51.5

applications. Three-dimensional modelling of the feed channel, as proposed by Vrouwenvelder *et al.* (2009), with the incorporation of a model for the growth of the biomass in the system will give a good starting point for selection, or development, of a feed spacer with minimal biomass attachment. The antiscalants themselves had a major influence on biomass growth, as the results showed. Holland NovoChem is currently developing phosphate-free antiscalants with a lower biomass accumulation potential. Initial tests at Vitens with new products showed that the potential was significantly reduced.

Comparison of biomass accumulation potential from the MFS and pilot plant experiments

The results from the MFS cells corresponded quite well to the results obtained with the 4″ pilot experiments. Visual observation and the development of the pressure drop over time gave the same conclusions and the trends in the results from the autopsy experiments were similar. Measuring the pressure drop over the length of an MFS cell also gives a good measurement of the amount of deposition in the cell. Although the measurement needs some refining, the duration after which fouling is noticeable in the 4″ modules and the test cells is similar.

There is still room for improvement nonetheless in future experiments; concentrations of deposited material on the membrane show that these values were higher for the pilot tests. This was most likely due to the absence of permeation in the MFS cells, something that will be countered with the newly developed pressure-resistant MFS cells (Vrouwenvelder *et al.* 2008).

CONCLUSIONS

The membrane fouling simulator (MFS) is a very valuable tool to study the effect of changing operating conditions on membrane fouling. In this work, MFS experiments were applied to study the effect of antiscalants on biomass accumulation potential. The phosphorous-based antiscalant, which is used in anaerobic membrane filtration, showed very good performance in the laboratory-scale tests. At DWTPs where Vitens will apply membrane filtration with aerobic feed water, Vitens is looking into using phosphorous-free antiscalants to meet concentrate discharge restrictions for phosphorous.

The use of biodegradable phosphorous-free antiscalants can result in serious biomass growth, and the energy consumption for the process as a whole increased. But the biomass accumulation itself did not necessarily result in a decrease in membrane filtration resistance. This was due to biomass mainly attaching to the spacer material. There was a significant difference in biomass accumulation potential of the two tested phosphate-free antiscalants.

The results from the MFS cells were compared to results with a 4″ pilot plant. When the two methods were compared, the conclusion is that the MFS gave a very good indication of the type of fouling that occurred on 4″ elements. There is still room for improvement of the experiments, since the effect of the flux on the results could not be taken into account in the used MFS cells.

Based on the results with the MFS and the low recovery pilot tests, experiments at the design recovery of 80% with a full-scale installation and the best performing antiscalant are currently run to study scaling inhibition and biofouling potential under full-scale conditions.

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