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Membrane properties change in fine-pore aeration diffusers: Full-scale variations of transfer efficiency and headloss

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ABSTRACT

Fine-pore diffusers are the most common aeration system in municipal wastewater treatment. Punched polymeric membranes are often used in fine-pore aeration due to their advantageous initial performance. These membranes are subject to fouling and scaling, resulting in increased headloss and reduced oxygen transfer efficiency, both contributing to increased plant energy costs. This paper describes and discusses the change in material properties for polymeric fine-pore diffusers, comparing new and used membranes. Three different diffuser technologies were tested and sample diffusers from two wastewater treatment facilities were analysed. The polymeric membranes analysed in this paper were composed of ethylene–propylene-diene monomer (EPDM), polyurethane, and silicon. Transfer efficiency is usually lower with longer times in operation, as older, dilated orifices produce larger bubbles, which are unfavourable to mass transfer. At the same time, headloss increases with time in operation, since membranes increase in rigidity and hardness, and fouling and scaling phenomena occur at the orifice opening. Change in polymer properties and laboratory test results correlate with the decrease in oxygen transfer efficiency.

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1. Introduction

Fine-pore aeration systems are used almost exclusively for aerobic biological processes in municipal wastewater treatment plants in the United States and Europe. Fine-pore diffusers have improved performance in terms of specific energy consumption, requiring approximately 50% of the energy of coarse bubble diffusers (Stenstrom et al., 1984). The bubbles produced by fine-pore diffusers typically have diameter less than 5 mm, and are released through by porous ceramic, punched polymeric membranes, or polymeric sintered aggregates.

Fouling (organic) and scaling (inorganic) phenomena are a disadvantage associated with fine-pore diffusers (Boyle and Redmon, 1983). One indicator of fouling/scaling phenomena is the measurement of the headloss across the diffuser, termed dynamic wet pressure (DWP). The increase in DWP with increasing time in operation is an intrinsic characteristic of fine-pore diffusers for all existing diffuser technologies (Kim and Boyle, 1993). Because of the chemical nature and morphology of these materials, they experience fouling and scaling depending on process conditions, water quality, diffuser type, and time in operation (US EPA, 1989). As a

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result, fine-pore diffusers need to be routinely cleaned. In order to limit the decline in transfer efficiency to less than 25% of the initial efficiency, periods between cleaning of less than 24 months are usually required (Rosso and Stenstrom, 2006). The choice of cleaning frequency and method determines the long-term efficiency and benefits of using fine-pore aeration.

Fine-pore diffuser fouling severely burdens the entire aeration system. Air blowers are typically designed on the basis of highest airflow demand, plus a safety margin. The blower discharge pressure requirement is generally based upon the pressure required for overcoming hydrostatic water head and the new diffuser's DWP. Often the limiting factor in aeration system operation is the total blower discharge pressure. Whilst hydrostatic water head remains constant over the lifespan of the aeration system, the DWP increases inexorably with time, due to fouling/scaling. In the case of blowers with insufficient discharge pressure, the aeration system will produce uneven bubble distribution, as the air can only be released through the pores with lower headloss. Uneven bubble distribution is typically associated with uneven dissolved oxygen (DO) concentration, which may lead to odour formation, sludge bulking problems, and poor mixing (Palm et al., 1980).

This paper analyses and compares clean- and process-water datasets for fine-pore membrane diffusers harvested in two wastewater treatment plants. Our clean water test results show the decline in aeration efficiency and the increase in headloss for used membrane diffusers. Microscopic quantitative and qualitative analyses characterise diffuser fouling/scaling phenomena and show material changes in the membranes as a concurrent cause for the decline in diffuser performance.

2. Materials and methods

2.1. Microscopic analyses

Microscopic analyses on selected membranes were performed with a Zeiss DSM 962 scanning electron microscope using Au surface sputtering. Each sample was air dried before sputtering. Deposits onto the membranes were sampled and analysed quantitatively and qualitatively with the energy-dispersive X-ray spectroscopic analysis technique and RFA X-ray irradiation.

2.2. Dynamic wet pressure and k_La measurements

Clean water tests on the diffusers were performed according to the American Society of Civil Engineers (ASCE, 2007) standard procedure. DO concentrations were measured and logged over time in a solution where oxygen was first sequestered with sodium sulphite, using cobalt chloride as a catalyst. DO was measured with YSI 58 DO meters (Yellow Springs Instruments, Yellow Springs, OH), and recorded via a NI DAQ-6015 (National Instruments, Austin, TX) acquisition board connected to a computer.

The diffusers were tested in a lab-scale tank, $915 \times 610 \times 610$ mm ($L \times W \times D$). The tank has a glass window on one side that allows the diffusers to be photographed during testing. Photographs were taken, and used to observe bubble characteristics and distribution. Airflow rate and DWP were concurrently measured during oxygen transfer testing. Fig. 1 shows a schematic diagram of the test tank. The pressure drop that the diffuser creates (the differential pressure between points A and B in Fig. 1) is the DWP, which accounts for the pressure drop across the membrane and the pressure required to overcome the water surface tension. To minimise the reading of pressure drop in the air lines, DWP was measured by connecting the pressure taps as close as possible to the membrane.

The volumetric mass transfer coefficients (k_La, time^{-1}), oxygen transfer rates in standard conditions (mass$_{O2}$ time^{-1}), oxygen transfer efficiency in standard conditions for clean water (SOTE, %), and oxygen transfer efficiency in process water (αSOTE, %) were calculated using the ASCE DO Parameter Estimation Program (DO_PAR 1.08, ASCE 2007; downloaded from: http://fields.seas.ucla.edu/research/dopar/). The α factor was calculated as the ratio of process- to clean-water SOTE, i.e.:

$$\alpha = \frac{\alpha \mathrm{SOTE}}{\mathrm{SOTE}}. \tag{1}$$

When it is desirable to differentiate the effects of wastewater contaminants and fouling, an αF factor is often used, where F is the fouling factor:

$$F = \frac{\mathrm{SOTE_{used}}}{\mathrm{SOTE_{new}}}. \tag{2}$$

Harvested diffusers were drained but not dried and stored in plastic bags until testing. They were then soaked in tap water for at least 24 h before testing. This allows the diffuser surface to be "wetted." Manufacturers report spurious results, especially with polyurethane membranes, if the diffuser surface is not allowed to equilibrate with the water being aerated.

DWP was initially measured for each diffuser. The procedure was to adjust the flow to 1.70 Nm^3/h (1 Standard ft^3/min, or 1 SCFM) and allow the DWP to stabilise. After the DWP stabilised, the flow was increased to $2\times$ the initial flow and maintained until the DWP stabilised. The DWP was recorded and the procedure repeated for flows of $3\times$, $4\times$, and $5\times$. Next the flow was decreased to $4\times$ and the stabilised DWP was measured again. This was repeated for $3\times$, $2\times$, and $1\times$. Clean water testing was next performed on each diffuser at $1\times$, $3\times$, and $5\times$ (1.70, 5.10 and 8.50 Nm^3/h).

3. Existing field conditions

3.1. Plant A

The first plant (Fig. 2a) where diffusers were harvested is a full biological nutrient removal (N and P) municipal facility in Germany. The plant has 2 activated sludge units for a total of 16 tanks, which treat a flow corresponding to 300,000 p.e. The aeration tanks were equipped with punched silicon membranes mounted on tube frames with approximate bubbling area of 0.18 m^2 per diffuser. Three membranes were harvested in three different basins, and

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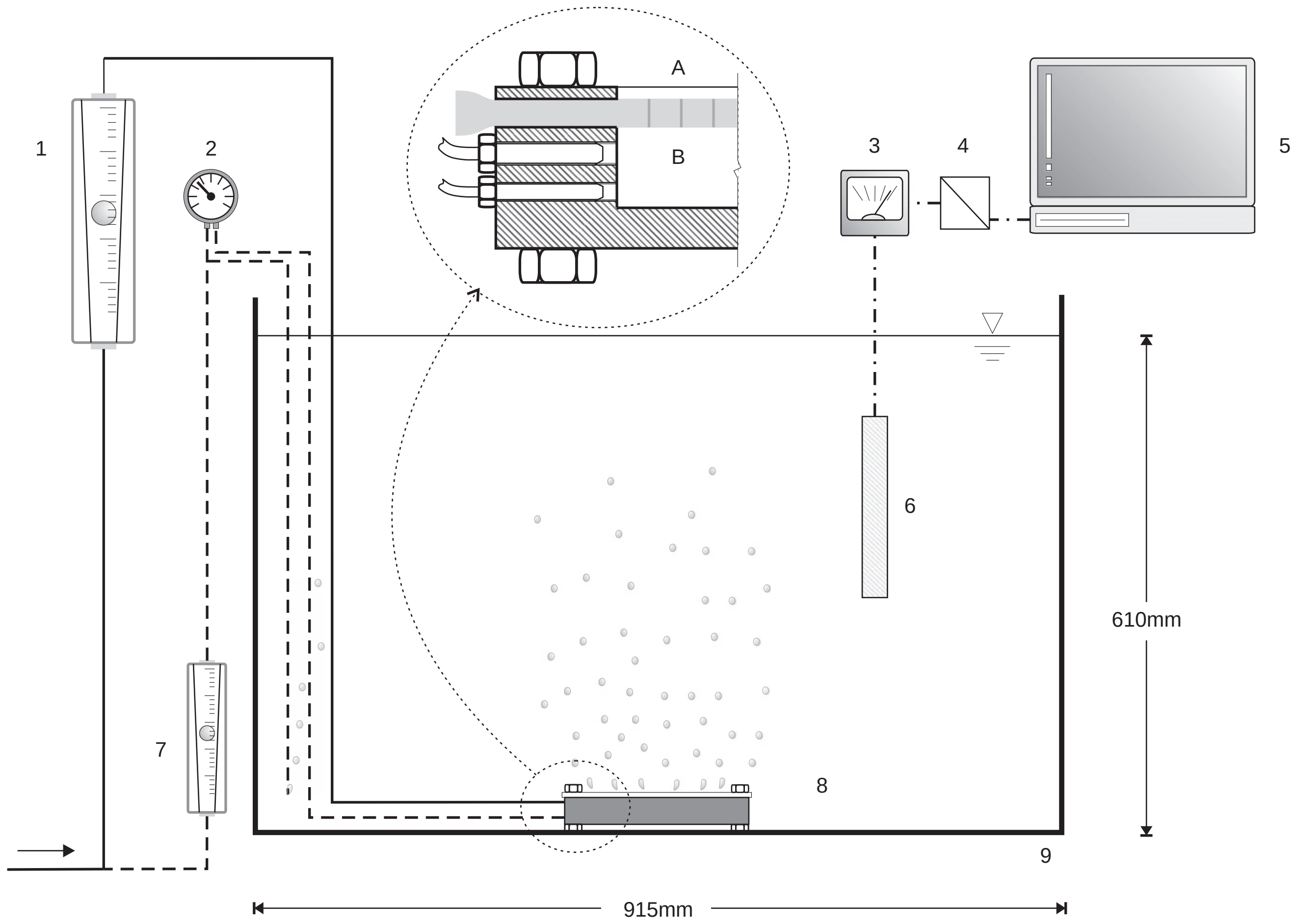

Fig. 1 – Aeration apparatus: (1) main rotameter; (2) pressure gauge; (3) computer for data logging; (4) D/A converter; (5) DO meter; (6) DO probe; (7) rotameter for DWP measurement; (8) aerator; (9) testing tank.

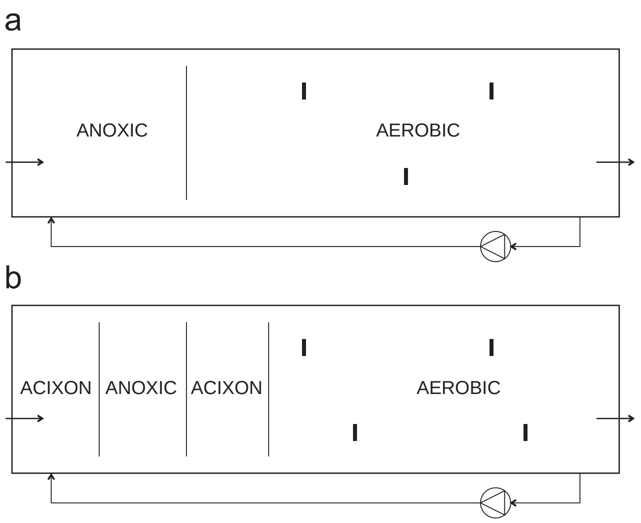

Fig. 2 – Wastewater treatment plant layouts for plants A and B. The marked points show the position of the harvested membrane diffusers.

tested together with a clean unused specimen. At the time of harvest, the used membranes had been less than 12 months in operation.

3.2. *Plant B*

The second plant (Fig. 2b) is a water reclamation plant located in Southern California. This facility is composed of six parallel aeration tanks, operated identically as a modified Ludzack-Ettinger nitrifying/denitrifying activated sludge process at mean cell retention time of approximately 20 d. The tanks have dimensions of approximately $55 \times 15 \times 6.5\,m^3$ ($L \times W \times D$), the first 23 m of each tank are divided into three anoxic zones in series, and the aerobic part of the tank is 32 m long.

Each tank was equipped with a combination of approximately 1000 new and old tube diffusers (bubbling area-$0.11\,m^2$). Some of the older diffusers had been rebuilt with new sheaths and some were still equipped with the original polyurethane membranes. The new sheaths were composed of ethylene–propylene-diene monomer (EPDM). The used diffusers were tested and had been removed from service during the previous maintenance cycle, which means that the EPDM sheaths were approximately 7–10 years in operation and the polyurethane membranes had been in service more than 10 years. Two diffusers (one for each membrane material) were harvested in each grid of a typical aeration tank. Two new, unused diffusers of each type, which had been

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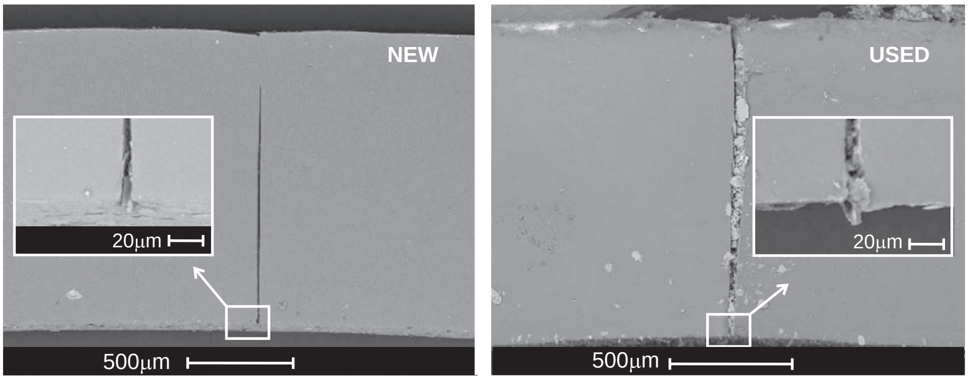

Fig. 3 – Microscopic photographs of silicon membrane sections harvested in plant A. The photograph on the left-hand side shows the section of a new membrane, and the enlarged detail shows no obstruction or deposit at the inner orifice boundary, other than the mica particles added by the membrane manufacturer for proper storage. The used membrane (photograph on the right) is characterised by deposits onto the outer and inner surfaces, and through the orifice.

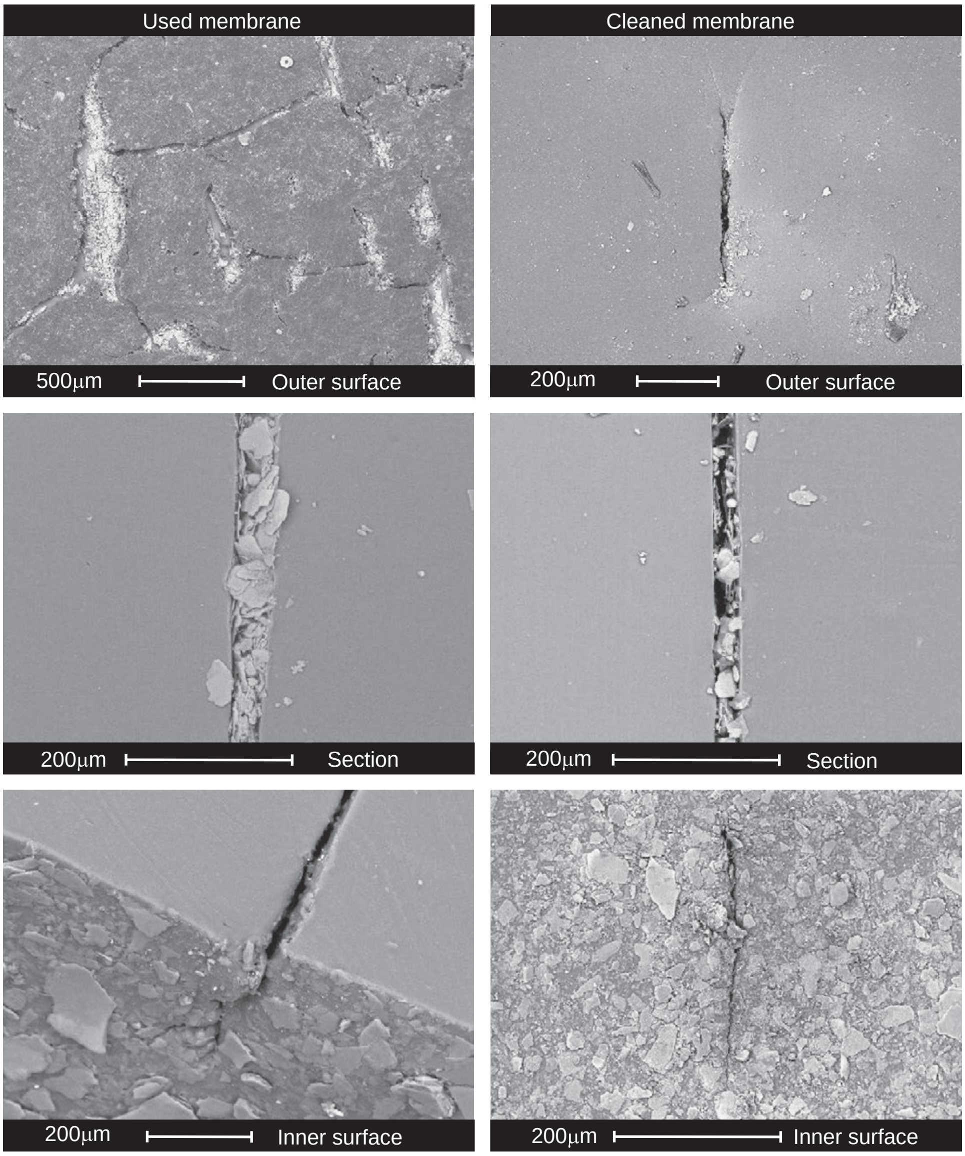

Fig. 4 – Comparison of used (photographs on the left) and cleaned (photographs on the right) silicon membranes (harvested in plant A). The outer membrane surface shows deposits of organic (dark) and inorganic (white) materials. Cleaning is effective in removing outer surface deposits and partially remove the deposits inside the orifice. The inner surface of both membranes show the inorganic mica scales used as adhesion prevention during manufacturing.

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in unrefrigerated storage since the original delivery, were also tested.

4. Results and discussion

4.1. *Microscopic observations*

Fig. 3 shows sections of new and used silicon membranes. EDX analyses were performed on the material in the pore channels, which was mainly mica [$K_2Al_6Si_6O_{20}(OH)_4$] for new membranes (used during manufacturing to prevent membrane adhesion), and mica residuals plus Fe, P, and Ca deposits for used membranes. The pore concentrations for used membranes are consistent with upper and inner surfaces, confirming that fouling/scaling can occur inside the diffuser. In fact, the details in Fig. 3 show that scales are present at the inner surface opening of the pore channel.

Fig. 4 shows a comparison of outer surface, section, and inner surface for used and cleaned (gentle water washing and brushing in the laboratory) silicone membrane diffusers. The upper surface of used membranes shows a composite of inorganic (white) and organic (grey) deposits. After surface scraping, the surface accumulation is reduced and pores are now visible (for the used diffusers, the pore is in the region where only inorganic scale is present). Inside the channel and on the inner surface there is no improvement after cleaning, due to the nature of the cleaning technique. After cleaning, the pore on the outer surface is dilated. The phenomenon of orifice creep is characteristic of every polymeric membrane we have observed after a period in operation, and it is due to polymer chain movements under stress. The energy necessary for polymer chain movement is supplied by the tensile stress applied to the membrane by air pressure. The points of accumulation of tensile stress correspond to the pore geometrical extremes, i.e. where the curvature is maximum.

The membrane thickness of the new and used silicone membranes ranged from 1.43 to 1.54 mm. We have also recorded new and used membrane thickness for EPDM, PVC, and polyurethane membranes, and differences between new and used membranes ranged from −6.5% to −14%, but there was no pattern with membrane performance. In our experience, membrane thickness is seldom useful as an indicator of membrane change. Other indicators such as DWP and even membrane ripping occur before a significant difference in membrane thickness can be detected.

Fig. 5 shows a silicon membrane section seen under reflective (left image) and polarised (right image) light.

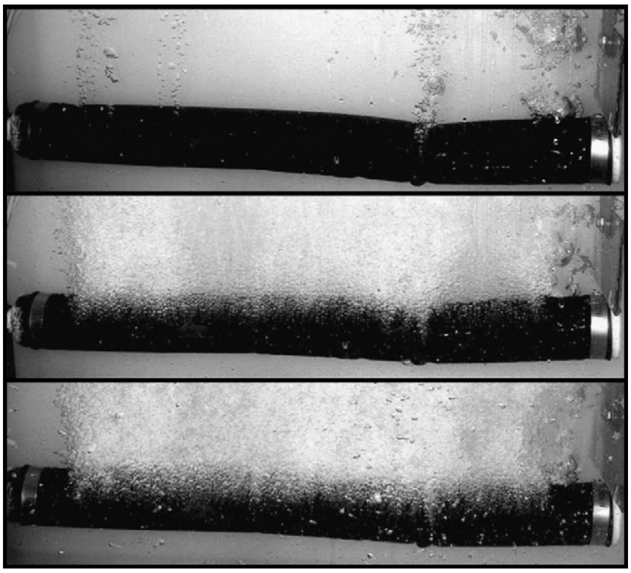

Fig. 6 – Used polyurethane membrane tube after cleaning (harvested in plant B). The airflow rates from the top are 1.70, 5.10, 8.50 Nm^3/h (1, 3, 5 Standard ft^3/min). For airflow rates below 5 Nm^3/h no pores release air, with the exception of some torn orifices that release coarse bubbles.

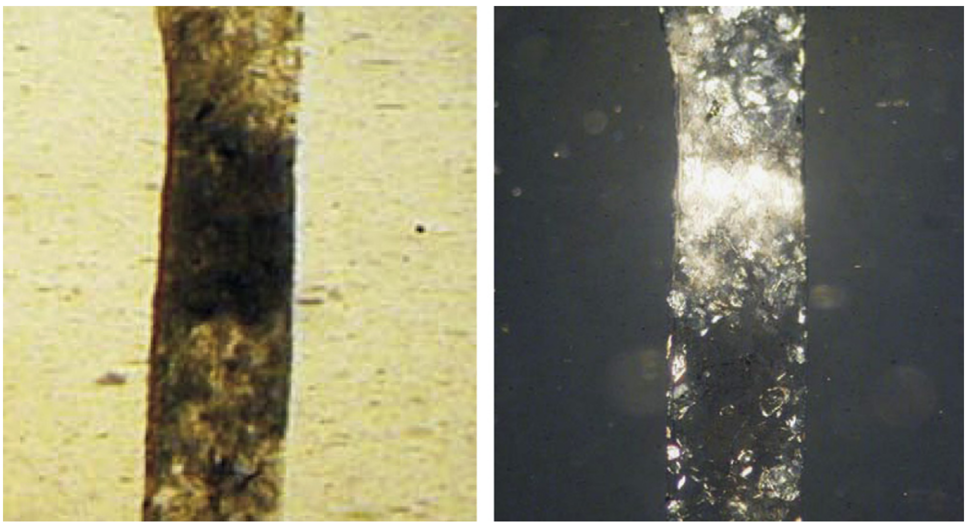

Fig. 5 – Silicon membrane section seen under reflective (left image) and polarised (right image) light. Polymeric substances (silicone) are not optically active, while crystalline formations (mica scales) interact with the polarised light and rotate the plane of polarisation (bright band in the right image).

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Polymeric substances (and amorphous substance, Fe-oxide, or humic substances) are not optically active, while crystalline formations (mica scales) interact with the polarised light and rotate the plane of polarisation. By viewing through a linear polariser, the image reveals bright and opaque zones, corresponding to crystalline and amorphous regions, respectively. The bright band in the middle of the pore canal (right image) suggests mica scales agglomeration.

4.2. *Diffuser performance*

Fig. 6 shows a used polyurethane membrane tube diffuser harvested from Plant B after cleaning. The airflow rates from the top are 1.70, 5.10, 8.50 Nm^3/h (1, 3, 5 Standard ft^3/min). For airflow rates below 5 Nm^3/h (3 SCFM), no pores release air, with the exception of torn or folded orifices that release coarse bubbles. There is a threshold at about 5.10 Nm^3/h where bubbles are released suddenly. This phenomenon is dependent on diffuser ageing, and is not characteristic of new membranes. The torn orifices are mainly located at the fold, which is a manufacturing characteristic of these diffusers. To compensate for membrane shrinkage during service, the polymeric membranes are typically longer than their mounting frame, and the excess length creates folds. With increasing flow rates, the membrane stretches and more bubbles are released along the entire length of the diffuser. Some coarse bubbles are still released at the far end of the diffuser, but their effect is mitigated by the large number of smaller bubbles.

A used EPDM membrane tube after cleaning is shown in Fig. 7. The airflow rate is 5.10 Nm^3/h (3 SCFM). The details show the typical bubble distribution pattern; the majority of bubbles are released in the proximity of the head of the diffuser (detail shown in "a"), with decreasing number of bubbles towards the far end of the diffuser (detail shown in "b"). The uneven distribution of bubbles is due to orifice fouling, which is overcome by air pressure in proximity of the air feed (left side of the photograph). The detail in "b" shows superficial fouling/scaling, which is composed of biological matter and inorganic precipitates. The uneven bubble distribution along the membrane tube confirms previous observations by Wagner and von Hoessle (2004).

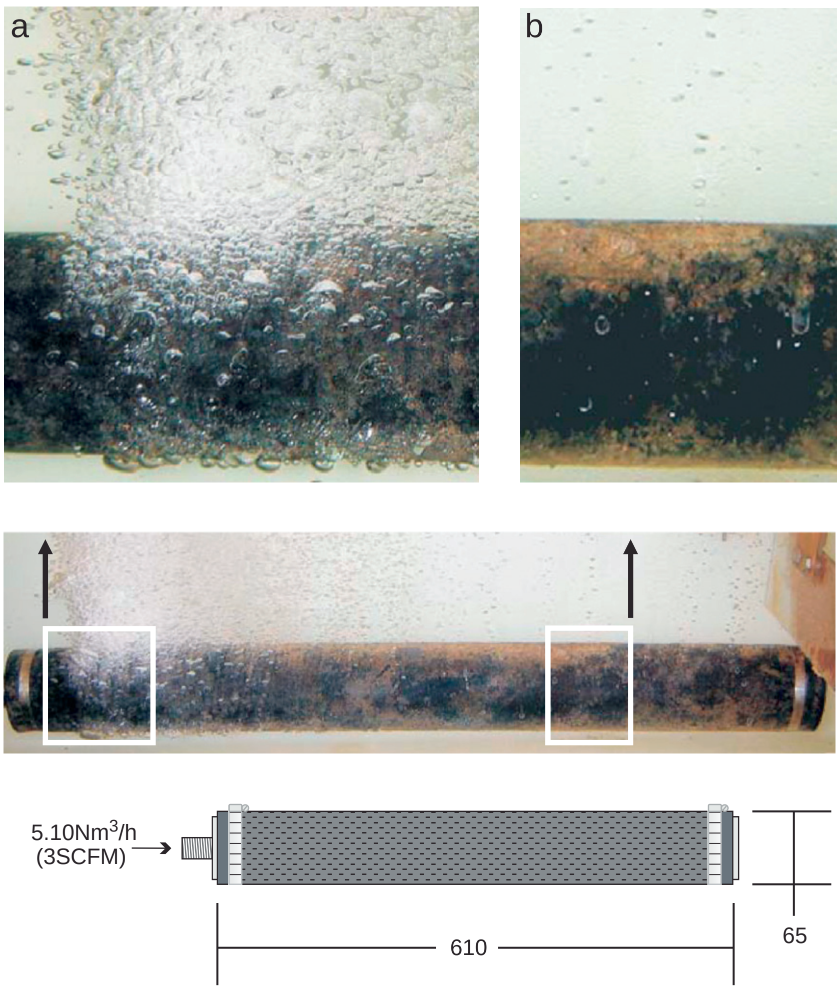

Fig. 7 – Used EPDM membrane tube after cleaning (harvested in plant B). The airflow rate is 5.10 Nm^3/h. The uneven distribution of bubbles is due to orifice fouling, which is overcome by air pressure in proximity of the air feed (left side of the diffuser).

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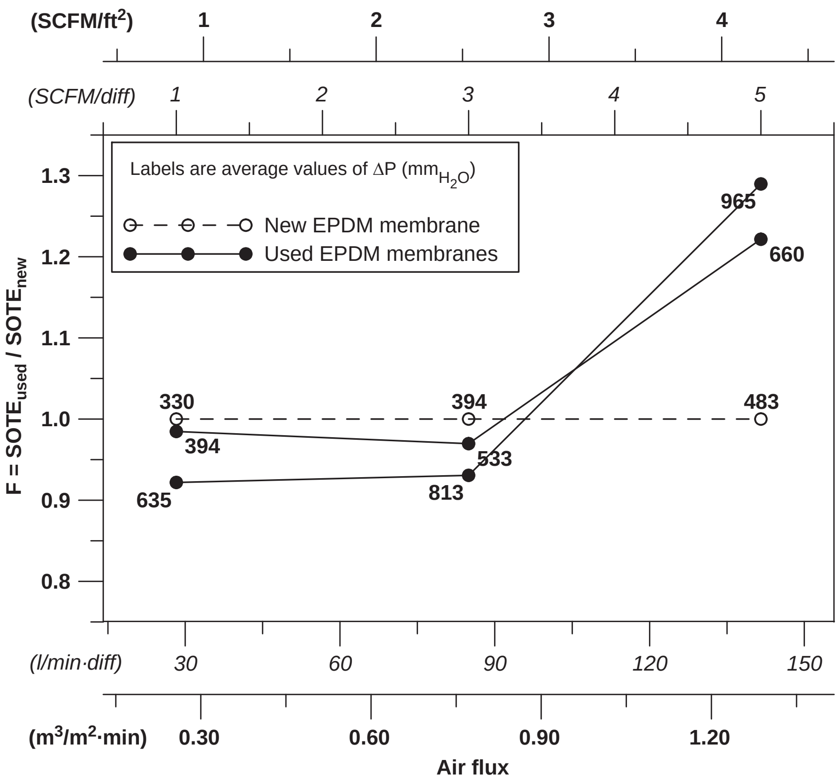

Fig. 8 – Ratio of standard oxygen transfer efficiency (SOTE) used for cleaned diffusers. The horizontal axis reports the unit airflow rate. Labels are average values of dynamic wet pressure (DWP) for each test. At low airflow rates new diffusers perform better than used diffusers, with the additional advantage of reduced DWP. At airflow rates above 100 l/min diff, used diffusers have specific efficiency about 20% higher than new diffusers, at the expense of DWP 100% higher. This is due to hardened orifices, which are unable to dilate and produce larger bubbles.

Fig. 8 shows the fouling ratio or fouling factor (see Eq. (2)) for used and cleaned diffusers. The diffusers selected for this graph were from plant B. The horizontal axes show the units for airflow rate per unit area and per diffuser. Labels are average values of DWP for each test. By definition, new diffusers have $F = 1.0$ at all flow rates. At low airflow rates new diffusers perform better than used diffusers, with the additional advantage of reduced DWP. At air flow rates above 100 l/min diff (~3 SCFM/diff), used diffusers can reach a specific efficiency about 20% higher than new diffusers, at the expense of 100% or higher increase in DWP. This is due to membrane hardening, which prevents the orifices from dilating, and they release smaller bubbles at the expense of severely increased pressure drop. The measurements of DWP and gas transfer rates in our laboratory are consistent with *in-situ* observations. The large difference between the two different specimens is due to their placement in the tank. The diffuser with the higher DWP was in the influent zone of the tank, and diffusers operating in influent zones usually experience greater rates of fouling and property change. At first this may seem to be an advantage, but in practice is not acceptable, since the blowers supplying the airflow cannot overcome the increased DWP, and would inevitably cause blower failure. In economic terms, the advantage offered by the increase in SOTE is largely offset by the cost of additional DWP, leading to a final result of increased operating cost associated with fouling, confirming results already reported and discussed elsewhere (Rosso and Stenstrom, 2006). Furthermore, the increase in DWP for diffusers in a large grid will not be uniform, and poor air distribution undoubtedly results.

DWP measurements for new and used polyurethane and EPDM membrane tubes at different airflow rates are plotted in Fig. 9. For each test, the airflow rate was increased and the value of DWP was recorded after a lag time. The airflow rate was increased from 1.70 to 8.50 and back to 1.70 Nm^3/h (1-5-1 Standard ft^3/min diff ~30-140-30 l/min diff). All membranes, at the end of each cycle, show a hysteric behaviour at 1.70 Nm^3/h (1 Standard ft^3/min diff ~30 l/min diff). This is due to the relaxation of polymers under stress, which results in orifice creep. After a long time in operation, this increased DWP becomes irreversible and larger orifices can be observed. Confirming expectations from previous studies on DWP (Frey and Thonhauser, 2004), used membranes have higher DWP than new membranes.

One important aspect of Fig. 9 is the reduced pressure drop of used polyurethane diffusers at 30 l/min diff (~1 Standard ft^3/min diff). This reduced pressure drop at the low flow rate results from a small but permanent enlargement of the orifices. It results from the extended period of operation with the diffuser being stretched. This small enlargement creates uneven flow distribution at low flow rates. Diffusers showing this type of wear often perform well at medium to high flow rates, but have poorer performance, relative to new diffusers,

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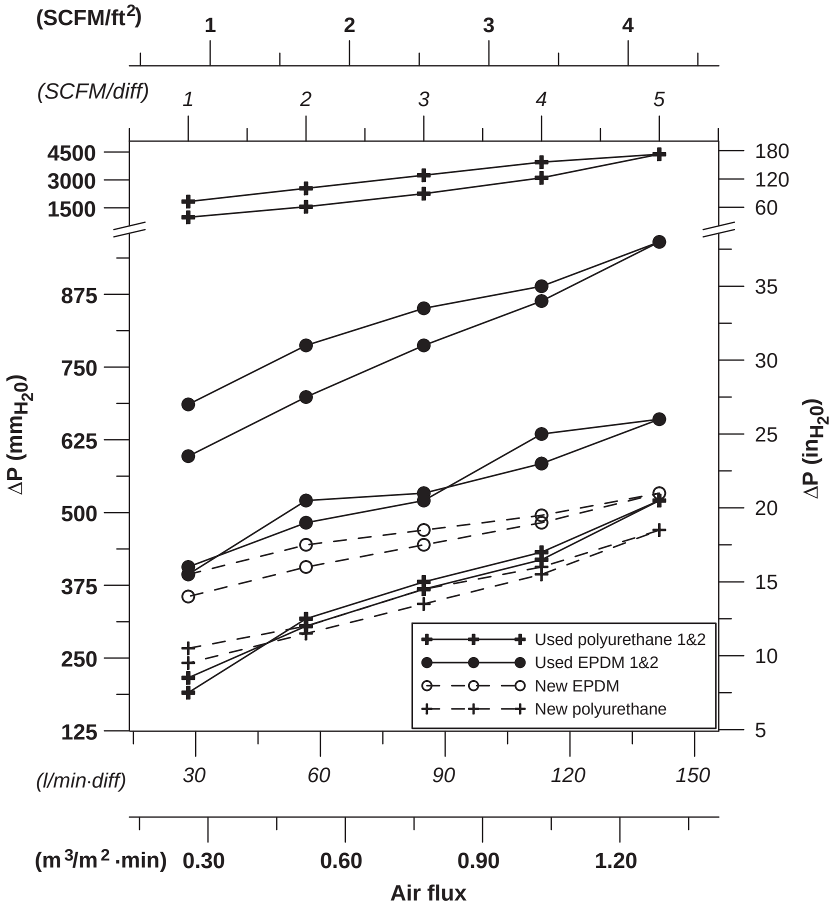

Fig. 9 – Dynamic wet pressure measurements for new and used polyurethane and EPDM membrane tubes at different airflow rates. For each test, the airflow rate was increased and the value of DWP was recorded after a lag time. The airflow rate was increased from 30 to 140 and back to 30 l/min diff (~1-5-1 Standard ft^3/min diff). There appears a hysteretic behaviour for all membranes at the end of each cycle at 30 l/min (~1 Standard ft^3/min). This is due to the relaxation of polymers under stress. After a long time in operation, this increased DWP becomes irreversible and larger orifices can be observed.

at low flow rates. This also causes problems in operability, because a minimum airflow rate threshold establishes with used diffusers, and below this threshold bubbles are released with same mean diameter independently of airflow rate. Bubble diameters range from 1 to 5 mm depending on specific airflow rate and diffuser condition (Stenstrom and Gilbert, 1981; McGinnis and Little, 2002; Rosso et al., 2005).

Any diffusers that remain indefinitely in service will undoubtedly have poor transfer rates, and may be operating at only 50% of their original efficiency with consequent decrease in process economics (Rosso and Stenstrom, 2006). For some diffusers, such as the used polyurethane 1&2 in Fig. 9, there may be diffusers that are completely blocked. These diffusers are typically very old and far beyond their expected life.

Extremely high DWP cases, as shown in Fig. 9, are usually associated with large changes in material properties, and may be associated with incompatibilities between the diffuser material and contaminants in the wastewater. In the specific case of one of the polyurethane membranes in Fig. 9, the membrane shrunk to approximately 90% of its original size, hardened severely, and had no bubbles released at a DWP corresponding to a realistic plant value. Methods to predict incompatibilities between diffusers materials and wastewater are generally not well developed and incompatibilities are often discovered only in full-scale operation. Methods to predict early diffuser failure are being studied in our laboratory (Kaliman et al., 2008).

We here define the pressure factor P as

$$P = \frac{DWP_{used}}{DWP_{new}}. \quad (3)$$

Since membranes are inexorably subject to fouling/scaling, for membrane diffusers DWP > 1.0. P represents the increased pressure burden to the blower unit due to diffuser ageing.

Fig. 10 shows the relative DWP increase P of the used silicon membranes, compared to the new ones. Silicon membranes show behaviour over time, which is consistent with other polymers reported in Fig. 9. This figure is useful for aeration energy requirement calculations, since for each specific location the increase in DWP can be a factor limiting the operability of blowers. In fact, most plants have blowers that can generate only limited discharge pressure before surging or overloading motors. The DWP required by fouled diffusers may be too high and some diffusers would release no air, resulting in uneven bubble distribution throughout the tank. In other facilities, blowers may be able to discharge the DWP

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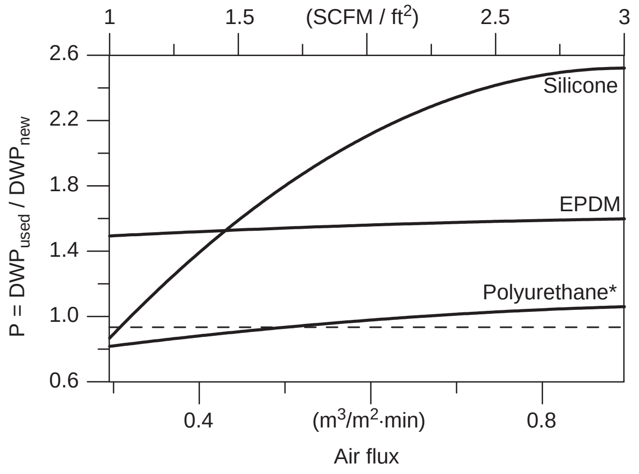

Fig. 10 – The pressure factor *P* (i.e., relative DWP increase between used and new membranes) for silicon membranes (harvested in plant A), EPDM, and PU membranes (harvested in plant B). For the relative ratio of PU membranes, only the membrane that did not undergo catastrophic shrunk was considered, since it was the only representative sample.

required by the fouled diffusers only when working outside their optimum efficiency region, hence resulting in increased power costs and possible damage to the blower.

Fig. 10 shows that *P* can be quite large for fouled diffusers. This has two implications. The first is for blowers, which must be able to accommodate higher DWP in anticipation of fouling. In our experience, blowers should be sized to accommodate a two-fold or larger increase in DWP. While this may seem onerous, it has an added benefit for *in-situ* diffuser maintenance. Some manufacturers recommend operating the diffusers briefly at higher airflow or "flexing." This flexing requires not only the additional air volume, but also the added pressure to overcome the fouled diffusers' increased DWP. The example of Fig. 10 shows that 2.2 times the initial DWP will be required to flex at 0.6 m^3/m^2 min, which is approximately twice the average operating air flux.

5. Conclusions

This paper describes and discusses the change in material properties for polymeric fine-pore diffusers, by comparing new and used membranes. The membranes analysed in this paper were composed of ethylene–propylene-diene monomer (EPDM), polyurethane, and silicon. All three types showed fouling and confirm the need for membrane cleaning. Plant designers and operators should anticipate the need for cleaning in the design of the treatment plant in order to facilitate cleaning and save energy (Rosso and Stenstrom, 2006). Additional experience with silicone diffusers is needed to thoroughly understand, compare, and select membrane material types.

Transfer efficiency is consistently lower with longer times in operation, as older, dilated orifices usually produce larger bubbles, which are unfavourable to mass transfer. At the same time, headloss increases with time in operation, since membranes usually increase in rigidity and hardness, and fouling and scaling phenomena occur at the orifice opening. Evidence here reported shows that the changes in polymer properties cause decreased oxygen transfer efficiency and our laboratory test results correlate these changes with the increase in DWP.

Air blowers should always be sized to accommodate the increase of DWP over time in operation, because of the inexorable fouling/scaling and ageing phenomena occurring with membrane diffusers. The quantification of this DWP increase can be achieved by defining a pressure factor *P*, which can be easily monitored over time *in situ*. Our experience suggests that blowers should be sized to accommodate a two-fold increase in DWP as the diffusers age. For diffusers with high initial DWP, this can be a severe restriction.

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