Full scale evaluation of diffuser ageing with clean water oxygen transfer tests

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ABSTRACT

Aeration is a crucial part of the biological wastewater treatment in activated sludge systems and the main energy user of WWTPs. Approximately 50 to 60% of the total energy consumption of a WWTP can be attributed to the aeration system. The performance of the aeration system, and in the case of fine bubble diffused aeration the diffuser performance, has a significant impact on the overall plant efficiency. This paper seeks to isolate the changes of the diffuser performance over time by eliminating all other influencing parameters like sludge retention time, surfactants and reactor layout. To achieve this, different diffusers have been installed and tested in parallel treatment trains in two WWTPs. The diffusers have been performance tested in clean water tests under new conditions and after one year of operation. A set of material property tests describing the diffuser membrane quality was also performed. The results showed a significant drop in the performance of the EPDM diffuser in the first year which resulted in similar oxygen transfer efficiency around 16 g/m^3/m for all tested systems. Even though the tested silicone diffusers did not show a drop in performance they had a low efficiency in the initial tests. The material properties indicate that the EPDM performance loss is partly due to the washout of additives.

Key words | aeration systems, diffuser ageing, membrane diffuser, oxygen transfer

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INTRODUCTION

For many years there has been a worldwide trend towards the use of fine bubble membrane diffusers which has mainly been driven by their higher efficiencies (Stenstrom *et al.* 1984). However, several practical tests show that surface aeration systems have a similar performance under operation, particularly for small waste water treatment plants (WWTPs) (Frey 2001; Bagg *et al.* 2009). There is a variety of different diffuser constructions and materials available. The objective of current diffuser developments has been the reduction of the pressure loss of the diffuser and thereby the reduction of the WWTPs energy consumption.

Lately, many operators of wastewater treatment plants reported problems relating to fine bubble membrane diffusers which can be mainly differentiated into long term diffusers ageing (Rosso & Stenstrom 2006; Rosso *et al.* 2008; Bagg *et al.* 2009) and short term diffuser clogging and fouling (Wagner 2001, 2004; Frey & Thonhauser 2004). While the diffuser clogging and fouling usually has a direct impact on the backpressure of the system, the diffuser ageing can also result in a loss of performance which is not always obvious. As a result, consultants and utilities have an ongoing uncertainty regarding the correct selection of diffusers.

The concept of the presented project was to install new diffusers on two municipal WWTPs with several parallel treatment trains and examine them whilst new and after one year of operation. This rarely happens as aeration systems are usually tested once in clean water or under operational conditions and never again. The aim of the study was to compare the performance and material properties of various diffuser materials. Along with the development of the pressure loss, the change in oxygen transfer efficiency was measured in clean water tests. This approach ensures that the results are not changing with changes in the wastewater composition over the period of the study which would have been the case if off gas tests were selected. This paper presents the results of the

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oxygen transfer tests and selected results for the material properties.

TEST METHODS

Oxygen transfer tests

The oxygen transfer efficiency measurements were carried out in clean water according to the specifications of DIN EN 12255 15 and the ATV advisory leaflet M 209E (1996). This method was chosen to measure solely the impact of the changing diffuser performance as outlined earlier. The reactors were drained and cleaned thoroughly for the purpose of the tests. The used diffusers were hosed down to remove sludge from the surface. Groundwater was used for the tests and examined for suitability in advance. Tests were conducted as absorption measurements. The DO concentration was lowered to approximately 0 mg/L by the addition of anhydrous, technical sodium sulphite. Starting from this low oxygen concentration in the reactor the aeration was turned on. The following increase of DO was recorded. The test was continued until the DO was constant for about 20 min.

Six DO electrodes with a fast response time were installed at two measurement points at different depths for each test. Each measurement was a double determination according to ATV (1996). Measurements and measuring points that differ by more than 10% of the mean were not considered for the evaluation.

Investigation of material properties

In addition to the oxygen transfer test, the material properties of the diffuser membranes and their changes were measured. The material analyses were carried out in cooperation with the IKP (Institute for Polymer Technology, University of Stuttgart, Germany). For each trial the mechanical properties of the diffuser membranes (hardness, tensile strength and elongation) were explored. Therefore stress strain behaviour and Shore A hardness tests were carried out. Similar tests were used by other groups (e.g. Frey 2006; Kaliman *et al*. 2008) to measure the ageing of diffuser membranes. The stress strain tests were conducted according to DIN 53504. For these tests the sample preparation is very important, since the results differ depending on the different directions of the perforation. The test only produces reproducible and meaningful results if the slits are arranged in parallel to the central part of the sample. Figure 1 (left side) shows the preparation of the samples for different diffuser types. A tension testing machine was used for the tests (Figure 1, middle and right side). The sample was concluded with a speed of 500 mm/min for tube diffusers and 200 mm/min for disc diffusers with a force of 2 Newton. The storage of samples and the tests were carried out under standard conditions according to DIN EN ISO 291-23/50-2. Of interest for future

Figure 1 | Material sampling method from disc (left top) and tube diffusers (left bottom) and implementation of the stress strain tests (middle and right).

considerations are the tensile strength and the ultimate elongation. Additionally Shore A hardness testing was performed at the IKP with the same samples. The tests were carried out in accordance with DIN 53505. This test was performed in a non-slit area of the diffuser membrane.

In addition, scanning electron microscopy (SEM) recordings with energy dispersive X-ray spectroscopy (EDX) were made of the inner surface of the slits. This method uses the SEM electron beam to stimulate the sample to emit characteristic X-rays which are then detected. This provides information about the basic chemical composition of the sample. This method was selected to examine potential material changes and scaling in the slits in more detail.

To evaluate the extent of the clogging and visualize any pollution of the slits, reflected light microscopy recordings were conducted at the ISWA. New and used diffusers were examined under the microscope and photos taken.

DESCRIPTION OF THE EXAMINED DIFFUSERS AND WWTPS

Tests at Heilbronn WWTP (Germany)

The sewage treatment plant Heilbronn has a design capacity of 500,000 PE. The average daily flow is 85,000 m^3/d. The mechanical treatment including primary sedimentation is followed by a biological phosphorus removal stage. Then the wastewater is equally distributed into four treatment trains, each of which is operated as Modified Ludzack Ettinger process with separate denitrification and nitrification in ditches. The total volume of the biological stage is approximately 112,000 m^3. At a water depth of 7.90 m, the volume per nitrification reactor is 8,240 m^3. The sewage treatment plant Heilbronn is equipped with disc diffusers. Under normal operation conditions the diffusers undergo a stretching or air-bumping programme during which they are loaded with maximum blower power and after that the whole pressure of the system is released.

For this investigation, three of the four nitrification basins were equipped with new diffusers (Table 1). The following materials were selected:

- Ethylene–Propylene–Diene Rubber (EPDM) disc diffuser as per original design (no information about the plasticiser content available).
- Plasticiser reduced EPDM disc diffuser (8% plasticiser content).
- High Density Polyethylene (HDPE) disc diffuser.

Table 1 | Installed diffusers at Heilbronn WWTP

	Plasticiser reduced EPDM disc diffuser	EPDM disc diffuser	HDPE disc diffuser
No. of diffusers	2,500	2,500	1,300
Diffuser density (%)	~10	~10	~6.5
Specific air flow at 100% blower capacity (m^3/h/disc)	~3.3	~3.3	~6.1

The EPDM membrane with reduced plasticiser content was selected as there were discussions about the loss of plasticiser being a major reason for EPDM membranes to experience accelerated ageing (Wagner 2003). It was possible to simply change the membrane in the existing diffuser body. Silicone membranes were not accepted by the operators and could therefore not be considered. The HDPE diffusers were selected as they have a reduced pressure loss compared to membrane diffusers, which has a positive effect on the energy consumption. They required a complete new installation on the reactor floor. However, at this stage the supplier did not install enough diffusers and as a result it was not possible to achieve the required oxygen transfer after the changeover in this tank. Therefore the HDPE diffusers have not been considered further.

Each setting was tested twice, under new conditions (after a sufficient pre aeration time) and after a year of regular operation. Only in the case of the plasticizer reduced EPDM disc diffuser the oxygen transfer efficiency test after one year of operation was interrupted by a partial shut-down of the blowers. The results of this evaluation were considered due to the plausibility checks of the data with the other trial (comparing the slope) until the incident. After a total of 2.5 years, the opportunity arose to test the tank with the conventional EPDM disc diffusers again. All tests were conducted as outlined before.

Tests at Stuttgart-Plieningen WWTP (Germany)

The wastewater treatment plant Plieningen has a design capacity of 133,000 PE. The basins for this investigation were two of four alternately operated reactors. Each reactor is divided into two equal chambers separated by a gate

Table 2 | Installed diffusers at Plieningen WWTP

	EPDM tube diffuser	Silicone tube diffuser
No. of diffusers	280	280
Diffuser density[a] (%)	~15.8	~15.8
Specific air flow at 100% blower capacity (m^3/m/h)	~9.0	~9.0

[a]Calculated with the whole circumference of the tube.

valve. The tests were carried out in one chamber. With a water level in the basin of 6.56 m, each reactor has a volume of 3,614 m^3 which equates to 1,807 m^3 per chamber.

Plieningen WWTP is equipped with tube diffusers and performs no regular cleaning of the diffusers. Shortly before the investigation, one reactor had been equipped with HDPE tube diffusers. Originally the experimental concept envisaged providing these diffusers for another reactor for the investigation. The HDPE diffusers were intended to be the link between both plants as the discs and tubes had the same diffuser material and the same internal EPDM non return valve. However, the HDPE diffusers had problems under the alternating operation, so the trial setup had to be changed. Ultimately, the following diffusers were examined (Table 2):

- EPDM tube diffusers (13% plasticiser content).
- Silicone tube diffusers.

No problems were encountered in the implementation of oxygen transfer tests, so that for each type of diffuser two measurements under new and used conditions are available.

RESULTS AND DISCUSSION

Comparative assessment of oxygen transfer tests

The results are compared based on the Specific Standard Oxygen Transfer Rate (SSOTR) in g/m^3/m. In the subsequent Table 3, the results for the individual materials in new condition and after approximately one year of operation are summarised. The table also shows the result for the test after 2.5 years at Heilbronn WWTP. To give a benchmark for the results of the new diffusers, the reference values of Wagner (2000) are stated as well. All tested EPDM diffusers achieved values which are in the range for favourable conditions. Alone the investigated silicone tube diffusers achieved average performance. It has to be highlighted that all diffusers were tested after a sufficient time of pre aeration. Looking at the results after a year of operation, a significant decrease of SSOTR is obvious for all EPDM diffusers. Only the silicone tube diffuser showed an increase in the oxygen transfer. Regardless of the installation situation and the diffuser type, all systems achieved almost the same specific standard oxygen after one year of operation, although each started with different results. No further reduction had occurred after 1.5 additional years of operation. This situation is illustrated graphically in Figure 2.

The results align with the findings of Rosso *et al.* (2008) who reported a change in α or αF in the same order of magnitude for new and used diffuser based on off-gas tests for similar plant configurations as tested here.

It has to be noted that the change of oxygen transfer efficiency was not indicated in an increasing pressure loss of the aeration system. This confirms a similar statement in the US EPA Design Manual 'fine pore aeration system' (US EPA 1989). It shows that the backpressure does not provide a good guide to oxygen transfer efficiency reductions. These are best tracked by noting increases in the specific blower power consumption (e.g. kWh/kg BOD_5).

As each test took place under comparable conditions (depth of submergence, air flow, clean water quality, etc.) changes of the oxygen transfer efficiency can only be contributed to the diffuser performance. For this reason, some of the diffusers were removed and compared with retained

Table 3 | Comparison of the results of the oxygen transfer tests

	Heilbronn WWTP		Plieningen WWTP	
	Plasticiser reduced EPDM disc	EPDM disc	EPDM tube	Silicone tube
SSOTR (g/m^3/m) new	22.5	19.4	20.1	14.4
SSOTR (g/m^3/m) used	16.9	16.3	14.4	16.0
Percentage change (%)	−25	−16	−28	+11
SSOTR (g/m^3/m) after 2.5 years		16.4		

Reference SSOTR values under clean water conditions (Wagner 2000)

SSOTR (g/m^3/m)	Mixing and aeration[a]	Area wide diffuser coverage[b]
Favourable	20.0	23.9
Average	15.0	17.9

[a]Situation at Heilbronn WWTP.
[b]situation at Plieningen WWTP.

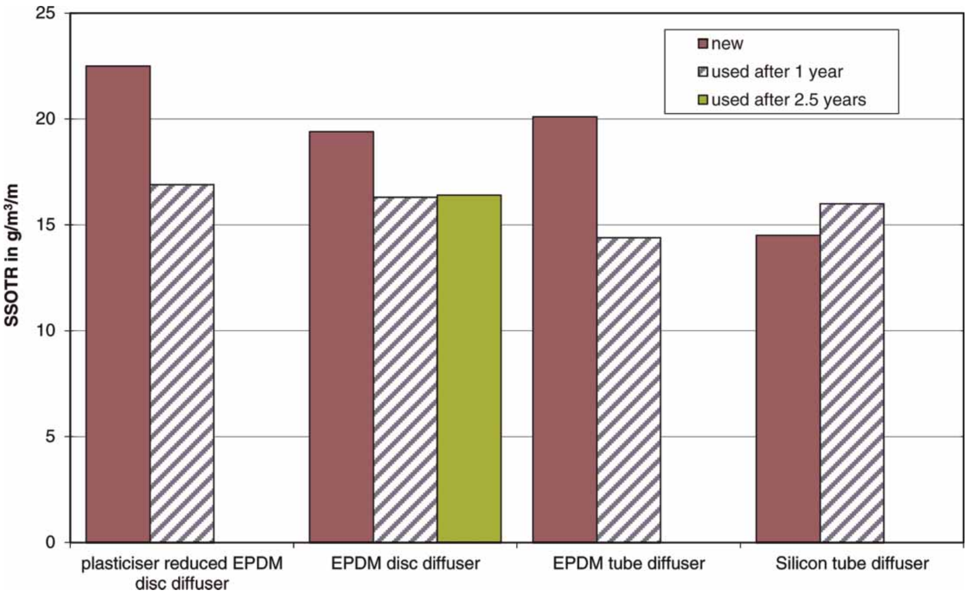


Figure 2 | Specific Standard Oxygen Transfer Rate for all tests in comparison.

samples of the new diffuser membranes. Periodic air-bumping did not appear to improve efficiencies and no efficiency loss differences could be determined between continuous or intermittently aerated systems.

Comparative evaluation of material properties

To assess the diffuser membranes, the tests outlined earlier were conducted. Table 4 shows the results of the stress strain tests and the Shore A hardness determination.

For all tested diffusers no significant differences in material behaviour and overall no signs of material deterioration were recognizable after one year of operation. However after 2.5 years of operation the EPDM disc diffuser showed slight cracks and the material deteriorated. This does not correlate with the oxygen transfer tests where the SSOTR dropped in the first year of operation but remained unchanged for the next 1.5 years of operation.

In Table 5 individual pictures from the reflected light microscopy of the various diffusers are presented. While the slits of the new diffusers had an even surface, there were strong differences in the blocking of the slits of the used diffusers. Particularly dirty slits were selected for the pictures. The blocking of the slits certainly represents one possible reason for the deterioration of the oxygen transfer efficiency. Similar experiences are for example reported by Frey & Thonhauser (2004). However, as the silicone diffuser also showed a similar blocking of the slits and at the same time increasing oxygen transfer efficiency, the blocking cannot be the sole cause for the deterioration.

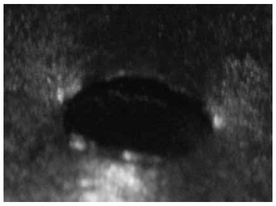
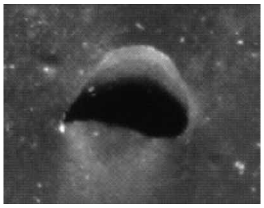
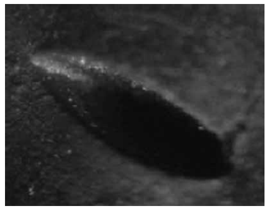
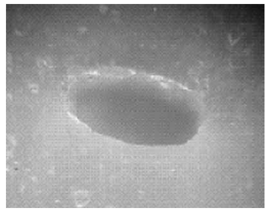
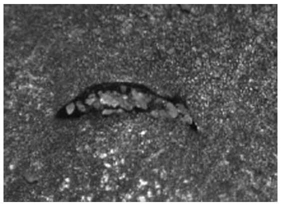
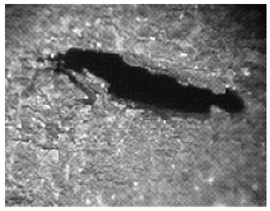
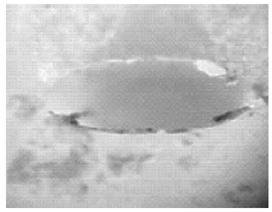
In addition to the reflected light microscopy, SEM micrographs of the slits were taken. Selected pictures of the new and used diffusers are compared in Table 6. The diffuser membranes were cut lengthwise in the level of a slit series. The enlarged images are from the wall of the slits.

Table 4 | Results of the stress strain and hardness tests as a mean of 10 samples

	Heilbronn WWTP				Plieningen WWTP			
	Plasticiser red. EPDM disc		EPDM disc		EPDM tube		Silicone tube	
	Spec[a]	New	Used	2.5 years	New	Used	New	Used
Tensile strength MPa	>8	7.9	7.3	3.7	10.3	11.0	10.9	10.6
Max elongation %	>400	424	410	268	747	747	673	665
Hardness (Shore A)	57 ± 5	52.3	54.0	–	51.0	52.7	55.7	56.0

[a]It wasn't possible to measure these parameters because the slits were radial and it was not possible to get representative samples.

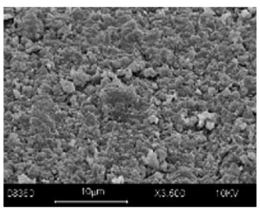
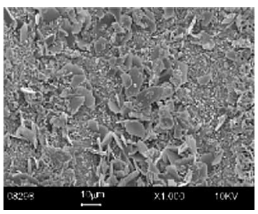
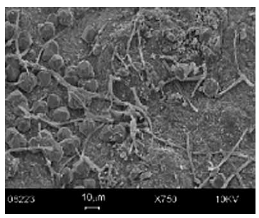
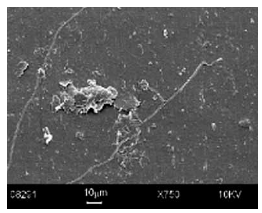
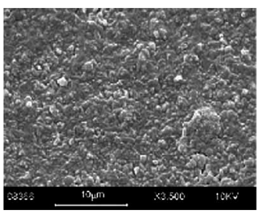
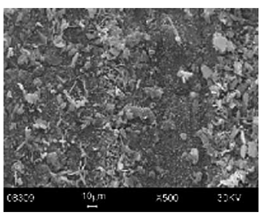
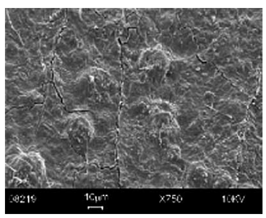
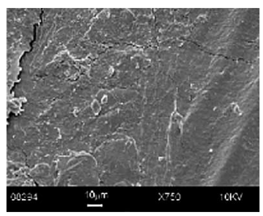
Table 5 | Reflected light microscopy photos

	Plasticiser reduced EPDM-disc diffuser	EPDM disc diffuser	EPDM tube diffuser	Silicone tube diffuser
New				
Used (1 year)				

The SEM micrographs show that the slits of the EPDM diffuser membranes are significantly rougher than the examined silicone membrane slits. In new conditions, the EPDM diffusers have different additives etc attached to the slits which cause very rough slits. After one year of operation, the sections of the slits have become significantly smoother. With the silicone diffuser a reverse tendency can be recognised. Here, the inside of the slit has become slightly rougher in the first year. This is expected to be another reason for the change of the oxygen transfer efficiency apart from the generally observed clogging of slits.

The EDX spectra indicate decreasing roughness of EPDM diffuser slits as a result of the attached additives being carried away during operation. Those additives (e.g. Sulphur, Calcium and Zinc) are used during the manufacturing of the membranes for example as an extraction agent during the extrusion. It can be assumed that the existence of the individual substances itself does not lead to deterioration of the oxygen transfer efficiency but the changes of the release behaviour of bubbles in the diffusers. According to Bruss (2006), the bubble size depends on the nature of the membrane surface in the exit region of the air. The more hydrophilic the membrane surface is around the slit, the faster the bubbles detach as the water can enclose the bubble better. This can be attributed to physical causes through the modified roughness or modified hydrophilic behaviour of the diffusers. For assessing the hydrophilic properties of the different membranes, contact angle

Table 6 | Comparison of the SEM micrographs

	Plasticiser reduced EPDM-disc diffuser	EPDM disc diffuser	EPDM tube diffuser	Silicone tube diffuser
New				
Used (1 year)				

measurements of diffusers were carried out. These were inconclusive due to sample conservation issues for this specific test. Therefore these results are not presented here but it is suggested to consider these contact angle measurements for further trials.

SUMMARY AND CONCLUSIONS

Firstly, the results reinforce that oxygen transfer tests under new conditions in clean water represent only a current snapshot of the system. In most cases, a significant decrease of the oxygen transfer has to be expected. In this test all tested membranes showed a similar SSOTR of around 16 $g/m^3/m$ after one year of operation and longer. The results indicate that changes in the material properties of the diffuser membrane are not the main influencing factor for the performance drop. The material properties only changed marginally after one year but more after 2.5 years. This does not correlate with the oxygen transfer tests where the SSOTR dropped in the first year of operation but remained unchanged for the next 1.5 years.

The changes in terms of the oxygen transfer efficiency in this study cannot be attributed to a single cause. The measurements strongly suggest that fast deterioration of the EPDM diffuser performance in the first year can be attributed to the release of additives from the EPDM membrane slits and the blocking of slits. The release of additives seems to cause changes in the diffuser membrane surface properties. This has an effect on the oxygen transfer efficiency via the change in the release behaviour of bubbles from the diffusers. The assessment of the hydrophilic properties of the different membranes with contact angle measurements was inconclusive due to sample conservation issues for this specific test but it is suggested to consider contact angle measurements for further trials as the hydrophilic behaviour has to be regarded as a key influencing factor.

Several other conclusions can be drawn from this study; in comparing both plants, periodic air-bumping did not appear to improve efficiencies. Significant efficiency losses could be determined for the continuous and intermittently aerated system apart from the silicon membrane. Also the plasticiser content of the EPDM membranes had no influence on the results in this study. Even though equipped with internal non return valves HDPE diffusers were not appropriate for intermittent operation.

It can also be concluded that the pressure loss of the diffusers is not a reliable criterion for assessing membrane diffusers in operation. This is because in two examined treatment plants, the oxygen transfer efficiency dropped significantly after a year of operation despite an almost constant pressure loss of the membranes. A sufficient key performance indicator for the aeration systems needs to consider the specific power consumption of the blowers (e.g. kWh/kg BOD_5) to pick up the changes in the oxygen transfer efficiency. For new aeration systems, higher oxygen transfer rates have to be demanded to ensure an adequate oxygen supply after several years of operation.

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