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910

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Three decades of oxygen transfer tests in clean water in a pilot scale test tank with fine-bubble diffusers and the resulting conclusions for WWTP operation

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Abstract

We summarized the experience from three decades of oxygen transfer testing and aeration research at the Technical University of Darmstadt to validate the oxygen transfer efficiency of modern fine-bubble diffusers. A total of 306 oxygen transfer tests in clean water of 65 different fine-bubble diffusers, carried out in the same test tank under identical test conditions, were analysed and compared with previous results. As a result, we could show that the performance of fine-bubble aeration systems has increased by 17% over the last three decades. Therefore, modern well-designed and operated aeration systems can achieve specific standard oxygen transfer efficiency (SSOTE) values between 8.5 and 9.8% $\cdot$ m^{-1}. Additionally, a comparison of various diffuser types and diffuser densities was done. Based on the new results, an exemplary cost/benefit analysis for a 100,000 PE WWTP shows the calculation of an optimized diffuser density with respect to investment and operating costs.

Key words: aeration system, dynamic cost comparison calculation, oxygen transfer efficiency

Highlights

- We summarized the experience from three decades of oxygen transfer testing and aeration research to validate the oxygen transfer efficiency of modern fine-bubble diffusers.
- We could show that the performance of fine-bubble aeration systems has increased by 17% over the last three decades. Therefore, we propose a new range of favourable SSOTE values between 8.5 and 9.8% $\cdot$ m^{-1}.
- We compared the performance of different diffuser types for the first time on a broad data basis and under identical test conditions.
- An exemplary cost/benefit analyses for a 100,000 PE WWTP shows the calculation of an optimized diffuser density with respect to investment and operating costs.

INTRODUCTION

Proper estimation of specific standard oxygen transfer efficiency (SSOTE; % $\cdot$ m^{-1}) is crucial for efficient aeration system design (Stephenson *et al.* 2010). For fine-bubble aeration systems typically mentioned, SSOTE values are between 5 and 7% $\cdot$ m^{-1} (Jolly *et al.* 2010; Rosso & Garrido-Baserba 2018). However, the last publications containing a comprehensive collection of oxygen transfer test results are now 30 years old (EPA 1989; Wagner 1992). However, some things have changed during this time, such as the materials used for diffuser membranes. Therefore, we summarize our experience of oxygen transfer tests in clean water from the last three decades to validate the oxygen transfer efficiency of modern fine-bubble diffusers. Results of 306 oxygen transfer tests with

65 different types of diffusers, determined in the same glass test tank and thus under identical test conditions, enable a representative comparison of the performance of various diffusers (types) from different manufacturers.

In addition, different factors influencing SSOTE were investigated. The relationship between SSOTE and specific properties of the aeration system and tank geometry is repeatedly tried to describe with (empirical) equations (EPA 1989; DeMoyer *et al.* 2001; Gillot *et al.* 2005; Schraa *et al.* 2017). To integrate the correlation of these parameters into simulation tools can improve current modelling capabilities of the entire wastewater treatment process (Nolasco *et al.* 2018). However, the equations are often delivered based on outdated data or based only on a few individual measurements. The progress made in material properties and manufacturing techniques of aeration devices over the past decades are not taken into account. Therefore, we used our broad database to validate existing approaches and investigated the influence from airflow rate, diffuser density and diffuser type on SSOTE. The consequences for the operation of a WWTP will be discussed on the basis of a conceptual WWTP design.

MATERIAL AND METHODS

Oxygen transfer tests

In total, 306 oxygen transfer tests of 65 different fine-bubble diffusers were analysed (13 plate diffusers from 7 different manufacturers, 29 tube diffusers from 8 different manufacturers, 23 disc diffusers from 10 different manufacturers). All tests were conducted in a fully glazed steel frame tank (L/W/H = 3.0 m/1.5 m/4.0 m) at a water level of 3.8 m. Diffuser submergence depth is on average 3.65 m and varies negligibly between the individual diffusers. The oxygen transfer was measured in clean water according to the ASCE/EWRI 2-06 standard (ASCE/EWRI 2-06) using the adsorption or desorption method. The airflow rate (Q_A) was normalized at standard (std) temperature and pressure conditions (0 °C; 101.3 kPa; 0% humidity). The results given as SSOTE and standard oxygen transfer rate per aerated tank volume ($SOTR_{VAT}$; $g \cdot m^{-3} \cdot h^{-1}$) are normalized to 20 °C water temperature, atmospheric pressure of 101.3 kPa and a salt concentration of 1,000 $mg \cdot L^{-1}$. For disc and plate diffusers, diffuser density is defined as the total projected media surface area of installed diffusers divided by the area of the tank floor (EPA 1989). For tube diffusers, diffuser density results from the ratio of the total membrane area ($= 2 \cdot \pi \cdot$ radius of tube diffuser $\cdot$ length of diffuser $\cdot$ number of installed diffusers) and area of the tank floor. By this definition, in the case of tube diffusers, it is possible to achieve a diffuser density of >100%, if the number of diffusers increases. Nevertheless, we have chosen this definition because it is very easy to use and thus ensures a better comparability of different diffusers and types, respectively. Other authors use the perforated area to calculate the diffuser density since the membranes of tube diffusers in particular are usually not completely perforated. Therefore, when comparing our results with other studies, attention must be paid to the method of calculating diffuser density.

RESULTS AND DISCUSSION

Oxygen transfer tests

To illustrate how much oxygen is transferred to the water in clean water conditions with fine bubble aeration systems in Figure 1(a), the $SOTR_{VAT}$ is plotted as the function of airflow rate per aerated tank volume ($Q_{A,VAT}$; std. $m^3 \cdot m^{-3} \cdot h^{-1}$). A linear trend line ($SOTR_{VAT} = 72.2 \cdot Q_{A,VAT} + 10.5$) was derived and plotted as a solid line. The coefficient of determination (R^2) of 0.93 indicates a good linear dependency. Already in the early 1990s, Wagner (1992) published an equation to calculate $SOTR_{VAT}$ as a

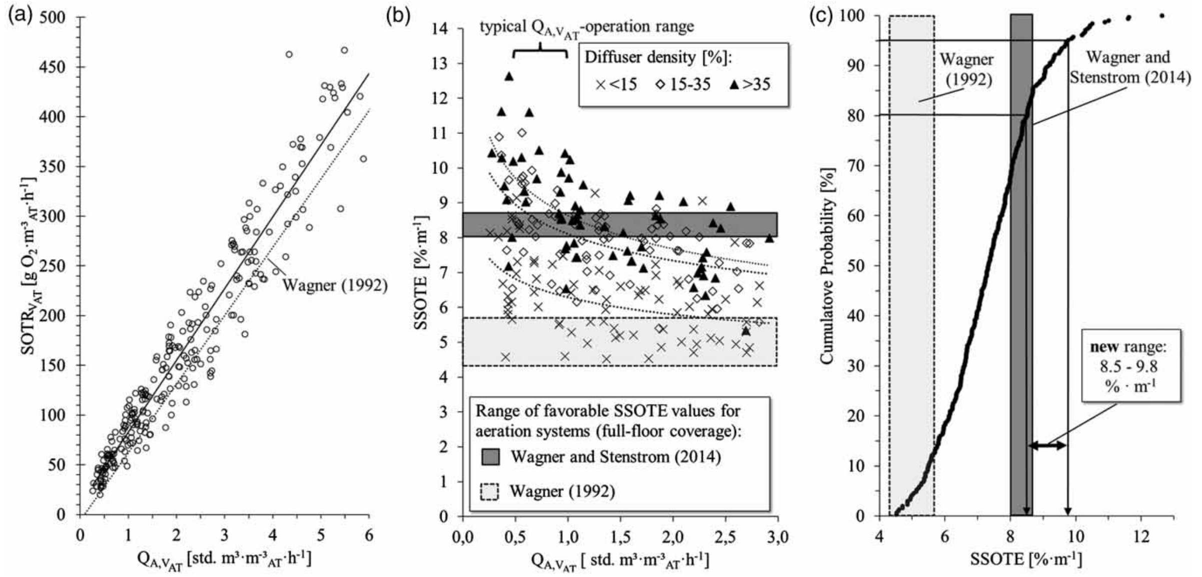

Figure 1 | Standard oxygen transfer rate per aerated tank volume as a function of airflow rate per aerated tank volume (a); SSOTE clustered according to diffuser densities as a function of standard airflow rate per aerated tank volume (b); cumulative probability of test results (c).

function of $Q_{A,VAT}$ (plotted as a dotted line). He carried out oxygen transfer tests with different types of diffusers in the same test tank as we used. This offers a unique opportunity to compare the performance of diffusers of today with those of 30 years ago. That the efficiency of fine-bubble diffusers increased tremendously within the last three decades is indicated by the fact that 80% of the experimental results are above the values calculated according to the equation from Wagner (1992). For WWTP operation, this means that today, with a $Q_{A,VAT}$ of 1.5 std. $m^3 \cdot m^{-3} \cdot h^{-1}$, a $SOTR_{VAT}$ of 120 g $\cdot$ $m^{-3} \cdot h^{-1}$ is achievable; enough, for example, to cover the typical oxygen demand on a German WWTP during peak loads. Previously, to achieve the same $SOTR_{VAT}$, a $Q_{A,VAT}$ of more than 1.8 std. $m^3 \cdot m^{-3} \cdot h^{-1}$ was necessary, which represents an improvement of 17%. However, not considered is the fact that we have performed more oxygen transfer tests at diffuser densities higher than 35% than Wagner (1992). A probable reason for this is that in the last 30 years, designers and manufacturers of aeration systems realized that this is a way to increase the oxygen transfer. Nevertheless, if we consider only the results with a diffuser density <35%, there is still an improvement of 9% in comparison to the results of Wagner (1992). The improvement may therefore be due to a combination of improved diffuser efficiency and increased diffuser density. For WWTP operation, the improvement means a reduction of the required blower capacity and thus lower investment and operational costs, provided that this increase also exists in activated sludge under process conditions. In addition, sufficient mixing in the aeration tank must still be ensured, which will be discussed later in the paper.

In Figure 1(b), all measured SSOTE values are plotted versus $Q_{A,VAT}$. The data are compared with two ranges of favourable SSOTE values for fine-bubble diffusers reported in literature (shown as frames). The results are clustered according to different diffuser densities. Figure 1(b) shows that SSOTE increases with increasing diffuser density and decreasing $Q_{A,VAT}$, which corresponds well to the results of Wagner & Pöpel (1998). SSOTE of more than 12% $\cdot$ m^{-1} were achieved with a high diffuser density and low airflow rate. However, only a minor improvement in SSOTE occurs if a diffuser density of 35% is achieved. According to Rosso *et al.* (2018), the maximum value for diffuser density in which SSOTE increase is minimal, and is determined by diffuser size, airflow rate and space between diffusers. Tests with disc diffusers of different diameters show a maximum diffuser density of 26% (Mueller *et al.* 2002), much lower than our results demonstrate. Nevertheless, the date shown also includes results of tube and plate diffusers. If the data are separated by diffuser type (see Figure 2), we can show that SSOTE increases for tube and for plate diffusers until diffuser density reaches 35%, as mentioned above. For disc diffusers, this maximum value of diffuser density is lower and therefore fits well with the test results reported in Mueller *et al.* (2002).

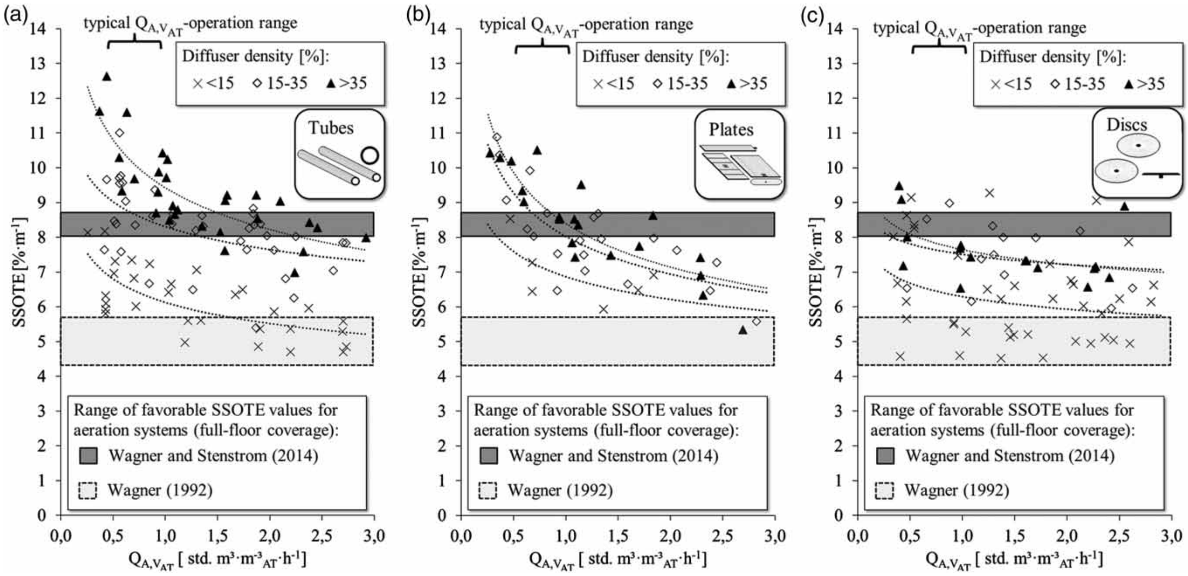

Figure 2 | SSOTE clustered according to diffuser densities as a function of std. airflow rate per aerated tank volume for tube diffusers (a); for plate diffusers (b) and for disc diffusers (c).

Almost all results are within or above the range of favourable SSOTE values reported in literature. As Figure 1(c) shows, 20% of all measured SSOTE values are higher than $8.5\% \cdot \mathrm{m}^{-1}$. Even 5% of all values are higher than $9.8\% \cdot \mathrm{m}^{-1}$. However, such high values can only be achieved with high diffuser density and low $Q_{A,VAT}$. Considering these circumstances, we propose a new range of favourable SSOTE values (see Table 1). This means that for modern, well-designed and operated aeration systems (uniform air discharge, good mixing) with typical diffuser densities (15–35%) and $Q_{A,VAT} < 1.5\,\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ for a water depth of 3.8 m, a SSOTE between 8.5 and $9.8\% \cdot \mathrm{m}^{-1}$ is achievable. Due to the decrease of SSOTE with increasing water depth, the values were converted for other water depths using the model represented in Mueller *et al.* (2002). Aeration tanks of municipal WWTPs typically have a water depth between 4 and 6 m (Rosso & Garrido-Baserba 2018). Therefore, as shown in the table below, SSOTE values of $7.8–8.9\% \cdot \mathrm{m}^{-1}$ can be achieved, depending on water depth. In 12 m deep tanks, common in industrial WWTPs, SSOTE between 6.2 and $6.7\% \cdot \mathrm{m}^{-1}$ is achievable.

Table 1 | Ranges of favourable SSOTE values

Fine-bubble aeration systems with full-floor coverage	**SSOTE [$\% \cdot \mathrm{m}^{-1}$]**
Wagner (1992)	4.3–5.7
Wagner & Stenstrom (2014)	8.0–8.7
New range of favourable SSOTE values ($d_W = 3.8$ m)[a]	8.5–9.8
Converted to other d_W according to Mueller *et al.* (2002):	
$d_W = 6.0$ m	7.8–8.9
$d_W = 8.0$ m	7.2–8.0
$d_W = 12.0$ m	6.2–6.7

[a] d_W, water depth [m]. Installation height of diffusers assumed with 0.15 m above tank bottom.

In Figure 2, a comparison of different diffuser types shows that SSOTE is lower for disc diffusers than for plate or tube diffusers in fully mixed tanks. At a typical $Q_{A,VAT}$ for WWTP operation of $1\ m^3 \cdot m^{-3} \cdot h^{-1}$, SSOTE of up to $10\% \cdot m^{-1}$ could be achieved with tube diffusers, while with disc diffusers SSOTE is significantly lower at nearly $9\% \cdot m^{-1}$. Wagner (1992) could already observe the same phenomenon and suspected the cause was the unfavourable bubble plume shape of disc diffusers, which typically looks like an hourglass (Hasanen *et al.* 2006). At the bottleneck, due to the high bubble density a high oxygen concentration and thus a poor oxygen transfer occurs (Wagner 1992). In addition, an increase of bubble coalescence occurs at this point, reducing the specific interfacial area (Hasanen *et al.* 2006; Behnisch *et al.* 2018). Nolasco *et al.* (2018) describe oxygen transfer tests in wastewater, in which the performance of tube diffusers was also better than of disc diffusers. Other references show that there is no difference in performance between disc and tube diffusers (EPA 1989; Mueller *et al.* 2002). However, all references point out that a comparison between different diffuser types is difficult because of the different calculation of the membrane area. Nevertheless, in our tests the highest SSOTE values were achieved with tube diffusers. Unfortunately, no particular reason can be found within the available data, although these results were collected over the last 30 years from a wide range of diffusers, material and manufacturers. Therefore, further investigations considering these influences are necessary.

In Figure 3, SSOTE is plotted as a function of the airflow rate per diffuser-membrane area ($Q_{A,Da}$; std. $m^3 \cdot m^{-2} \cdot h^{-1}$). According to DWA (2017) typical $Q_{A,Da}$-operational range for disc and plate diffusers is 35–150 $m^3 \cdot m^{-2} \cdot h^{-1}$ and 2–60 $m^3 \cdot m^{-2} \cdot h^{-1}$, respectively. This corresponds very well with our own results, as we always tried during the tests to cover the operational range of airflow rate as given by the manufacturer of the diffuser. For tube diffusers, the airflow rate is often related to the tube length, whereby our results show that tube diffusers operate at a similar $Q_{A,Da}$-range to plate diffusers. However, this only applies if the diffuser density is defined as in this work.

As shown in Figure 3, a clear influence of diffuser density on SSOTE is no longer visible. The reason for this is the dependence of $Q_{A,Da}$ and diffuser density. Low $Q_{A,Da}$ are usually obtained at high diffuser density and vice versa, as already introduced by Rosso *et al.* (2005). However, Figure 3 also shows that similar SSOTE are achieved with the same $Q_{A,Da}$ but with different diffuser density. Thus, the highest SSOTE values are not necessarily achieved at the highest diffuser density. Compared

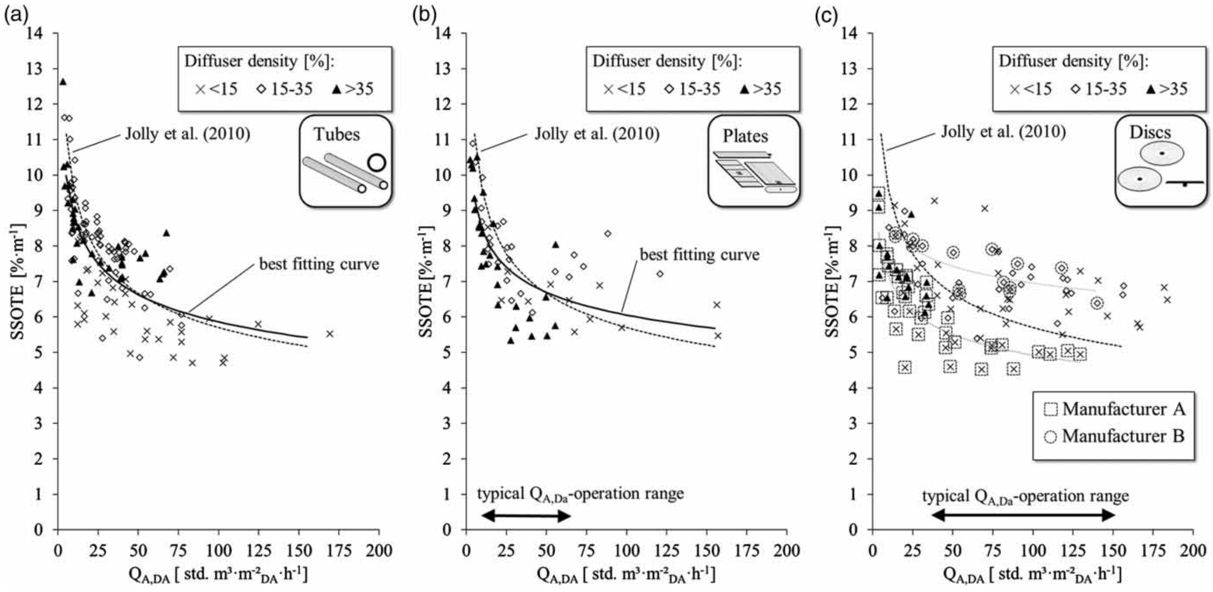

Figure 3 | $SSOTE_{1000}$ clustered according to diffuser densities vs. std. airflow rate per diffuser area for tube diffusers (a); for plate diffusers (b) and for disc diffusers (c).

to Figure 2, the results in Figure 3 show a better correlation, except for disc diffusers. Best fitting curves have been derived for tube diffusers (SSOTE $= 13.3 \cdot (Q_{A,Da})^{-0.178}$; $R^2 = 0.56$) and for plate diffusers (SSOTE $= 11.8 \cdot (Q_{A,Da})^{-0.145}$; $R^2 = 0.59$) and plotted as solid lines in Figure 3. The coefficients of determination (R^2) of 0.56 and 0.59 confirmed that there is a significant correlation between $Q_{A,Da}$ and SSOTE, as already shown by Jolly *et al.* (2010) and Rosso *et al.* (2005). According to Gillot & Héduit (2008), SSOTE can be described even better when using the surface air flow rate ($Q_{A,Aa}$; std. $m^{-3} \cdot m^{-2} \cdot h^{-1}$), which is defined as the air flow rate per total area covered by the grids of diffusers ($Q_{A,Aa} = Q_A \cdot (A_A)^{-1}$). In the tests we conducted, A_A is identical to the tank surface, because the diffusers were always evenly distributed in the tank and A_A can be easily calculated by dividing the tank volume (V; m^3) by the water depth (d_W; m). Due to the fact that V and d_W were always identical in our tests, it follows that $Q_{A,Aa} = Q_{A,VAT} \cdot (d_W)^{-1} = Q_{A,VAT} \cdot (3.8\ m)^{-1}$ and so nothing would change in the presented data and the conclusions of Figures 1(b) and 2, respectively. Therefore, to describe the variation of SSOTE, $Q_{A,Da}$ is more relevant than $Q_{A,VAT}$ or $Q_{A,Aa}$, respectively. The conclusion of Gillot & Héduit (2008) can therefore not be confirmed with our results. The reason for this could be the different arrangement of the diffusers in the tank. We always distributed the diffusers evenly throughout the entire tank, whereas in Gillot *et al.* (2005) it is to be seen that the diffusers were installed in a highly concentrated manner. However, this can only be concluded with further investigations, which consider the distribution of the diffusers.

For disc diffusers, a best fitting curve would have an R^2 of 0.15, which shows the missing correlation between $Q_{A,Da}$ and SSOTE for this diffuser type. A possible reason is the differences in properties of the membrane material and manufacturing techniques of the diffusers. Clustering the results according to the different manufacturers improve the correlation substantially for disc diffusers as well as for tube and plate diffusers, as exemplified in Figure 3(c). Nevertheless, although the number of different manufacturers of tested diffusers is similar for all diffuser types, it cannot be conclusively clarified why the dispersion of results is higher for disc diffusers than for tube or plate diffusers. This may also be due to the different $Q_{A,Da}$ operational range, which is much wider for disc diffusers than for the other two diffuser types. Further research is therefore necessary to answer this question.

We have compared our results for tube and plate diffusers from Figure 3 with those of Jolly *et al.* (2010). They developed a similar equation (SSOTE $= 16.0 \cdot (Q_{A,Da})^{-0,224}$; $R^2 = 0.83$) based on their own measurements in a test tank using different types of diffusers (shown as a dotted line in Figure 3). Relative deviation (s; %) between the equation from Jolly *et al.* (2010) and our own previously named equations was calculated. On average, the trend of SSOTE from our own measurements is well represented by the equation developed by Jolly *et al.* (2010). The best agreement is found with tube diffusers, showing the small average deviation of the functions of 3%. In the case of plate diffusers, the average deviation rises to 6%. At low $Q_{A,Da}$ s increases up to 18%. Nevertheless, the dispersion of the results, especially for disc diffusers, as well as the deviation from the results of Jolly *et al.* (2010) show that other factors than those considered in this paper have an influence on SSOTE. For example, the quality of the membrane material used and the manufacturing process, as well as the geometry of the diffusers. In models to predict SSOTE, these properties can only be represented with model parameters, which need to be determined individually for each diffuser and system configuration. Thus, testing of diffusers under various operational and installation conditions to validate the developed models are also inevitable in the future.

Cost comparison and conclusions for WWTP operation

The results of oxygen transfer tests and the resulting consequences for the operation of a WWTP are discussed on the basis of a conceptual 100,000 population equivalent (PE) WWTP for various diffuser installations with different diffuser densities (15%; 28%; 35%; 57%). The different variants (V1–V4) are compared based on their Net Present Costs (NPC, €), we calculated by Dynamic Cost Comparison

Calculation (DCCC) according to DWA (2011) for different scenarios (S1–S6). NPC are the present value of all the costs a project incurs over its lifetime. For the calculation, inflation as well as price increases in the future are taken into account. Thus, different scenarios; for example, for the design of aeration systems, can be compared from an economic point of view (Sander *et al.* 2016). The scenarios considered in this work differ in the assumed energy prices and life cycle of diffusers (t_d). We dimensioned the WWTP based on typical population-specific wastewater volumes and concentration of pollutants applicable in Germany (DWA 2019). The volume of the fictional activated sludge tank is 14,000 m^3 (7,000 m^3 aerobic). The plant is to be equipped with tube diffusers (membrane area = 0.5 m^2 per diffuser). For SSOTE and pressure drop of diffusers, we selected the results of oxygen transfer tests with tube diffusers with similar diffuser density as in the variants, and converted them, using the model represented in Mueller *et al.* 2002, to the assumed depth of the activated sludge tank (d_W = 6.0 m). To design the aeration system, we calculated the average oxygen demand ($SOTR_{av}$), the maximum oxygen demand ($SOTR_{max}$) and the minimum oxygen demand ($SOTR_{min}$). From respective SOTR values and SSOTE, the required airflow rates $Q_{A,av}$, $Q_{A,max}$ and $Q_{A,min}$ result. The annual energy consumption of the selected positive displacement blowers is calculated according to the formula given by Mueller *et al.* 2002 as a function of the blower inlet air flow rate (Q_1), overall efficiency (η) and the overall pressure drop (Δp). For Q_1, $Q_{A,av}$ was corrected to actual temperature (20 °C) and pressure conditions (101.3 kPa) and η is set at 0.62, as is usual for positive displacement blowers (DWA 2015). The hydrostatic pressure results from the diffuser depth of submergence (57.4 kPa). The pressure drop of diffusers depends on the specific air flow rate, what we could pick up from our test results with tube diffusers (here between 7.3 and 8.9 kPa). For the remaining pressure drops, a constant value of 3.0 kPa is assumed. In sum, this results in Δp. Based on $Q_{A,max}$ and $Q_{A,min}$, blowers were selected. Table 2 summarizes the initial data for DCCC for all four considered variants.

For the further discussion, some points have to be taken into account:

1. $SOTR_{VAT}$ ranges between 14 and 124 $g\cdot m^{-3}\cdot h^{-1}$ (respective to load case) are typical values for Germany (Krause *et al.* 2003). In other countries with other wastewater characteristics, different values may result, which affects the ratio of $Q_{A,max}$ to $Q_{A,min}$ and thus the required blower capacity and the operational range of the diffusers. A compilation of wastewater characteristics of different countries can be found in DWA (2019). In our calculation, the ratio $Q_{A,max} : Q_{A,min}$ is 10:1, which is the usual value in Germany (DWA 2017).
2. With increasing diffuser density, the required airflow rates decreases, which also means low airflow rates per diffuser and superficial gas velocity (SGV), respectively. Insufficient mixing can be the result. Commonly used design criteria provide an SGV of 2.2 $m\cdot h^{-1}$ for fine bubble aeration systems to ensure sufficient mixing, whereby such values do not take into account plant-specific conditions and only apply under worst case conditions (Pretorius *et al.* 2018). The low specific air flow rates also influence the lifetime of the diffusers (Rosso *et al.* 2018). What this implies for the WWTP operation will be discussed later.
3. SSOTE were selected from test results, but are very high in variant V3 and V4. As mentioned before, these high values are only achievable with very high diffuser densities and low airflow rates. For design practice, the above-proposed range of favourable SSOTE values applies. Furthermore, in practice it is sometimes not possible to achieve such high diffuser densities because space between diffusers for maintenance must be provided, or structural elements limit the number of diffusers to be installed. Additionally, the diffuser density is limited by the acceptable $Q_{A,Da}$ operational range specified by the manufacturer.

To calculate NPCs, we applied a discount factor of 3% and an electricity inflation factor of 2% (DWA 2011). Only cost types that are significantly affected by the change in the number of diffusers are taken into account: investment and replacement costs for the diffusers, the costs for blowers and

Table 2 | Initial data for DCCC for all four considered variants

		V1 (DD = 15%)			**V2 (DD = 28%)**			**V3 (DD = 35%)**			**V4 (DD = 57%)**		
n	**[-]**	**350**			**650**			**810**			**1,320**		
		Average	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**
SOTR	$[kg \cdot h^{-1}]$	330	870	100	330	870	100	330	870	100	330	870	100
$SOTR_{VAT}$	$[g \cdot m^3_{AT} \cdot h^{-1}]$	47	124	14	47	124	14	47	124	14	47	124	14
$SSOTE^a$	[%/m]	7.3	6.3	7.8	9.0	8.4	9.4	10.0	8.9	10.5	11.0	9.8	11.4
Q_A	$[std.\ m^3 \cdot h^{-1}]$	2,600	7,900	760	2,100	5,900	630	1,900	5,600	570	1,700	5,100	520
$Q_{A,DA}$	$[std.\ m^3 \cdot m^{-2} \cdot h^{-1}]$	15	45	4	6	18	2	5	14	1	3	8	1
SGV	$[m \cdot h^{-1}]$	2.2	6.8	0.7	1.8	5.1	0.5	1.6	4.8	0.5	1.5	4.4	0.4
Δp	[kPa]	69.3	70.3	65.0	68.2	66.7	64.6	68.0	66.2	64.6	67.7	65.4	64.5
Q_1	$[m^3 \cdot h^{-1}]$	2,900			2,400			2,100			1,900		
E^b	$[MWh \cdot a^{-1}]$	787	–	–	631	–	–	566	–	–	512	–	–
SAE	$[kg \cdot kWh^{-1}]$	3.7	–	–	4.6	–	–	5.1	–	–	5.6	–	–

Number of diffusers (n); Diffuser Density (DD); Standard Oxygen Transfer Rate (SOTR); Specific Standard Oxygen Transfer Rate per aerated tank volume ($SOTR_{VAT}$); Specific Standard Oxygen Transfer Efficiency (SSOTE); standard airflow rate (Q_A); airflow rate per diffuser-membrane area ($Q_{A,Da}$); annual energy demand (E); Standard aeration efficiency (SAE); blower inlet air flow rate at actual temperature (20 °C) and pressure (101.3 kPa) conditions (Q_1); pressure drop including hydrostatic pressure drop and the pressure drop of the diffusers (Δp); superficial gas velocity (SGV).

[a] taken from clean water tests with tube diffusers with similar diffuser density (DD) converted to 6 m depth of submergence.

[b] $= (Q_1 \cdot \Delta p)/\eta \cdot t_a$; with $\eta = 0{,}62$ (-) for positive displacement blowers according to DWA (2015) and $t_a = 8{,}760\ h \cdot a^{-1}$.

for energy consumption. The observation period was set at 15 a, which represents a common period of use of blowers. According to the current price range of a diffuser manufacturer, typical investment cost of 80 € per tube diffuser was selected. The costs for the blowers were requested from a blower manufacturer depending on $Q_{A,max}$ of the individual variants. Due to the different $Q_{A,max}$, V1 has the highest (54 k€) and V4 the lowest costs for blowers. V2 and V3 have identical costs for the blowers (38 k€) due to a similar $Q_{A,max}$.

Figure 4 shows that the share of energy costs varies between 94 and 58% of NPC depending on the scenario. The investment and replacement costs for diffusers increase with increasing diffuser density and account for 3%–37% of NPC. Investment costs for blowers decreases with increasing diffuser density due to lower required airflow rates and has a 3%–7% share of NPC. Due to the high share of energy costs, the energy price has a great influence on the economic efficiency of the individual variants. This becomes clear when the first three scenarios are considered. In S1, the NPC decreases with increasing diffuser density, which leads to the result that V4 has the lowest NPC (1,295 k€). In this case, due to the improved SSOTE, the additional costs for diffusers are compensated by the reduced energy and investment costs for blowers. However, if the energy price falls, this compensation no longer takes place (S2) and NPC of V3 (941 k€) are similar to V4 (939 k€). The difference of V2 (657 k€) and V4 (654 k€) to V3 (626 k€) increases if the energy price falls to 0.06 € · kWh^{-1} (S3) further (3 k€ resp. 31 k€).

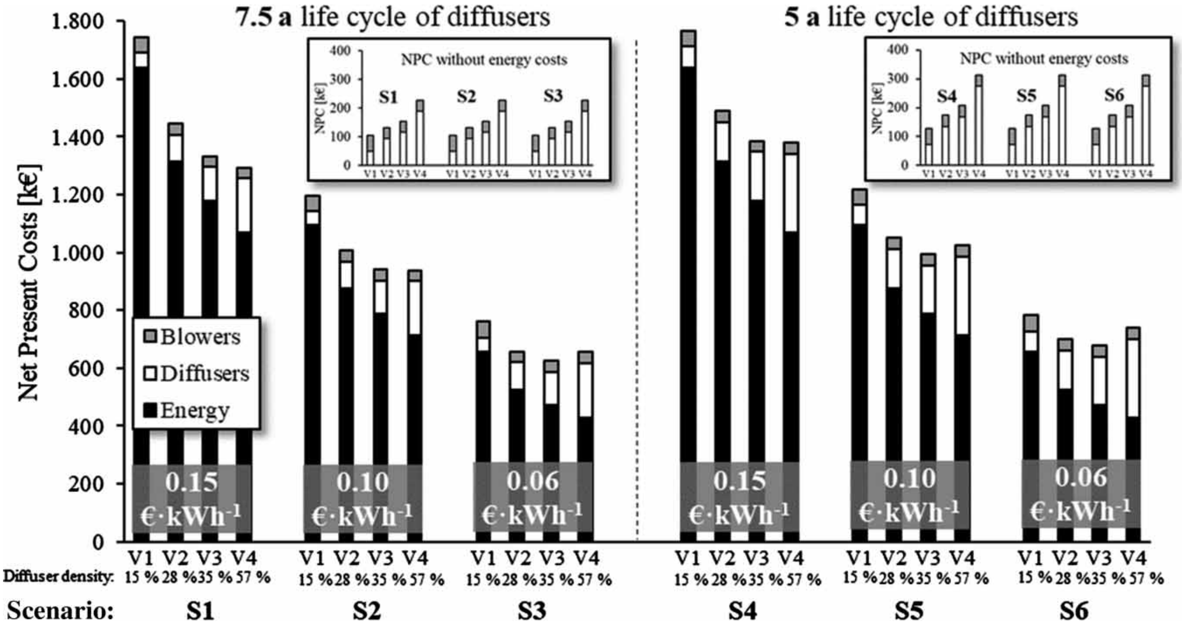

Figure 4 | Net Present Costs (NPC) in k€ (1 k€ = 1,000 €) for different scenarios (different energy prices and life cycles of diffusers) for all four variants and considered cost types; separately highlighted NPC for all scenarios without energy costs.

Due to the high diffuser density, the specific airflow rate is very low, especially in the case of V3 and V4 (see Table 2). This results in an increased risk of fouling and diffuser efficiency loss over time. To restore the efficiency of diffusers, more frequent cleaning or replacement of diffusers is necessary (Rosso *et al.* 2018). To take this into account in the used cost model, the life cycles of diffusers are reduced in scenarios S4, S5 and S6 from 7.5 a (corresponds to the average life cycle of diffusers) to 5 a. Thus, the costs for diffusers increases compared with S1–S3. The result is that V3 has the lowest NPC in scenarios S5 and S6. Only if the energy price is very high (S4), V4 has the lowest NPC. However, the absolute difference of 6 k€ is quite low. In this case, we recommend a more detailed analysis.

CONCLUSION

- A comparison of results of oxygen transfer tests in clean water shows that the performance of fine-bubble aeration systems has increased by 17% over the last three decades. Therefore, we propose a new range of favourable SSOTE values, which can be used, for example, for first design calculation of new aeration systems, to assess the performance of diffusers in clean water or to model the activated sludge process accordingly. However, with the available data we cannot show whether this efficiency increase also exists in activated sludge.
- A comparison of different diffuser types shows that SSOTE is lower for disc diffusers than for plate or tube diffusers in fully mixed tanks. The highest SSOTE values were achieved with tube diffusers.
- When diffuser density increases, so does SSOTE. The maximum diffuser density (in which SSOTE increase is minimal) is higher for tube and plate diffusers than for disc diffusers.
- In literature, the air flow is often expressed per diffuser element. Our results show that there is a significant correlation between $Q_{A,Da}$ and SSOTE: the lower $Q_{A,Da}$, the higher is SSOTE. Therefore, when comparing diffusers, it is better to relate the airflow per membrane area. This requires a distinct definition of the calculation of membrane area and diffuser density, which this study proposes depending on the type of diffuser. Accordingly, the typical $Q_{A,Da}$-operation range for tube diffusers is between 2 and 60 $m^3 \cdot m^{-2} \cdot h^{-1}$ and thus is similar to that of plate diffusers. Typical $Q_{A,Da}$-operational range for disc diffusers is between 25 and 150 $m^3 \cdot m^{-2} \cdot h^{-1}$.
- An exemplary cost/benefit analysis carried out for different diffuser densities (15, 28, 35 and 57%) for a 100,000 PE WWTP shows that a high diffuser density does not automatically imply optimised WWTP operation. The result of the analysis is mainly influenced by the cost per diffuser, the energy costs and the life cycle of the diffusers. The rule of thumb is that the higher the energy price and the lower the life cycle of the diffusers, the higher the diffuser density should be. Therefore, when building an aeration system, an individual cost/benefit analysis is required to achieve an optimised WWTP-operation, whereby our calculation can be used as a template.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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