

Towards more accurate design and specification of aeration systems using on-site column testing

Diego Rosso, Lu-Man Jiang, David M. Hayden, Paul Pitt,
Charles S. Hocking, Sudhir Murthy and Michael K. Stenstrom

ABSTRACT

Fine-pore diffuser systems are selected for their potential energy efficiency, and during design their propensity for fouling and for an increase in pressure drop with time must be considered. Both fouling and pressure-drop increase cause an increase in blower power requirements. This paper presents a new approach to improve this design procedure, without altering the technical structure of the classical approach. While the administrative and bidding milestones are being carried out (i.e., in the first 6 months of the project milestones), an independent aeration team can test candidate diffusers suitable for design in an aeration column *in situ*. An extended fouling test in the plant's aeration tanks allows the collection of site-specific aeration performance data. These improve the accuracy of the design process, and limit the reliance on safety factors.

Key words | activated sludge, aeration, design, energy footprint, fouling, oxygen transfer efficiency

Diego Rosso (corresponding author)

Lu-Man Jiang

Department of Civil and Environmental
Engineering,
University of California, Irvine, CA 92697-2175,
USA
E-mail: bidui@uci.edu

David M. Hayden

Irvine Ranch Water District,
3512 Michelson Drive, Irvine, CA 92612-1799,
USA

Paul Pitt

Charles S. Hocking
Hazen and Sawyer, P.C.,
498 7th Avenue, New York, NY 10018,
USA

Sudhir Murthy

DC Water, 5000 Overlook Avenue, SW,
Washington, DC, 20032,
USA

Michael K. Stenstrom

Department of Civil and Environmental
Engineering, University of California,
Los Angeles, CA 90095-1593,
USA

INTRODUCTION

Fine-pore diffusers are now the most commonly used aeration system in wastewater treatment in the USA and Europe. They have higher efficiencies on the basis of energy consumption (IWA 2008). Even though more than 50 years have passed since studies on the effects of contaminants on oxygen transfer began (Eckenfelder *et al.* 1955), we are still unable to predict oxygen transfer efficiency (OTE) parameters accurately. In the majority of large municipal wastewater treatment plants (WWTPs) in the developed world, fine-pore diffusers are presently installed and operated, due to their higher aeration efficiency (i.e., mass of O₂ transferred per unit energy spent) when compared with other aeration technologies (IWA 2008). Ceramic discs and elastomeric membranes composed of EPDM (ethylene-propylene-diene monomer) or polyurethane (PU) are currently the most commonly used materials, although other polymers such as Teflon-coated molds and silicone are in use in numerous installations. Fine-pore diffusers shear the air flow into

small bubbles ($d < 5$ mm) at the moment of release, and to do so they have to create a pressure drop to the air flow, usually referred to as dynamic wet pressure (DWP). DWP is another key design parameter, especially when the aeration system pressure may be limiting. This is the typical case of upgrading an aeration system from coarse- to fine-bubble diffusers while maintaining the old blowers, initially specified for an aeration system characterized by very low DWP (and lower α SOTE (see next paragraph), typically the driving force for the upgrade to more energy-efficient diffusers).

In order to standardize aeration systems testing, the research and practice community developed a fine-pore diffuser manual (US EPA 1989), clean-water oxygen transfer standards (ATV 1996; prEN 1999; ASCE 2006) and guidelines for process-water testing (ATV 1996; ASCE 1997). The OTE (percent of oxygen transferred to the wastewater) measured with the off-gas method (Redmon *et al.* 1983) is

the ratio of oxygen transferred to oxygen fed to the aeration tank. OTE is normalized to standard conditions (20°C , $0\text{ mg}_{\text{DO}}\text{ l}^{-1}$, 1 atm, no salinity) to obtain a standard OTE, or SOTE (%). In order to quantify the deviations from clean-water conditions, process-water mass transfer rates are scaled by an α factor (ratio of the mass transfer coefficient of process water to clean water; [Stenstrom & Gilbert 1981](#)). The product of α and SOTE gives the field OTE at standard conditions, or αSOTE (%). To compensate for the effects of diffuser submergence, SOTE and αSOTE per unit depth (%/m) can be defined (often called SOTE/Z and $\alpha\text{SOTE}/Z$ in the USA or SSOTE and αSSOTE in Europe).

Fouling is inevitable and inexorable for all types of fine-pore diffusers, and is dependent on process parameters such as the mean cell retention time or MCRT, water quality, diffuser type, and time in operation but generally independent of diffuser make and model ([US EPA 1989](#); [Rosso & Stenstrom 2006](#); [Rosso *et al.* 2008b](#)). Due to fouling, αSOTE and DWP vary inevitably, with DWP increasing and SOTE decreasing over time ([Rosso & Stenstrom 2006](#)). To account for the effects of fouling, a fouling factor F is introduced ([US EPA 1989](#)), and its time-dependence ([IWA 2008](#)) was described previously ([Rosso *et al.* 2008a](#)). The increase in DWP is different for different materials, indicating different material properties and response with time in operation ([Rosso *et al.* 2008b](#)). Another indicator of diffuser performance is hence the pressure factor Ψ , i.e., the ratio of DWP for used and new diffusers. The extent of F and Ψ variation in different plants, processes, and wastewaters is highly variable and highly site-specific, and it is therefore difficult and at times risky to predict diffuser performance based on results collected elsewhere.

Currently, the most common scenario for fine-pore diffuser system design is an upgrade of an existing system to a newer, more energy-efficient technology. Other scenarios may include expansion of an existing system, and less frequently the design of a new installation. In any of the cases above, the typical project milestones begin with the decision of designing or upgrading the aeration system, and after a request for proposals is formalized, posted and bid on, a proposal team is selected. From the initial moment of deciding to embark on the aeration design/upgrade to the project team selection, typically a time frame of 5–6 months elapses. After the project team is selected, a period spanning between 1 and 1.5 years may elapse, during which the engineering team completes the design of the aeration system. The initial step of the design entails a request for data and design procedures from suitable diffusers manufacturers. Typically, the

manufacturers provide the design team detailed guidelines to adhere to, in order to complete a successful aeration system design. The efficiency parameters provided and warranted by manufacturers, in this common scenario, are based on historical experience in other similar installations and on their internal know-how. During the construction phase, following the design phase, some design amendments may have to be discussed and implemented, and the construction typically is completed in a term of 24–30 months since the initial milestone inception. [Figure 1](#) illustrates this *inter alia*.

In [Figure 1](#), we also present a new approach to improve this design procedure, without altering the technical structure of the classical approach. While the administrative and bidding milestones are being carried out (i.e., in the first 6 months of the project milestones), an independent aeration team can be selected and hired to test candidate diffusers suitable for design in an aeration column *in situ*. [Hwang & Stenstrom \(1985\)](#) conducted the earliest example of using an aeration column in order to determine aeration efficiency and fouling rates. The details of the current, improved methodology are described in the following section. This testing can be performed in clean and process water at the same wastewater treatment facility where the design is to be implemented, thus bypassing the uncertainty due to extending results from different wastewaters to this particular site. In a subsequent phase, after the project design team is selected, and the design procedures are being carried out, there is an additional period of months before the design is finalized. The time elapsed from day 1 to the finalized design allows the independent testing team to test the diffusers for their initial process water performance in this very wastewater, and to install the candidate diffusers in the same wastewater for a period of a few months, thus allowing fouling to establish just like it is bound to happen after start-up. As the first months after start-up or cleaning are the most crucial for aeration efficiency decline ([Rosso & Stenstrom 2006](#)), this site-specific fouling study provides a realistic (not estimated) quantification of fouling effects on the aeration efficiency parameters. By the time the aeration system design is finalized, the concurrent fouling studies can be concluded. An *in situ* study as described will also reveal incompatibilities between diffuser material and constituents in the wastewater.

The goal of this paper is to present the practice of on-site column testing for aeration diffusers, and to demonstrate the increase in accuracy of quantifying aeration parameters. We discuss case studies where column on-site testing and extended fouling studies were performed to improve the

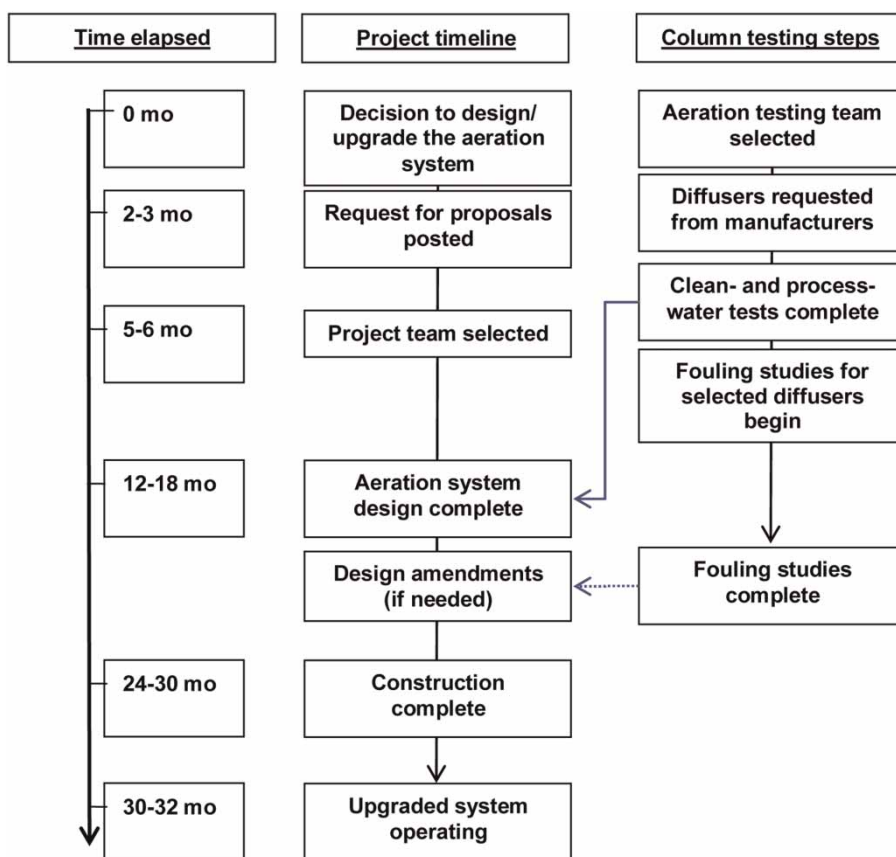


Figure 1 | Timeline of aeration design/upgrade projects, and corresponding step pathway for column testing and fouling studies (timeline not to scale).

accuracy during design and specification of aeration systems.

METHODS

Process conditions

In an effort to extend the results of this project to as many treatment plants as possible, a reclamation plant operating biological nutrient removal (BNR) was chosen. The Michelson water reclamation plant (MWRP) is owned and operated by the Irvine Ranch Water District (Irvine, CA). The plant's average flow is $60,500 \text{ m}^3 \text{ d}^{-1}$ with influent grinding, chemically enhanced primary settling followed by an equalization basin to abate peak loads, activated sludge process with pre-anoxic denitrification and methanol addition, dual-media filtration after secondary clarification, followed by Cl_2 disinfection. The activated sludge is operated at an average sludge retention time of 8.5 d over the yearly cycle, ranging from 6 to 10 d to compensate for the seasonal temperature variations. Each activated sludge tank is composed of two pre-anoxic reactors

with a volume of 1/6 of the tank followed by two oxic reactors with a volume of 1/3 of the tank volume. Aeration is supplied by automatically controlled centrifugal blowers with dissolved oxygen (DO) set points of 2.4 and 2.7 mg l^{-1} in the two oxic reactors, respectively. The oxic reactors are equipped with 228 mm (9 in) membrane disc diffusers.

Testing tank set-up

We constructed a testing tank $3 \times 3 \times 5 \text{ ft}$ ($L \times W \times D$) for both clean- and process-water tests (Figure 2). Clean-water tests and off-gas tests were performed on all 17 different fine-pore diffusers. Diffusers were tested in single and multiple configurations. Details on the diffusers are reported in Table 1. Oxygen transfer in clean water was measured for all diffusers for several air flow rates specified by their manufacturers, according to standard protocol procedures (ASCE 2006). The same testing tank was transported to the MWRP and part of the activated sludge was continuously circulated from the first aerated zone to the research tank and discharged back to the aeration tank. Oxygen transfer rates in process conditions were measured using

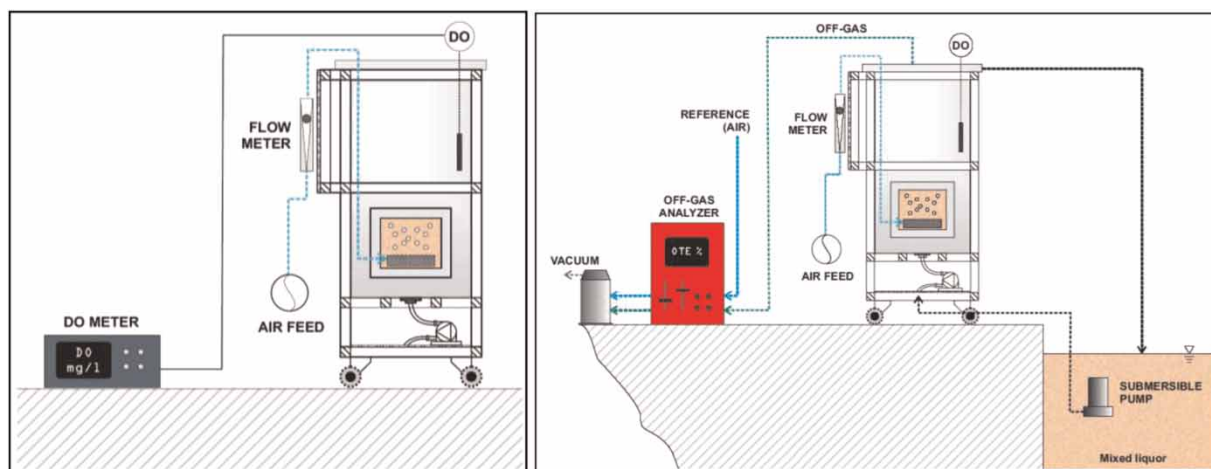


Figure 2 | Schematic of on-site column testing for clean water (left) and of an on-site process-water test (right).

the off-gas technique according to the ASCE testing protocol (ASCE 1997). Results are reported as SOTE, α SOTE and as DWP.

Diffusers selection

Selected diffusers were tested for 1 year in process water to quantify fouling effects on diffuser performance.

A sidestream continuously fed tank was utilized, and four 228 mm (9 in) discs were installed (three EPDM discs, one ceramic disc) and continuously operated at $1.70 \text{ m}^3 \text{ h}^{-1} \text{ diff}^{-1}$. Diffusers 1 and 2 (i.e., one ceramic and one EPDM with small pores) were selected as reference for the others, due to the long-term experience of testing and specifying them in the past 25 years. Diffusers 3 and 4 were selected to compare fouling behaviour. Oxygen transfer was measured

Table 1 | Characteristics of diffusers tested. Diffusers 1–4 were selected for the 1-year fouling study

Code	Type	Material	Diameter (m)	Length ^a (m)	Area (m ²)
Diffuser 1	Disc, small pores	Ceramic	0.22	/	0.039
Diffuser 2	Disc, small pores	EPDM	0.22	/	0.039
Diffuser 3	Disc, large pores	EPDM	0.22	/	0.039
Diffuser 4	Disc, small pores	EPDM	0.22	/	0.038
Diffuser 5	Tube, small pores	Silicone	0.07	0.72	0.115
Diffuser 6	Tube, large pores	Silicone	0.07	0.72	0.115
Diffuser 7	Tube, small pores	EPDM	0.12	0.66	0.113
Diffuser 8	Disc, small pores	Silicone	0.22	/	0.036
Diffuser 9	Disc, small pores	PTFE Coated	0.22	/	0.036
Diffuser 10	Disc, small pores	Polyurethane	0.22	/	0.036
Diffuser 11	Disc, small pores	EPDM	0.22	/	0.036
Diffuser 12	Disc, small pores	EPDM	0.22	/	0.036
Diffuser 13	Disc, small pores	EPDM	0.22	/	0.039
Diffuser 14	Disc, large pores	EPDM	0.22	/	0.039
Diffuser 15	Disc, small pores	EPDM	0.30	/	0.073
Diffuser 16	Tube, small pores	EPDM	0.06	0.53	0.087
Diffuser 17	Tube, large pores	EPDM	0.06	0.53	0.087

^aLength defined for tubes only.

with weekly tests using the off-gas method (ASCE 1997), at the nominal air flow rate $1.70 \text{ m}^3 \text{ h}^{-1} \text{ diff}^{-1}$, and at increasing multiples (i.e., 2.55 and $3.40 \text{ m}^3 \text{ h}^{-1} \text{ diff}^{-1}$). Tests at $0.85 \text{ m}^3 \text{ h}^{-1} \text{ diff}^{-1}$ were performed during the initial project period, but the DO concentration was rarely high enough to guarantee data significance, and these results were abandoned.

RESULTS AND DISCUSSION

Figure 3 shows all results, with clean-water results displayed on the top and process-water results displayed on the bottom. In both cases the horizontal axes show air flow per unit area of active diffuser surface, often called air flux. The vertical axes are the transfer efficiencies per unit of diffuser submergence. The size of the circles in the clean-water graph represents the DWP, and the actual pressure drops are displayed as circle sizes. The graph shows the impact of air flow on diffuser efficiency. The higher diffuser efficiency is always associated with low air flux, regardless of diffuser type. Occasionally, panel- or strip-type diffusers are called ‘super-fine’ bubble diffusers in the belief that they in some way produce smaller bubbles, or ‘microbubbles’. This graph shows that the real effect is low air flux, which ensures the smallest bubble size for each orifice, as well as spreading the rising bubble plume to avoid bubble collisions and coalescence. The graph also shows a trend in DWP with larger circles generally occurring at larger air fluxes.

Some of the results can be explained through bubble dynamics. A fixed orifice produces essentially the same size bubbles over a range of low air flow rates. As the air flow rate increases, the additional gas volume produces more bubbles of the same size. This region is referred to as ‘increasing bubble frequency’. At higher gas flow rates, bubbles cannot be formed and released at sufficient speed to accommodate the gas flow rate, and larger bubbles are produced. In this regime of ‘increasing bubble diameter’, the SOTE begins to decline due to the reduced bubble surface area per unit of air flow rate. At the same time, in the proximity of the orifice, i.e., where the gas transfer is maximum, these bubbles show a ‘channelling’ effect, where trailing bubbles are drafted to the wake of the leading bubbles, and the overall area available to gas transfer is represented by the cylindrical envelope of bubbles (Fan & Tsuchiya 1990). The DWP also begins to exponentially increase once the regime of increasing bubble diameter is reached, due to the compressive friction of air at the orifice. This phenomenon creates an inverse correlation between SOTE or αSOTE and DWP. Low DWP is

associated with low air flux, where the pores are operating at the increasing bubble frequency regime. This is an artefact of fine-pore diffusers: in order to release small bubbles (associated with elevated SOTE) the diffusers have to be operated at low flow rate, associated with low pressure drop (i.e., low DWP). Also, multiple configurations increase SOTE and αSOTE , while not affecting DWP as multiple diffusers are mounted in parallel.

Some diffusers, such as ceramic discs or domes, exhibit slightly different behaviour. The DWP does not increase so sharply, because additional pores are open at higher air flow rates. This is the reason why ceramic discs are usually not used in ‘swing zones’ where air may or may not be used, to match denitrification requirements. Pores not passing air may never reopen when the air is restored. This phenomenon usually does not occur with membrane diffusers, due to the fixed number of pores, unless the membrane is not fully functioning. In some cases, especially with tube diffusers, membranes are oversized in anticipation of membrane shrinkage. The ‘slack’ membrane may rest against the holder and retard air flow through the pores. At higher DWP, the membrane fully opens and the additional pores partially compensate for the higher air flow per diffuser. These diffusers show flatter DWP versus air flux curves. Upon first reflection, this may sound like a good way of producing ‘turn up’ and ‘turn down’ capability in an aeration system. In our experience in observing aeration systems at working treatment plants, the slack area tends to foul more heavily, and when additional air flow is provided, the slack area may never release bubbles, due to the plugging of pores with fouling or scaling material, at times even inside the membrane (Rosso *et al.* 2008b).

The pore geometry also makes a difference to DWP. Round rigid pores, such as a control orifice, have a steeper pressure versus flow curve. Membrane pores, which are often formed by punching with a straight knife edge, are actually slits. The slits expand at higher air flow rate if the slits are perpendicular to the axis of membrane expansion (e.g., slits arranged in the direction of the long axis of a tube diffuser, as it expands radially with increasing air flow rate). It should also be noted that the minimum DWP is not always the best DWP. A minimum DWP is required to ensure proper air distribution. Ceramic discs have flatter DWP versus air flow curves for the reasons noted above (as well as slack tube diffusers), and ceramic discs are usually installed with some type of fixed orifice to provide increased DWP. Air flow distribution problems are more likely at the lowest DWP and with diffusers which exhibit a flatter DWP versus air flow curve. From an energy

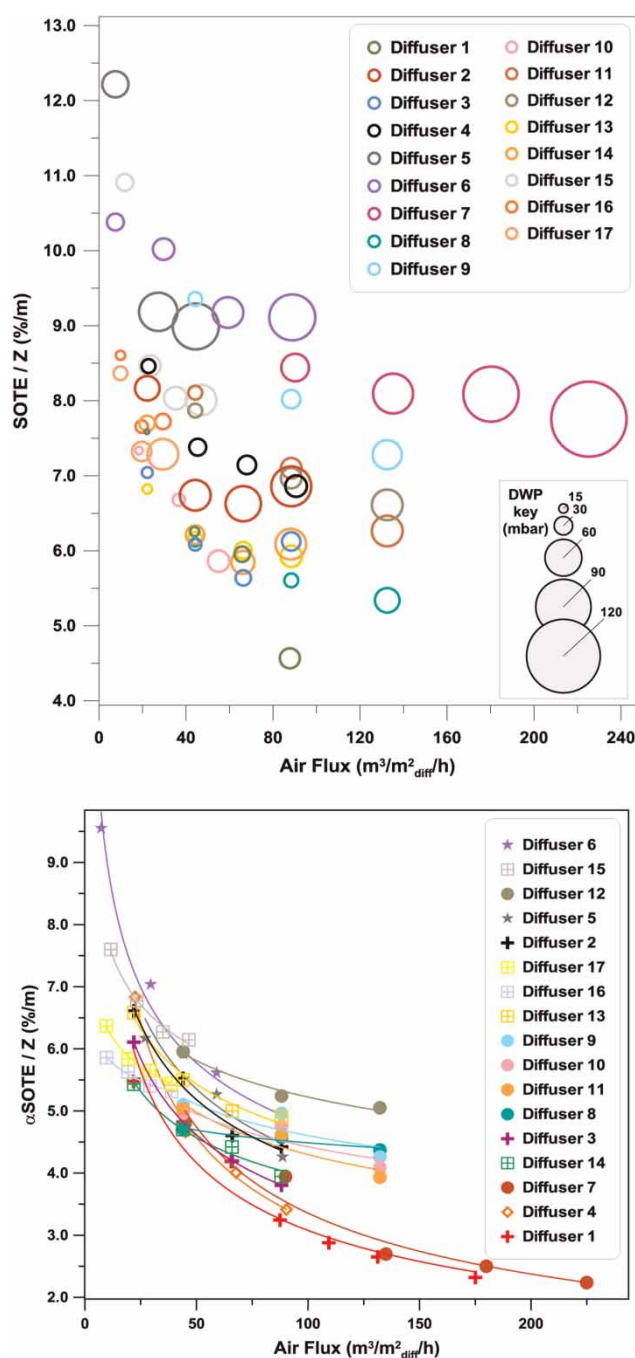


Figure 3 | Clean-water (top) and process-water (bottom) test results for all 17 diffusers tested. In the top graph, the size of each data point is proportional to the DWP, from smallest to largest for each diffuser (symbol sizes are actual DWP in millibar).

perspective, it is more desirable to have the lowest DWP, but this may be risky as poor air distribution may occur, causing a potentially worse energy impact. Installation of diffusers in smaller grids and with control valves helps avoid air distribution problems, in addition to providing more flexible aeration tapering.

Four of these diffusers were selected for the 1-year fouling study (results in Figure 4). An important conclusion that can be drawn from our results is that DWP, SOTE, and alpha span over wide ranges. Therefore, considering constant values during design or process modelling may lead to improper sizing of aeration systems or model inaccuracies. Figure 4 shows the fouling factor, F , and pressure factor, Ψ , for the four selected diffusers. All diffusers tested foul inevitably, regardless of the diffuser type. Non-linear regression analysis shows increased fouling (i.e., declining F) and increasing Ψ for all diffusers and at all flow rates. Results show large scatter due to varying wastewater conditions and seasonal temperature variations, reflected in the running averages (thin trend lines). To compensate for these variations and to describe the general trend of the data, we also plotted exponential fits (thick trend lines).

The behaviour of F over time may appear counter-intuitive in that the higher the air flux the less severe the fouling F . One must remember that F being the ratio of α SOTE for a used and a new diffuser, the definition of F becomes a function of both the elapsed time in operation and the air flux at which α SOTE is measured. As α SOTE is not a linear function of the air flux and, as the curvature of α SOTE's trend with air flux may vary over time in operation, the ratio of the α SOTE values for used and new diffusers may differ substantially between low and high air fluxes, which is confirmed in Figure 4(a). In fact, when the diffusers are operated at their lowest air fluxes, F is most severely declining, suggesting an inability of the bubbles to be released as small and numerous as when the diffusers were new. Conversely, high air fluxes suffer the least from fouling since the performance in this case was poor for a new diffuser and is comparatively poor for a used one. This is because at high air fluxes fine-pore diffusers discharge faster and larger bubbles, which are expected to be able to travel through the fouling biofilm without as much impediment as those released at low air fluxes.

Even though the variation over the tested period may appear as a decline in Ψ after the summer period (month 8), which could be attributed to orifice creep for the membrane diffusers (phenomenon discussed by Kaliman *et al.* 2008), the ceramic diffuser (diffuser 1) which is immune from creep shows the same trend. This suggests that during extended fouling tests a ceramic diffuser acting as control would indicate whether there is membrane orifice creep by comparing the Ψ performance trends over time. Rather than creep, we believe that the seasonal temperature and consequent MCRT compensation have a role in the Ψ variation: warmer months (months 6–10 in Figure 4) appear

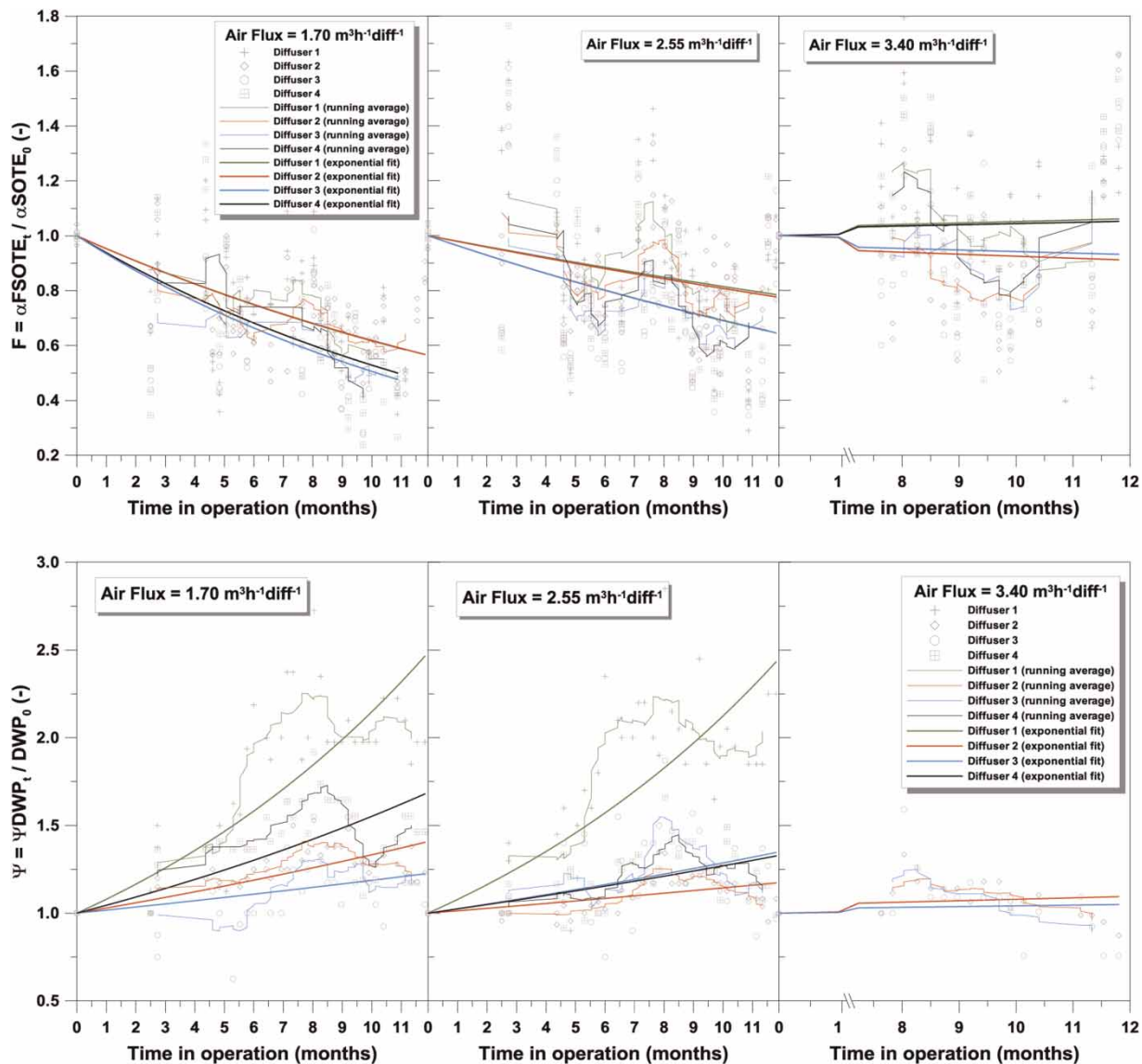


Figure 4 | Summary of fouling (F) and pressure factor (Ψ) testing results for four selected diffusers. Diffuser 1 is a ceramic disc, the other diffusers are EPDM membrane discs. For each panel, the thin trend lines are running averages (3-month period) and the thick trend lines are exponential fits.

to be associated with the transient peak Ψ values, possibly due to an increased biofilm growth at higher temperatures and lower MCRTs (during these months the MCRT at the MWRP is decreased to 6 d from the winter value of 10.5 d).

The implications for aeration system design and specification are immediate. After testing all candidate diffusers (Figure 3) and choosing the most likely diffusers for the final design selection (Figure 4), the margin of variability in terms of performance parameters is narrowed. Moreover, during the aeration system design, the design team must scale down the diffuser performance by a safety factor to account for the loss of performance over time. The trend lines in Figure 4 help the design team quantify such a safety

factor for each of the candidate diffusers. In the case of diffuser 1, for example, even though the efficiency decline (i.e., F) may be moderate, the increase in DWP could be prohibitive in the case of an upgrade conserving existing pressure-limited blower units. As another example, diffuser 4 has moderate relative increase in DWP, but after 12 months in operation its efficiency must be scaled by a factor $F = 0.5$. This factor more than doubles the blower power requirements, compounding the effect of increased air flow (to compensate for lower transfer efficiency) and increased blower discharge pressure (mandated by increased air flow). Constant safety factors would not be the most accurate approach to this design question, even though most aeration

designs have historically been carried out using them. This increase in accuracy corresponds to increased energy savings.

One caveat must be specified regarding the applicability of this technique. By comparison with the full-scale treatment plant, equipped with diffusers identical to one of the four tested for the 12-month period, we concluded that the fouling rate in the testing tank was accelerated. The MWRP routinely cleans the diffusers every year, and their fouling factors are much contained by this preventive procedure (F is typically above 0.8 in this facility). This suggests that *in situ* column testing may be able to simulate the fouling with an approximately three-fold acceleration, i.e., the results from a 12-month column test may correspond to approximately 3 years in operation in a real full-scale plant. This may be due to the fact that during peak period the MWRP operated diffusers at increased air flux to meet oxygen requirements, while the testing tank had the diffusers set at a constant air flux. During peak loading, therefore, there could be periods of low DO in the testing tank that may accelerate fouling. Future research must focus on the calibration of *in situ* column testing result for full-scale application during design.

CONCLUSIONS

The results we present here confirm that OTE is always consistently lower with longer time in operation. Furthermore, the pressure drop of a fine-pore diffuser increases with increasing time in operation due to fouling and scaling, except in the rare cases of membrane damage by constituents in the wastewater. Both effects cause the diffuser performance decrease over time, and increase blower power requirements. *In situ* measurements of aeration performance parameters for new diffusers and for an extended period of time (e.g., 12 months) can be performed in parallel to the design and procurement phases. The results of *in situ* tests can aid the aeration design process and increase the accuracy of aeration system sizing and specification.

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