Reverse flexing as a physical/mechanical treatment to mitigate fouling of fine bubble diffusers

Victory O. Odize, John Novak, Haydee De Clippeleir, Ahmed Al-Omari, Joshua D. Smeraldi, Sudhir Murthy and Diego Rosso

ABSTRACT

Achieving energy neutrality has shifted focus towards aeration system optimization, due to the high energy consumption of aeration processes in modern advanced wastewater treatment plants. A study on fine bubble diffuser fouling and mitigation, quantified by dynamic wet pressure (DWP), oxygen transfer efficiency and alpha was carried out in Blue Plains, Washington, DC. Four polyurethane fine bubble diffusers were installed in a pilot reactor column fed with high rate activated sludge from a full scale system. A mechanical cleaning method, reverse flexing (RF), was used to treat two diffusers (RF1, RF2), while two diffusers were kept as a control (i.e., no reverse flexing). There was a 45% increase in DWP of the control diffuser after 17 months of operation, an indication of fouling. RF treated diffusers (RF1 and RF2) did not show significant increase in DWP, and in comparison to the control diffuser prevented about 35% increase in DWP. Hence, reverse flexing potentially saves blower energy, by reducing the pressure burden on the air blower which increases blower energy requirement. However, no significant impact of the RF treatment in preventing a decrease in alpha-fouling (αF) of the fine pore diffusers, over time in operation was observed.

Key words | alpha, dynamic wet pressure, fouling, reverse flexing

Victory O. Odize (corresponding author)
John Novak
Virginia Polytechnic Institute and State University,
Blacksburg, VA 24061,
USA
E-mail: *victory1@vt.edu*

Victory O. Odize
Haydee De Clippeleir
Ahmed Al-Omari
Joshua D. Smeraldi
Sudhir Murthy
DC Water and Sewer Authority,
5000 Overlook Ave., SW,
Washington, DC 20032,
USA

Diego Rosso
Civil and Environmental Engineering Department,
University of California,
Irvine, CA,
USA
and
Water-Energy Nexus Center,
University of California,
Irvine, CA,
USA

INTRODUCTION

Energy consumption of aeration processes in modern advanced wastewater treatment plants comprises 45 to 75% of the plant total energy requirement, making aeration the most energy intensive aspect of wastewater treatment (Houck & Boon 1981; Rosso & Stenstrom 2005). Fine bubble diffusers compared to coarse bubble and other mechanical aeration diffusers, have grown to become the most popular aeration technology employed in municipal activated sludge processes. This is because fine bubble diffusers produce bubbles which are less than 5 mm in diameter and therefore have a higher surface to volume ratio and longer travel time. This leads to higher oxygen transfer and standard aeration efficiency (SAE) than other diffuser types. An SAE of 0.7–1.0 kgO_2 kWh^{-1} for fine bubble diffusers compared to 0.3–0.7 for coarse bubble diffusers at a low dissolved oxygen (DO) of 2 mg/L) have been previously reported (IWA 2008). However, application of fine pore diffusers in wastewater treatments plants to save energy and operating cost has been limited by fouling. This has led to numerous research studies on causes of fine bubble diffuser fouling, different fouling mitigation techniques, their impact on oxygen transfer efficiency (OTE) and alpha fouling factor. Alpha fouling factor is a parameter that indicates the fouling impact on OTE.

Diffuser fouling as reported by the different researchers (Boyle & Redmon 1983; Kim & Boyle 1993; Rosso *et al.* 2007) normally occurs over time and at an increased influent loading. It also increases the dynamic wet pressure (DWP) across the membrane diffuser, with an adverse blower effect and large bubble production, which results in a decrease in OTE (%) and alpha factor (Cheng *et al.* 2000; Rosso *et al.* 2007; Wagner & von Hoessle 2003).

Other studies have established that fine bubble diffusers experiences fouling, and consequent DWP increase and OTE decrease within the first 12 to 24 months of installation or after cleaning (USEPA 1989; Rosso & Stenstrom 2006a, 2006b; IWA 2008; EPRI 2013). According to these studies,

doi: 10.2166/wst.2017.171

the fouling process is dependent on the materials they are made of, their interaction with wastewater characteristics, plant operating conditions and time in operation. In order to mitigate fine bubbles diffuser fouling and its effect on plant energy and operational costs, routine cleaning or treatment is therefore a necessity.

Le-Clech *et al.* (2006) did a comprehensive review on sludge characteristics, operational parameters and membrane materials as factors responsible for fine bubble diffuser fouling. The review concluded that no known single parameter can predict or model fouling of fine bubble diffusers, due to changes in biomass characteristics from plant to plant. However, an understanding of foulants and their interaction with diffuser polymeric material may provide a new direction for their cleaning and mitigation strategy.

Surfactants and other wastewater characteristic such as chemical oxygen demand (COD) has also been reported to have adverse effect on OTE and alpha (Rosso *et al.* 2005; Leu *et al.* 2009; Hebrard *et al.* 2014).

Fine pore diffuser fouling was grouped into three categories of bio, organic and inorganic fouling in a previous study (Meng *et al.* 2009). They defined biofouling as the deposition, growth and metabolism of bacteria's cells or flocs on diffuser membranes. Other studies reported that selected bacteria with higher hydrophobicity than suspended sludge selectively adhere and grow on diffuser surfaces, making their fouling difficult to remove (Jinhua *et al.* 2006; Miura *et al.* 2007). Organic fouling was defined as the deposition of biopolymers (i.e., proteins and polysaccharides) on membrane surfaces. The deposited biopolymers were found to be composed of three different layers, a loosely bound cake layer similar to the sludge floc which causes reversible fouling, an intermediate layer with a high polysaccharide content, bacteria aggregates and soluble microbial products (SMP) which causes reversible fouling, and, finally, a lower layer with high concentration of SMP and proteins which causes irreversible fouling (Metzger *et al.* 2007). Inorganic fouling, which is the last category type of fouling, was defined as the chemical and biological precipitation of numerous cations and anions. Biopolymers with ionisable groups (i.e., COO^-, $CO_3^{2-}SO_4^{2-}$, PO_4^{3-}, and OH^-) are easily captured by metal ions (i.e., Ca, Fe, and Mg) present in wastewater. They can form dense cake layers with deposited microbial cells and biopolymers on membrane surface, to cause irreversible fouling (You *et al.* 2006; Costa *et al.* 2006; Wang *et al.* 2008). Reversible fouling as described by Meng *et al.* (2009) is caused by loosely bound foulants on membrane surfaces, and can be removed by physical cleaning like backwashing. Irreversible fouling is caused by fine pore clogging and strongly attached foulant to the membrane surface, due to their affinity for the membrane, and can only be removed through chemical cleaning.

Both physical and chemical cleaning methods have been applied as fouling mitigation technique to fine pore diffusers. Some of the physical cleaning methods applied in previous studies include gas or air sparging, membrane relaxation, pressure and backwashing or flushing (Schiewer & Psoch 2005, 2006; Le-Clech *et al.* 2006; Meng *et al.* 2009; USEPA 2010). Most manufacturers propose chemical cleaning for fine pore diffuser fouling mitigation, which normally differ in chemical compounds used, concentration, and application frequency. In general, the choice of cleaning chemicals depends on wastewater feed characteristics, as acidic cleaning chemicals are most suitable for removing precipitated salt while alkaline cleaning chemicals are suitable for adsorbed organic removal (Van der Bruggen & Vandecasteele 2003). There is also insufficient information on the effectiveness of the different types of fouling mitigation technique with respect to DWP escalation and OTE decrease, respectively.

This study investigates the long-term use of a physical/mechanical cleaning method called reverse flexing (RF), in the mitigation treatment of fine bubble membrane diffusers fouling, its impact on DWP, OTE and alpha factor over a 17 month period. Reverse flexing (RF) is the interruption of air feed and release of pressure from the air feeding line through a constructed vent channel, causing the rapid collapse of the membrane onto the diffuser frame under the action of hydrostatic pressure. Re-inflating the membrane diffuser by opening the air feed aims to scour fouling biofilm, particulates and colloids from the diffuser surface and pores as illustrated in Figure 1.

It is therefore hypothesized that the RF treatment method will help to remove both reversible and irreversible fouling, thereby preventing DWP escalation and decrease in OTE and alpha factor. This treatment method is unique and novel because the reactor can be running while the treatment process is going, thereby eliminating the bottle neck of plant shut down and down time as done in other treatment methods.

MATERIALS AND METHOD

Pilot reactor installation

This study was performed at the Blue Plains advanced wastewater treatment plant, Washington, DC, USA. An

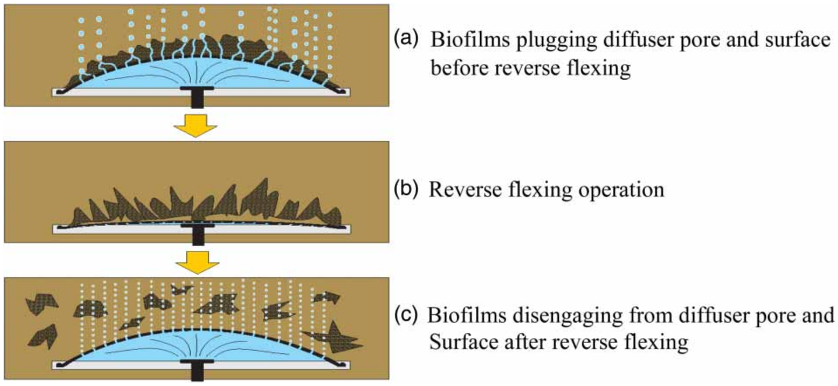

Figure 1 | Description of the reverse flexing process and the resultant effect.

aeration tank of 60 m^3 volume was constructed in which both clean and process water testing occurred. Four 1 m^2 polyurethane panel diffusers were installed separately in each quadrant of the four quadrants partitioned inside aeration tank with height of 7.62 m and a 3.96 m internal diameter. Clean water test and off gas testing with activated sludge were performed on all four membrane diffuser panels at water depth of 4.88 m inside the aeration tank. Standard oxygen transfer efficiency (SOTE, %) in clean water was measured for all diffusers according to the ASCE standard (2007) protocols. High rate activated sludge (HRAS) pushed through the pilot reactor, was pumped from the first pass of the west secondary reactor in blue plains, one of the largest wastewater treatment facility in the world with a treatment capacity of 1,419,529.7 m^3/day (375 MGD). The west secondary reactor treats about 23,091 m^3/day (6.1 MGD) of wastewater, and operates at a low DO of 0.1 to 1 mg/L, sludge retention time of 1.5 to 2 days with a targeted average total suspended solid of 2,500 mg/L. Low DO in secondary reactors has been proposed by Mueller & Stensel (1990) to favor oxygen transfer. The HRAS from the full scale reactor was recycled to maintain an average hydraulic retention time (HRT) and volumetric flow rate of 20 min and 3,028 L/min, respectively. Air was supplied to the diffusers by a positive displacement blower (Aerzen Blower Model GM 3S). The blower air to the diffusers was regulated at an optimum airflow of 10 m^3/h per 1 m^2 diffuser, by valved acrylic flowmeters (5–20 m^3/h range) supplied by Cole-Parmer. An YSI Pro Plus DO meter with probe placed at 50% of the water depth was used to measure DO concentration, while the pilot reactor was operated at an airflow rate of 10 m^3/h. Since there are no existing guidelines or protocols on the number of times reverse flexing should be done on any diffuser, two of the fine bubble diffusers (RF1 and RF2) were reverse flexed five times daily, intermittently at 2–3 min interval, as suggested by the manufacturer and kept constant throughout the 17 months of this study.

Dynamic wet pressure measurement

DWP, also known as the diffuser headloss or pressure drop, is the pressure differential of a submerged diffusion material normally measured and expressed in inches of water at a specific air flow rate. DWP was measured for the reverse flexed and control diffusers twice a week, using a calibrated Dwyer mercury differential pressure gauge in the range of 0 to 100 in H_2O (0 to 24 kPa). The differential pressure gauge is designed to measure the difference between two pressure points around the diffuser (i.e., the water head (static pressure exerted on the diffuser by the reactor water height) and the blower air inlet pressure to the diffuser), which automatically is the pressure drop across the diffuser. This was to monitor the potential headloss variations caused by fouling over time.

Oxygen transfer and alpha fouling factor measurements

The volumetric mass transfer coefficient (k_La, h^{-1}) and oxygen transfer efficiency (αSOTE, %) in process water corrected to standard conditions were evaluated for all diffusers according to the ASCE standard 1997 protocols twice a month on all four diffusers, using the off-gas technique (Redmon et al. 1983) and real-time self-calibrating Off-Gas analyzer (Leu et al. 2009). The alpha fouling factor was evaluated as the ratio of process water SOTE over time to clean water OTE, to determine the effect of wastewater contaminants and fouling on the fine bubble diffuser transfer efficiency over time (Equation (1)).

$$\alpha F = \frac{\alpha SOTE}{SOTE} \quad (1)$$

The decrease of aeration performance/efficiency due to fouling of fine pore diffuser was quantified by evaluating the fouling factor (F), which was defined as the ratio of SOTE of the diffuser at any time (t) to SOTE at the initial time (t_0) (Equation (2)).

$$F = \frac{\alpha FSOTE}{\alpha SOTE} \quad (2)$$

Both DWP and off gas measurements were performed on each diffuser, one at a time, shutting the air supply to the diffusers not being measured in the other quadrants, to prevent any form of air intrusion or interference.

Sample analysis

Mixed liquor samples were obtained and analyzed for COD, mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) after each DWP and off gas measurements using the Hach kits method. Other operating parameters, i.e., DO, influent volumetric flow, blower temperature and pressure were also measured. A summary of the pilot reactor operating conditions and average wastewater characteristics, based on samples analysis during each off gas and DWP measurement is reported in (Table 1).

RESULTS AND DISCUSSION

Choice of HRAS system for study

The choice of a high rate system as feed sludge for this study was to establish the effectiveness of the RF cleaning method in the worst fouling systems. High rate systems are expected to have high mixed liquor suspended solids concentration which inhibits oxygen transfer at the gas to liquid interface. There is also the presence of high concentration of COD and surfactants that also have adverse effect on OTE in high rate systems (Wagner & Von Hoessle 2003; Rosso *et al.* 2007). The pilot feed point in this study was from the first pass in the HRAS reactor where return activated sludge from the secondary clarifiers, are fed back into the HRAS reactor to improve treatment and maintain optimum efficiency. The total suspended solid concentration in this section of the HRAS reactor is increased and always higher than the other section of the reactor.

Table 1 | Summary of pilot operational and process condition over the test period

Parameters	Unit	Average values
Total influent COD	mg/L	7,925 ± 1,349
Organic loading rate	kgCOD/m^3 day	217 ± 40
MLSS	mg/L	6,247 ± 1,676
MLVSS	mg/L	5,236 ± 1,453
NH3	mg/L	17 ± 3
NO2	mg/L	0.026 ± 0.003
NO3	mg/L	0.45 ± 0.1
DO	mg/L	0.11 ± 0.08
pH	–	6.78
HRT	min	20 ± 0.4
Standardized air flow	m^3/hr	5, 10, 13
Average volumetric flow	L/min	3,028 ± 110
Temperature	°C	21 ± 4
Duration	months	17

Quantification of fouling via DWP measurements

The DWP of both the reverse flexed and control diffusers did not show any significant change in the first 7 months in operation as shown in Figure 2. Only one out of the two control diffusers installed was studied as the one was damaged during installation. An increase in DWP of the control diffuser after 7 months of operation was observed, indicating that fouling of the fine bubble diffuser has started. Previous studies indicated fouling occurrence when no treatment was applied after 12–24 months of installation (Rosso & Stenstrom 2006a, 2006b). Given the high risk of fouling in a high rate secondary treatment system, the period indicated

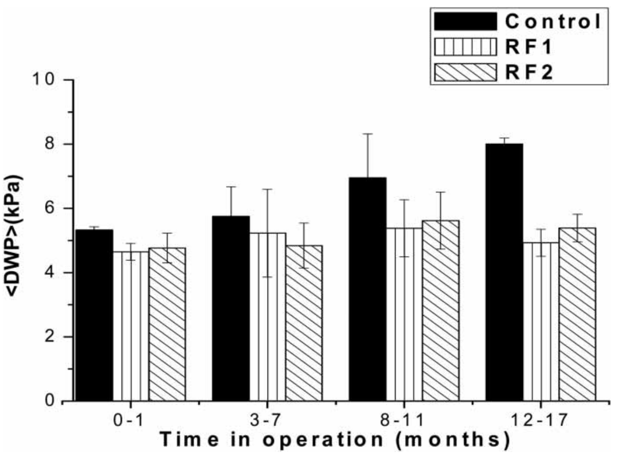

Figure 2 | Impact of reverse flexing (RF) on weighted dynamic wet pressure (DWP) of polyurethane Messner panel diffusers over time in operation.

to reach fouling in this study was in the expected range (USEPA 1989; Rosso & Stenstrom 2006a, 2006b; IWA 2008; EPRI 2013). Rosso & Stenstrom (2006a, 2006b) reported that foul diffusers can double their initial DWP over time due to the accumulation of foulants on the surface and pores of the diffusers. The foulant on the diffuser surface thickens over time, reducing its permeability and subsequently increasing its pressure drop. In another investigation of a treated highly alkaline wastewater, the DWP of one of the diffusers increased by 39% of the initial pressure after 3 months and 10 days of operation (Eusebi & Battistoni 2014). In this study, about $45 \pm 2\%$ increase in DWP of the control diffuser initial pressure was measured at the end of the 17 month study, which correlates with previous studies (Rosso & Stenstrom 2006a, 2006b). The high increase in DWP of the control diffuser was expected due to high concentration of COD, MLSS and surfactant presence in the HRAS feed used in this study.

However, no apparent or significant change of DWP was observed between the two RF diffusers during and after the 17 month period in operation as shown in Figure 2. A supplementary figure (Figure S1) is provided in the appendix section (available with the online version of this paper). This suggested the effectiveness of the RF treatment method in scouring deposited biofilms, colloids and particulates potentially responsible for fouling from the diffuser surface and blocked pores. The RF treatment method was estimated to have prevented an increase of $35 \pm 3\%$ in DWP for the treated diffusers with respect to the control diffuser. This is a potential pressure burden savings on the blower as described by Rosso *et al.* (2007), where a pressure factor P was used to quantify the pressure burden on the blower. When there is excessive pressure burden on the blower as a result of increased DWP caused by fouling, there is a possible air blower compressor surge which inhibits its performance and subsequently damages it, as most air blowers have a designed discharge output pressure which must not be exceeded.

Impact of reverse flexing on αF and F

A significant decrease in the evaluated α F of both the control and RF treated membrane diffusers was observed after the first 5 months in operation Figure 3(a). The decline in α F continued over the remaining 12 months in operation but at a slower rate. Rosso & Stenstrom (2006a) reported a high rate of decline in α F (0.5 to 0.33) in the first 24 months of operation, and a slower decline after the 24 months in their study. A result similar to that obtained in this study where α F decrease of 0.55 to 0.35 was observed in the after the first 5 months in operation. Leu *et al.* (2009) in his study also reported an 18.3% to 16.3% decrease in OTE of their installed diffusers after 5 months in operation, which can also be directly correlated to the result obtained in this study. The result in Figure 3(a) did not show any impact of RF in preventing the decrease in α F observed in reverse flexed (RF 1 & RF 2) diffusers, as no apparent difference was observed between the declining α F of the control and RF diffusers over the period of time in operation.

Potential reverse flexing impact limitations on α F and F

The ineffectiveness of reverse flexing on α F for both RF 1 and RF 2 did not correlate with the DWP measurement observed in Figure 2, as one expects a prevention of the continuous decrease in α F for both RF 1 and RF 2, since their DWP increase caused by fouling was shown to be mitigated

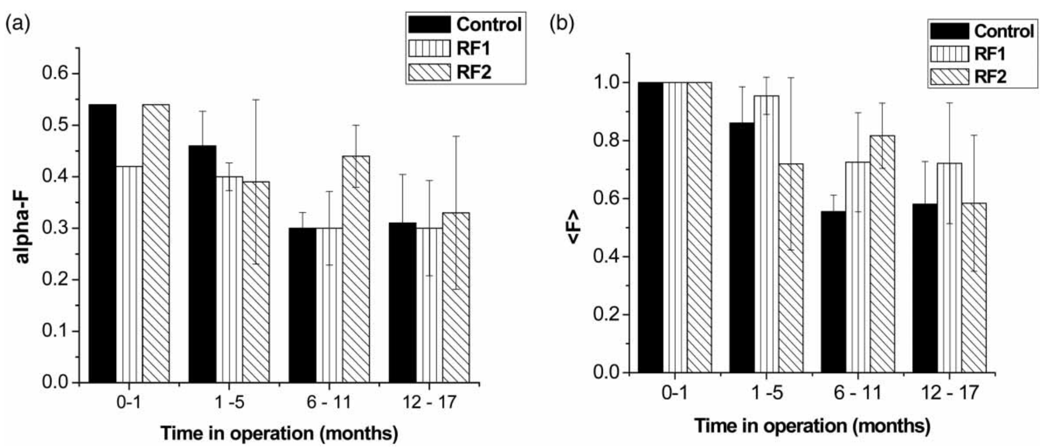

Figure 3 | Impact of reverse flexing (RF) on the evaluated weighted; (a) alpha fouling (α F) and (b) fouling factor (F) of the polyurethane Messner panel diffusers over time in operation.

by the RF process. Diffuser fouling and the consequent increase in DWP as observed in this study impacts most aeration systems with insufficient blower discharge pressure. They bear additional pressure burden (due to DWP increase) caused by fouling, which also produces large bubbles with OTE and α F limitation, because they can only discharge air through diffuser pores with lower head loss (Palm *et al.* 1980; Rosso *et al.* 2007). Other studies also reported reduction in diffuser pore permeability caused by blocked pores, leading to an increased pressure drop across the membrane diffuser and large bubble production. This is due to fewer pressurized pore openings which produce large bubbles that decrease OTE and α F (Boyle & Redmond 1983; Kim & Boyle 1993; Leu *et al.* 2009). Another important factor, is the fact that, over time in operation, the diffuser membrane polymeric properties deteriorate by either hardening or softening due to their constant contact with wastewater contaminants and bacteria. This causes an expansion of the diffuser pore size when blocked by biofilms, colloids and particles which, even after treatment, remain unchanged due to their inability to recover from RF stretching. They thereby produce large bubbles with poor OTE and lower α F (Rosso *et al.* 2007).

Moreover, reverse flexing is a physical cleaning method which has also been reported by past studies to remove only reversible fouling caused by loosely bound foulants on fine bubble diffuser surfaces and pores. While irreversible fouling caused by strongly attached inorganic and biofoulant to diffuser surfaces and pores, can only be removed through chemical cleaning (Kim & Boyle 1993; Le-Clech *et al.* 2006; Meng *et al.* 2009).

Therefore, the non-beneficial impact of RF in preventing the decrease in both α F and F, as observed in Figure 3(a) and 3(b), suggests the impact of some level of irreversible fouling of the diffusers. It is also possible that the positive impact of the fouling mitigation in RF1 and RF2, as indicated in Figure 2, was not significant enough to offset the wastewater characteristics (MLSS and COD) effect on alpha. As wastewater characteristics and contaminants have been reported by previous studies to have adverse effect on alpha (Rosso *et al.* 2005; Leu *et al.* 2009; Hebrard *et al.* 2014). The pilot reactor in this study was fed with MLSS from the plants secondary system, which operated with variable MLSS concentration throughout the testing period. There was no evolution trend in MLSS rather a normal variability over time was observed (see Figure S2 in appendix section for additional information, available with the online version of this paper). However, measured MLSS and influent variability throughout the study period did not explain evolution of α F with time (see Figures S3 and S4 in appendix section for additional information, available with the online version of this paper).

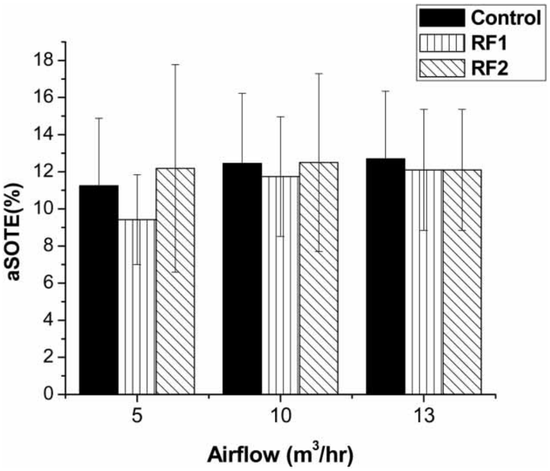

Figure 4 | Comparing evaluated oxygen transfer efficiency (αSOTE) standardized to process conditions at three different standardized airflow of 5 m^3/h, 6 m^3/h and 8 m^3/h.

Impact of airflow on SOTE

The impact of varying the airflow rates on the αSOTE of both the control and RF treated diffusers is shown in Figure 4. The result showed no effect of increasing air flow on αSOTE for both the control and RF treated diffusers. The observed result agrees with the Stephenson *et al.* (2007) report of no change in alpha or αSOTE with increasing air flux. Although other studies have reported contradictory results that show an increase in air flux decreases alpha in fouled diffusers due to fewer pores and slit openings. However, in this study, increasing the air flow did not show any impact on the αSOTE for either the controlled or RF treated diffusers. This is an important information in saving some energy with respect to increasing airflow which increases blower power requirement.

CONCLUSIONS

Measured DWP indicated the fouling dynamics of fine pore diffusers over time in operation. The applied diffuser fouling physical treatment (RF) method was able to prevent the increase in DWP normally observed in fouling fine pore diffusers over time in operation, saving about 35% of increase in DWP. The increase in DWP observed in the control diffuser is a potential pressure burden on the blower, which increases the blower energy requirement. However, the RF treatment method did not show any significant impact in preventing the decrease in α F of the fine pore diffusers. Most probably because the RF treatment method could maintain pore openings, remove reversible fouling better but could not fully remove irreversible fouling. There could also have been a dominant impact of other wastewater characteristics on OTE and alpha. Further investigation is therefore needed to evaluate the impact of chemical cleaning method that removes reversible and irreversible fouling; this future study will also accommodate oxygen transfer measurements of the foul diffusers in clean water conditions at the end of the study to give an insight on the impact of fouling in alpha fouling decrease. Other future studies include the impact of wastewater characteristics (i.e., surfactants and particulate COD) and operating conditions on OTE and α F, to have a clear understanding on the role of different wastewater characteristics' impact on alpha.

ACKNOWLEDGEMENTS

I want to appreciate God Almighty for the grace to complete this work. Also, this research was funded by the Water Environment Research Foundation (contract number INFR2R12) and the United States Environmental Protection Agency, with the support of the Irvine Ranch Water District, Hampton Roads Sanitation District, DC Water, and Southern California Edison. The assistance of all the personnel at the Blue Plains AWTP research laboratory is gratefully acknowledged.

REFERENCES

Boyle, W. C. & Redmond, D. T. 1983 Biological fouling of fine bubble diffusers: state of the art. *ASCE Journal of Environmental Engineering* **109** (5), 991–1005.

Cheng, H. F., Chen, S. Y. & Lin, J. G. 2000 Biodegradation of di-(2-ethylhexyl)phthalate in sewage sludge. *Water Science and Technology* **41** (12), 1–6.

Costa, A. R., de Pinho, M. N. & Elimelech, M. 2006 Mechanisms of colloidal natural organic matter fouling in ultrafiltration. *Journal of Membrane Science* **281** (1–2), 716–725.

EPRI 2013 *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*. Final Report EPRI 3002001433.

Eusebi, A. L. & Battistoni, P. 2014 Behavior of air diffusers and oxygen transfer efficiencies in the biological treatment of matrices at high alkalinity concentrations: experimental and full scale application. *Chemical Engineering Journal* **255**, 274–281.

Hebrard, G., Jimenez, M., Dietrich, N. & Grace, J. R. 2014 Oxygen mass transfer and hydrodynamic behavior in wastewater: determination of local impact of surfactants by visualization techniques. *Water Research* **58**, 111–121.

Houck, D. H. & Boon, A. G. 1981 Survey and Evaluation of Fine Bubble Dome Diffuser Aeration Equipment, Res. Develop. EPA-600/S2-81-222, Municipal Env. Res. Lab., EPA, Washington, DC, USA.

IWA 2008 *Biological Wastewater Treatment*. International Water Association, London, UK.

Jinhua, P., Fukushi, K. & Yamamoto, K. 2006 Bacterial community structure on membrane surface and characteristics of strains isolated from membrane surface in submerged membrane bioreactor. *Separation Science and Technology* **41** (7), 1527–1549.

Kim, Y.-K. & Boyle, W. C. 1993 Mechanisms of fouling in fine-pore diffuser aeration. *Journal of Environmental Engineering* **119** (6), 1119–1138.

Le-Clech, P., Chen, V. & Fane, T. A. G. 2006 Fouling in membrane bioreactors used in wastewater treatment. *Journal of Membrane Science* **284** (1–2), 17–53.

Leu, S. Y., Rosso, D., Larson, L. E. & Stenstrom, M. K. 2009 Real-time aeration efficiency monitoring in the activated sludge process and methods to reduce energy consumption and operating costs. *Water Environment Research* **81** (12), 2471–2481.

Meng, F., Chae, S. R., Drews, A., Kraume, M., Shin, H. S. & Yang, F. 2009 Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. *Water Research* **43** (6), 1489–1512.

Metzger, U., Le-Clech, P., Stuetz, R., Frimmel, F. & Chena, V. 2007 Characterization of polymeric fouling in membrane bioreactors and the effect of different filtration modes. *Journal of Membrane Science* **301**, 180–189.

Miura, Y., Watanabe, Y. & Okabe, S. 2007 Membrane biofouling in pilot-scale membrane bioreactors (MBRs) treating municipal wastewater: impact of biofilm formation. *Environmental Science & Technology* **41** (2), 632–638.

Mueller, J. S. & Stensel, H. D. 1990 Biologically enhanced oxygen transfer in the activated sludge process. *Research Journal of the Water Pollution Control Federation* **62** (2), 193–203.

Palm, J. C., Jenkins, D. & Parker, D. S. 1980 Relationship between organic loading, dissolved oxygen concentration, and sludge settleability in the completely-mixed activated sludge process. *Journal of Water Pollution Control Federation* **52** (10), 2484–2506.

Redmon, D., Boyle, W. C. & Ewing, L. 1983 Oxygen transfer efficiency measurements in mixed liquor using off-gas techniques. *Water Pollution Control Federation* **55** (11), 1338–1347.

Rosso, D. & Stenstrom, M. K. 2005 Comparative economic analysis of the impacts of mean cell retention time and denitrification on aeration systems. *Water Research* **39**, 3773–3780.

Rosso, D. & Stenstrom, M. K. 2006a Economic implication of fine-pore diffuser aging. *Water Environment Research* **78** (8), 810–815.

Rosso, D. & Stenstrom, M. K. 2006b Surfactant effects on alpha-factors in aeration systems. *Water Research* **40** (7), 1397–1404.

Rosso, D., Iranpour, R. & Stenstrom, M. K. 2005 Fifteen years of offgas transfer efficiency measurements on fine-pore aerators: key role of sludge age and normalized air flux. *Water Environment Research* **77** (3), 266–273.

Rosso, D., Libra, J. A., Wiehe, W. & Stenstrom, M. K. 2007 Membrane properties change in fine-pore aeration diffusers: full-scale variations of transfer efficiency and headloss. *Water Research* **42** (10–11), 2640–2648.

Schiewer, S. & Psoch, C. 2005 Critical flux aspect of air sparging and back flushing on membrane bioreactors. *Desalination* **175**, 61–71.

Schiewer, S. & Psoch, C. 2006 Anti-fouling application of air sparging and back-flushing for MBR. *Journal of Membrane Science* **283**, 273–280.

Stephenson, T., Nelles, F., Drews, A., Pearce, P., Kraume, M., Reid, E., Judd, S. J. & Germain, E. 2007 Biomass effects on oxygen transfer in membrane bioreactors. *Water Research* **41** (5), 1038–1104.

USEPA 1989 Fine Pore (Fine Bubble) Aeration Systems, EPA/625/1-89/023, Cincinnati, OH, USA.

USEPA 2010 Evaluation of Energy Conservation Measures For Wastewater Treatment Facilities, EPA 832-R-10-005.

Van der Bruggen, B. & Vandecasteele, C. 2003 Removal of pollutants from surface water and groundwater by nanofiltration: overview of possible applications in the drinking water industry, *Environmental Pollution* **122**, 435–445.

Wagner, M. & von Hoessle, R. 2003 Biological coating of EPDM-membranes of fine bubble diffusers. *Water Science and Technology* **50** (7), 79–85.

Wang, Z., Wu, Z., Yin, X. & Tian, L. 2008 Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: membrane foulant and gel layer characterization. *Journal of Membrane Science* doi: 10.1016/j.memsci.2008.07.035.

You, H. S., Huang, C. P., Pan, J. R. & Chang, S. C. 2006 Behavior of membrane scaling during crossflow filtration in the anaerobic MBR system. *Separation Science and Technology* **41** (7), 1265–1278.

First received 6 September 2016; accepted in revised form 6 March 2017. Available online 22 April 2017