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Aeration of large-scale municipal wastewater treatment plants: state of the art

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ABSTRACT

Aeration is the most energy-intensive operation in wastewater treatment, amounting to 45–75% of plant energy costs. Fine-pore diffusers are today almost ubiquitous in municipal wastewater aeration, due to their advantageous aeration efficiency (mass of oxygen transferred per unit energy required). Nevertheless, older municipal treatment facilities and many industrial treatment plants are still equipped with coarse-bubble or surface aerators. Fine-pore diffusers are subject to two major disadvantages: a) fouling, if not cleaned periodically; b) decrease in oxygen transfer efficiency caused by dissolved surfactants. Coarse-bubble and surface aerators are typically not subject to the traditional problems affecting fine-pore diffusers. Nonetheless, they achieve oxygen transfer at the expense of increased energy intensity. The increased biomass concentration associated with high mean cell retention time (MCRT) operations has a beneficial effect on aeration. Nutrient-removing selectors are able to further increase aeration efficiency, as they sorb and utilize the readily available substrate which otherwise would accumulate at bubble surfaces and dramatically decrease aeration efficiency. We summarise here our 30-year long experience in aeration research, and results obtained with clean- and process-water tests are used to show the beneficial effects of high MCRT operations, the beneficial effect of selectors, and the decline of aeration efficiency due to dissolved surfactants.

Key words | activated sludge, aeration, alpha, efficiency, oxygen transfer, wastewater

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INTRODUCTION

Aeration systems

Aeration is an essential process in the majority of wastewater treatment plants and accounts for the largest fraction of plant energy costs, ranging from 45 to 75% of the plant energy expenditure (Reardon 1995). Aeration systems transfer oxygen into the liquid media by either shearing the liquid surface with a mixer or turbine, or by releasing air through macroscopic orifices or porous materials. Falling droplets and rising coarse bubbles have large interfacial gas-liquid velocity gradients and can be grouped as high flow regime interfaces, whereas fine bubbles have low interfacial velocity gradients and can be grouped as low flow regime interfaces (Rosso & Stenstrom 2006*a*).

Fine pore diffusers (which produce fine-bubbles) have become the most common aeration technology in wastewater treatment in developed countries, due to their higher efficiencies on the basis of energy consumption (Stenstrom *et al.* 1984). They are routinely used in full floor configurations, which take maximum advantage of their efficiency. Fine pore diffusers are a subset of fine bubble diffusers; fine pore diffusers produce their small bubbles by releasing compressed air through small orifices or pores in either punched membranes or porous material, such as ceramic stones or sintered plastic. Other aeration equipment, such as submerged turbines or jet diffusers, also creates fine bubbles, but does so without using small orifices. Fine bubbles from turbines or jets should be grouped with high

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flow regime interfaces, since mechanical energy is used to shear large bubbles into fine bubbles.

The impact of cell retention time

The most important process parameter to affect aeration efficiency is the mean cell retention time (MCRT). MCRT is directly related to the biomass concentration, and dictates oxygen requirements. Aeration efficiency and alpha factors (ratio of process-water to clean-water mass transfer) are higher at higher MCRTs. Biological nutrient removal processes, by operating at increased MCRTs, have improved aeration efficiency. Furthermore, anoxic and anaerobic selectors in nutrient removal plants have beneficial effects that go beyond nutrient removal or improved settling characteristics. By utilising the readily available carbon in the wastewater, they remove the faster acting surfactants, which have the most dramatic impact in reducing oxygen transfer.

Literature studies (US EPA 1989; Rosso *et al.* 2005) showed that the oxygen transfer efficiency is directly proportional to MCRT, inversely proportional to air flow rate per diffuser, and directly proportional to geometry parameters (diffuser submergence, number and surface area of diffusers). The MCRT determines the net oxygen requirement and relates to the degree of treatment and removal of oxygen transfer reducing contaminants, such as surfactants. Higher MCRT systems remove or sorb the surfactants early in the process, which improves average oxygen transfer efficiency. The net effect of increasing MCRT is to increase the oxygen requirements, improve removal of biodegradable organics (Khan *et al.* 1998), and improve the overall oxygen transfer efficiency. The increase in oxygen requirement is partially or more than offset by the savings produced by the higher transfer efficiency.

The air flow rate influences the fluid dynamics of bubbles: the higher the air flow rate per diffuser or orifice, the larger the bubbles, which creates lower surface to volume ratio and higher bubble rise velocity. The net result is smaller gas to liquid area and shorter bubble residence time, reducing mass transfer. Geometry affects the efficiency because at greater submergence and tank coverages (ratio between diffusing area and total tank area) the mass transfer time and surface area are greater.

Role of selectors

Almost all new activated sludge process designs utilize selectors, either anoxic or anaerobic. An indirect benefit of selectors is improved oxygen transfer efficiency (Fisher & Boyle 1999), and is in addition to the well known oxygen credit provided by anoxic removal of influent substrate and reduction in filamentous organisms (Harper & Jenkins 2003). There is growing evidence that processes operating at higher MCRT are more efficient in removing anthropogenic compounds, such as pharmaceuticals (Soliman *et al.* 2004).

For these and other reasons, anoxic selectors for nitrification/denitrification (NDN) should always be evaluated as an alternative to conventional treatment. Our previous analysis showed that NDN operation can have lower total operating cost (aeration + sludge disposal costs - methane credit) than a nitrifying-only or a conventional treatment plant (Rosso & Stenstrom 2005). If conventional process operating cost was normalized to 1.00, nitrifying-only will have a total cost of 1.13, and NDN operations will have a total cost of 0.88. NDN operation offers an oxygen credit due to its process nature, and higher oxygen transfer efficiencies associated with the higher MCRT. The two factors overcome the additional oxygen demand that produced by the longer MCRT.

Diffuser fouling, scaling, and cleaning

Different methods have been used to clean fine-pore diffusers and vary in complexity and cost. The simplest method is to dewater the aeration tank and wash the diffusers from the tank top. This form of cleaning, called tank top hosing, is effective in removing biological slime accumulation, and generally restores or partially restores efficiency. For cases where inorganic precipitates (silica, calcium carbonate, gypsum, etc.) have caused scaling, acid cleaning may be required. Manually washing with low-strength hydrochloric acid (10 to 15% wt) is popular and acid gas cleaning using hydrochloric acid gas or acetic acid injected to air distribution lines is also possible (Schmit *et al.* 1989).

The oxygen transfer efficiency of fine-pore diffusers inevitably decreases over time. At the same time, back pressure (often called dynamic wet pressure or DWP) usually increases, and in some cases dramatically.

This DWP increase is due to clogging of pores in ceramic diffusers (USEPA 1989), or is associated with a permanent change in orifice characteristics for polymeric membranes (Kaliman *et al.* 2008). Both effects account for the decrease in overall process efficiency and power wastage. Cleaning fine-pore diffusers is almost always required and restores process efficiency and reduces power costs. Observations of 94 field tests show that efficiency decreases with time and the greatest rate of decrease occurs in the first 24 months of operation (Rosso & Stenstrom 2006*b*). Efficiency decline was quantified and included in cost analyses, and the net-present worth was compared to cleaning costs. The cleaning frequency is always higher for higher fouling rates and optimal frequency was as short as 9 months and never more than 24 months.

BACKGROUND

Clean water tests

Clean water testing (ASCE 2007) can be performed to compare different equipment and configurations. The results are reported as Standard Oxygen Transfer Efficiency (SOTE, %), Standard Oxygen Transfer Rate (SOTR, kgO_2/hr), or Standard Aeration Efficiency (SAE, kgO_2/kW-hr). Care must be exercised in using SAE, since different power measurements can be made. Generally "wire" power is usually preferable, which includes blower, coupling, gearbox and motor inefficiencies. Standard conditions are well defined, and correspond to 20°C, zero DO, mean atmospheric pressure, and zero impact of water salinity or other contaminants (e.g., α factor $= 1.0$, β factor $= 1.0$). Clean water test results can be used as warranty to verify performance and can also create a competitive bidding environment among manufacturers.

Process water tests

For process water conditions, results are reported as OTE, OTR and AE, which include the impacts of non-standard conditions. For off-gas results, it is convenient to use αSOTE, or αSOTR; these two parameters are corrected for all non-standard conditions except the α factor. This is possible because the other non-standard conditions are easily measured and corrected. The α factor, which is a ratio of mass transfer coefficients in process to clean water, can be calculated from off-gas results if clean water data are available. In fouled aeration systems, a second parameter, F, is used to define the degree of fouling. Therefore the efficiency of a new fine pore aeration system could be defined by αSOTE and a used or fouled system by αFSOTE. In this paper, αSOTE or αFSOTE is used for process water transfer efficiencies. To compare the results presented here to actual process conditions, the other corrections, such as DO concentration and temperature must be applied.

In order to better define aerator performance, off-gas testing has been extensively used to measure diffused aeration efficiency. Off-gas testing was developed by Redmon *et al.* (1983) in conjunction with the US EPA sponsored ASCE Oxygen Transfer Standards Committee. This committee produced a fine pore manual (US EPA 1989), a clean water oxygen transfer standard (ASCE 1984, 1991, 2007) and guidelines for process water testing (ASCE 1997). Clean water testing and off-gas testing are described in detail in these publications. The net result of the improved testing methods is an increase in our accuracy and precision in designing and quantifying aeration systems. These methods are now widely used in the United States (e.g., Redmon *et al.* 1983; Mueller & Stensel 1990; Iranpour *et al.* 2002), Europe (e.g., Kayser 1979; Frey 1991; Libra *et al.* 2002; Wagner *et al.* 2003; Gillot *et al.* 2005). Off-gas analysis is also being proposed as an additional aeration control mechanism (Trillo *et al.* 2004). The results reported in this paper all conform to methods sanctioned by the ASCE standard and guidelines.

RESULTS AND DISCUSSION

Conventional treatment, typically performed at lower MCRT has lower biomass concentrations, and less chance for the dissolved substrate to be quickly sorbed by the biomass. Higher MCRT operations have the advantage of higher biomass concentration. Given the same average MCRT, treatment systems using anaerobic selectors or coupling nitrification and denitrification have the additional advantage of partial removal or sorption of readily biodegradable substrate (rbCOD) in the selector zone. This is beneficial because of the decreased overall oxygen requirements (in the case of anoxic or nitrate-reducing selectors), and the decreased rbCOD accumulation at bubble surfaces that severely reduces oxygen transfer (Eckenfelder & Ford 1968; Rosso & Stenstrom 2006*a*).

Figure 1 shows both effects. The first 30% of the aeration tank was under aerated and functioned as a *de facto* anaerobic selector. The α factors are low at the head of the aeration tank, depressing transfer rate, where unfortunately is location of greatest oxygen uptake rate.

The tanks shown in Figure 1 are from a low MCRT system and show a rapidly increasing alpha factor. In cases where the process is at high MCRT, the average alpha factor will be greater and if there is internal mixed liquor recirculation, the gradient is reduced. Internal recirculation is normally used to improve nitrogen removal, but also distributes load, reducing amount of aeration tapering that is required. Figure 2 shows the results of 28 off-gas tests at plants that are low MCRT, carbon-only removal, nitrifying only and nitrifying-denitrifying (NDN, such as the MLE process). This figure also shows the effect MCRT and diffuser condition (new, used, old) on transfer rate. Increased MCRT is the major effect on transfer rate, with the average MCRT increasing from approximately 5 days for conventional to approximately 15 days for both nitrifying and NDN treatment plants. The average alpha factor increases from 0.37 to 0.48 to 0.59 for conventional, nitrifying and NDN systems, respectively. The change in alpha from nitrifying to NDN is the impact of rbCOD removal in the selectors. Also note the effect of diffuser condition. Points in the upper range for each process are tests of new or recently cleaned diffusers (i.e., α factors), while the lower numbers (i.e., αF factors) are used (<24 months operation) and old (>24 months).

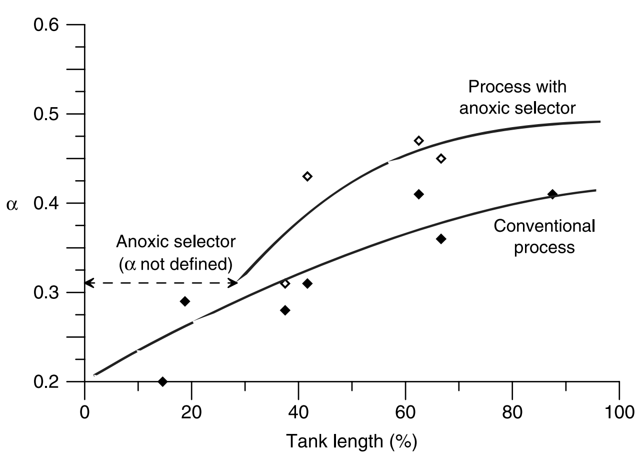

Figure 1 | Effect of tank length and anoxic selectors on α.

The rbCOD is partially composed of surface active agents or surfactants, which are typically discharged as oils, soaps and detergents. The surfactants, because of their amphiphilic nature, accumulate at the air-water interface of rising bubbles. The surfactant accumulation increases the rigidity of the interface and reduces internal gas circulation and overall transfer rate (Rosso & Stenstrom 2006*a*). The surfactant effect can be partially offset by increasing the flow regime (i.e., coarse bubbles). Figure 3 shows alpha factor as a function of the bubbles' Reynolds (Re) number. At low (Re), an increase in (Re) decreases alpha. This occurs because the bubble is rising as a solid sphere. At higher (Re), the buoyancy and drag forces are sufficient to cause internal bubble circulation. At very high (Re), practically achievable only with coarse bubbles, surfactant effects are nearly offset, increasing alpha factor at the expense of energy efficiency or low SAE.

Figure 3 also shows the impact of two different surfactants, a "fast" with high diffusivity (sodium dodecyl sulphate, a.m.u $\sim 10^2$) and a "slow" with lower diffusivity (polyvinylpyrrolidone, a.m.u $\sim 10^4$) surfactant. The fast surfactant more dramatically suppresses the transfer rate because of its greater diffusion rate and greater accumulation at the bubble surface.

Figure 4 shows this effect in process and clean water. The horizontal axis is air flow per diffuser. At low air flow, fine bubbles are created while at high flow coarse bubbles occur. In clean water high transfer efficiencies result, and are depressed to a greater degree (low alpha factor) at low air flow rate (i.e., the middle (Re) range of Figure 3), while at high air flow rates (i.e., the upper range of (Re) in Figure 3), less depression occurs. This explains why fine bubble diffusers have lower alpha factors. Note that even though the alpha factors are lower for fine bubble diffusers, they are still more energy efficient, with αFSAE of 1.38 kg_{O2}/kWh as opposed to 1.00 kg_{O2}/kWh αFSAE for coarse bubble diffusers. Also note that the data presented in Figure 4 are for a low density fine pore diffuser system, and more recent high density systems have higher transfer rates.

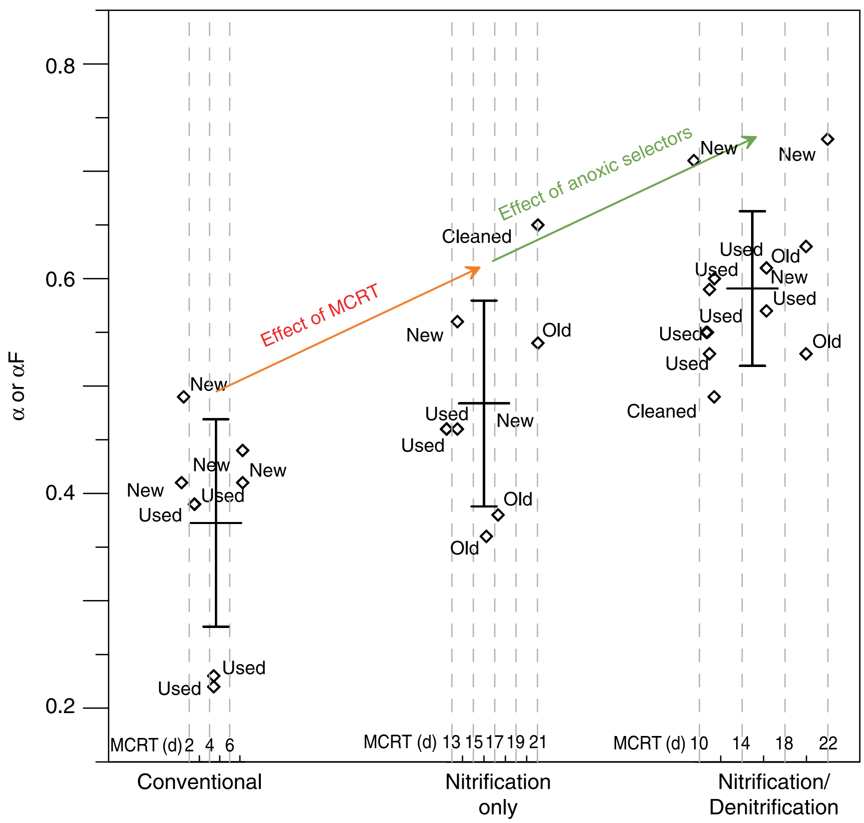

Figure 2 | Effect of mean cell retention time (MCRT), diffuser condition and selectors on α.

SUMMARY AND CONCLUSIONS

The required energy for aeration is the largest fraction of plant operating costs. Fine-pore diffusers have higher aeration efficiency, but their efficiency declines with bacterial fouling and with the presence of surfactants in the water. Coarse-bubbles and droplets can partially or completely offset these problems at the expense of energy efficiency ($mass_{O2}$/energy).

In this paper we summarise our research over the past three decades. Clean- and process-water tests show the

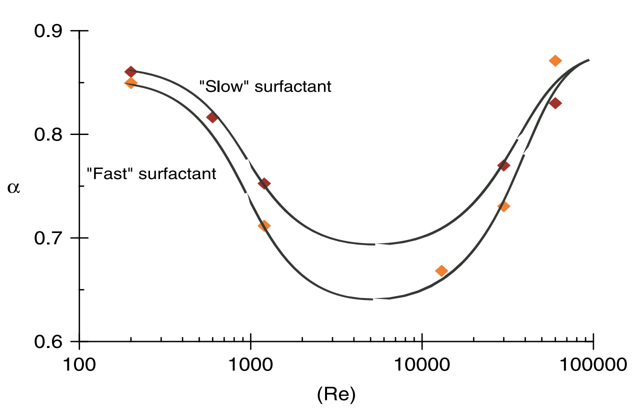

Figure 3 | Effect of flow regime on alpha factors for fine- (low Re) and coarse- (high Re) bubbles in two different surfactant solutions.

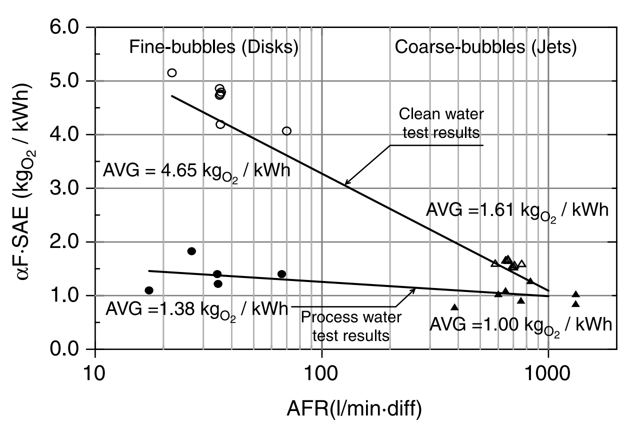

Figure 4 | Variation in standard aeration efficiency for fine- and coarse-bubble diffusers in clean and process water (data from Yunt & Stenstrom 1996).

advantage of fine- versus coarse-bubble diffusers. When high transfer rates ($mass_{O2}$/time) are required, coarse-bubbles may be the only solution, but have higher energy demand and operating costs. When the choice between fine- and coarse-bubble diffusers is permitted, fine-bubble diffusers have the advantage of higher transfer efficiency, lower energy requirements (lower operating costs), but require periodic cleaning.

Operations at high mean cell retention time have a beneficial effect on aeration efficiency and, when nutrient-removing selectors are employed, aeration efficiency is further increased. Whilst removing nutrients, selectors uptake readily available substrate, which otherwise accumulates on bubble surfaces and dramatically reduces aeration efficiency.

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