

# Aeration Efficiency in Oxidation Ditches

## **ABSTRACT**

Oxygen transfer and efficiency in water reclamation facilities are studied. In particular, design aspects of the factors affecting aeration performance in biological reactors are emphasized.

Due to the growing importance of energy consumption, a comparison study has been conducted, evaluating the features and performance of mechanical surface aerators and diffused aeration systems. This has been done with special consideration to oxidation ditches which need to be assessed with regard to creating sufficient horizontal flow in addition to high oxygenation capacity and efficiency.

It was concluded, based on a number of case studies that diffused aeration systems offer significant advantages over mechanical surface aerators in terms of increased oxygen transfer capacity, enhanced levels of process control capability, and reduced energy requirements to produce high quality effluent.

The potential to improve energy efficiency even further with the use of high density, low flux fine bubble diffusers in combination with mid-size, low speed mixers is also discussed.

## **KEYWORDS**

Aeration, mechanical surface aerators, fine bubble aeration, oxidation ditch, horizontal flow, aeration efficiency, energy, power, oxygen transfer, control system

## **INTRODUCTION**

Research and experiences within biological treatment have led to greater ability among municipal water resource recovery facilities to review and upgrade equipment and subsystems to reduce energy consumption. In most cases, processes and equipment concerning aeration are the major consumers of energy. It has been estimated that up to 60% of a plant's power consumption can be attributed to aerobic reactors in the activated sludge process of secondary treatment.

Factors pertaining to power requirement and oxygen transfer of aeration systems in biological treatment are discussed, with emphasis on the difference and effects on energy efficiency between fine bubble aeration and mechanical surface aerators. In particular, oxidation ditches are discussed, which are common in the United States and worldwide, presenting a number of engineering challenges with respect to aeration and mixing.

## GENERAL CONSIDERATIONS IN AERATION EFFICIENCY

### Oxygen Transfer and Efficiency

In order to discuss aeration efficiency, the term efficiency must be clearly defined. It is generally acknowledged that oxygen transfer efficiency (OTE) plays an important role.

$$\text{OTE} = \frac{\text{oxygen transferred}}{\text{oxygen supplied}}$$

eq. 1

**Where** OTE = oxygen transfer efficiency, %

Oxygen transferred = oxygen transferred from bubble to mixed liquor, kg (lb)

Oxygen supplied = oxygen supplied aeration equipment, kg (lb)

If OTE is measured under standardized conditions, as described by American Society of Civil Engineers (2007), the term Standard OTE (SOTE) is used. When comparing performance of different equipment for aeration, it must be done under standardized conditions to validate and normalize performance data.

With regard to energy consumption, the common expression for efficiency is the standard aeration efficiency (SAE) which factors in pressure and efficiency of the mechanical equipment required to achieve a de facto oxygen transfer. The standard aeration efficiency is the amount of oxygen transferred per unit of energy consumed:

$$\text{SAE} = \frac{\text{SOTR}}{\text{P}}$$

eq. 2

**Where** SAE = aeration efficiency, kg O<sub>2</sub>/kWh (lb O<sub>2</sub>/hp.h)

SOTR = oxygen transfer rate, kg/h (lb/hr)

P = power required to transfer one mass unit of oxygen per unit time, kW (hp)

It should be noted that the definition of power must always be stated clearly. In this paper, power is defined as the total input power of any mechanical equipment required to achieve the rate of oxygen transfer for the biological process as stipulated by the European Committee of Standardization (2009).

### Technologies

There is a wide range of equipment suitable for delivering oxygen to aerobic reactors in biological treatment. Aeration devices such as mechanical aerators, and submerged coarse and fine bubble diffusers cover a large portion of aeration equipment installed at water resource recovery facilities globally. The aeration equipment selection process should consider system capacity, operating range, and equipment reliability. Assessment of the aeration system performance should consider total system efficiency, evaluating individual aeration system component efficiencies along with the aeration control algorithm.

Table 1 shows a brief summary of estimated SAE values for common types of aeration equipment used for biological treatment. Aerator types include high and low speed surface aerators, submersed jet aerators (such as nozzles which distribute air below the liquid surface) fine bubble disc diffusers and high density low flux (HDLF) fine bubble diffusers.

**Table 1. Summary of efficiency ranges for various types of aeration equipment (Tschobanoglous et al, 2003).**

Type	SAE, kg O <sub>2</sub> /kWh	SAE, lb O <sub>2</sub> /hp. h
Low speed surface aerators	1.5-2.1	2.5-3.4
High speed surface aerators	1.1-1.4	1.8-2.3
Submersed jet aerators	0.9-1.4	1.6-2.3
Fine bubble diffusers, discs	2-7	3-10
HDLF fine bubble diffusers	3-8	5-13

Note that the SAE values in Table 1 should be used as reference, exact figures are equipment and application specific.

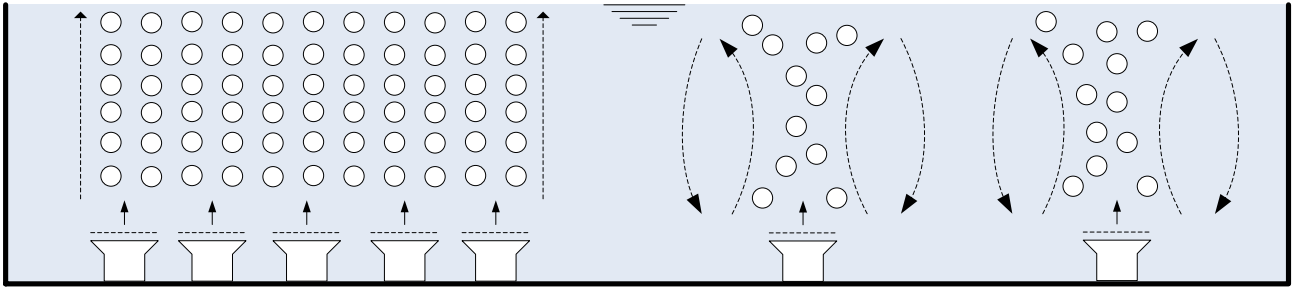
Fine bubble diffusers in particular present major advantages in terms of both capacity and power consumption, however in order to achieve maximum oxygen transfer to energy consumed (SAE), a number of factors relating to the floor density and air flux of the diffusers must be evaluated.

When full floor diffuser coverage systems are considered, diffuser floor density refers to the ratio of area covered by diffuser membranes to the total floor area. Diffuser flux, expressed as flow per membrane area is directly related to the diffuser density if a fixed oxygen transfer rate requirement is considered. In order to model oxygen transfer accurately, Computational Fluid Dynamics (CFD) may provide great insight into the mass transfer mechanisms present in any biological reactor on a case by case basis. However, with extensive oxygen transfer test data at hand, oxygen transfer can be accurately predicted utilizing modern multivariate statistical methods by taking into account the variables associated with the configuration of any full floor coverage diffuser installation.

In summary, the driving forces behind oxygen transfer in fine bubble systems in clean water can be attributed to the following:

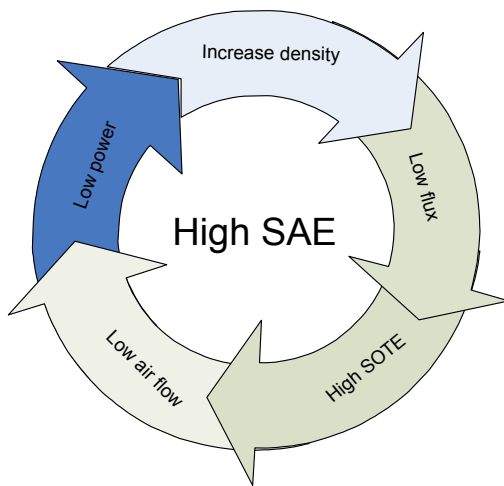
- Diffuser flux
- Diffuser density
- Depth

Obtaining a high transfer efficiency requires optimizing the bubble retention time, thereby increasing the total amount of oxygen transferred per volume of air supplied to the system. Bubble retention time correlates to spiral flow effects, which are more or less present in any bottom diffuser installation and depend on the density and membrane flux of the installed system. The phenomenon of spiral flows is described in Figure 1 below. A densely installed diffuser system with low membrane flux mitigates secondary flow effects, allowing slower bubble rise within the reactor.



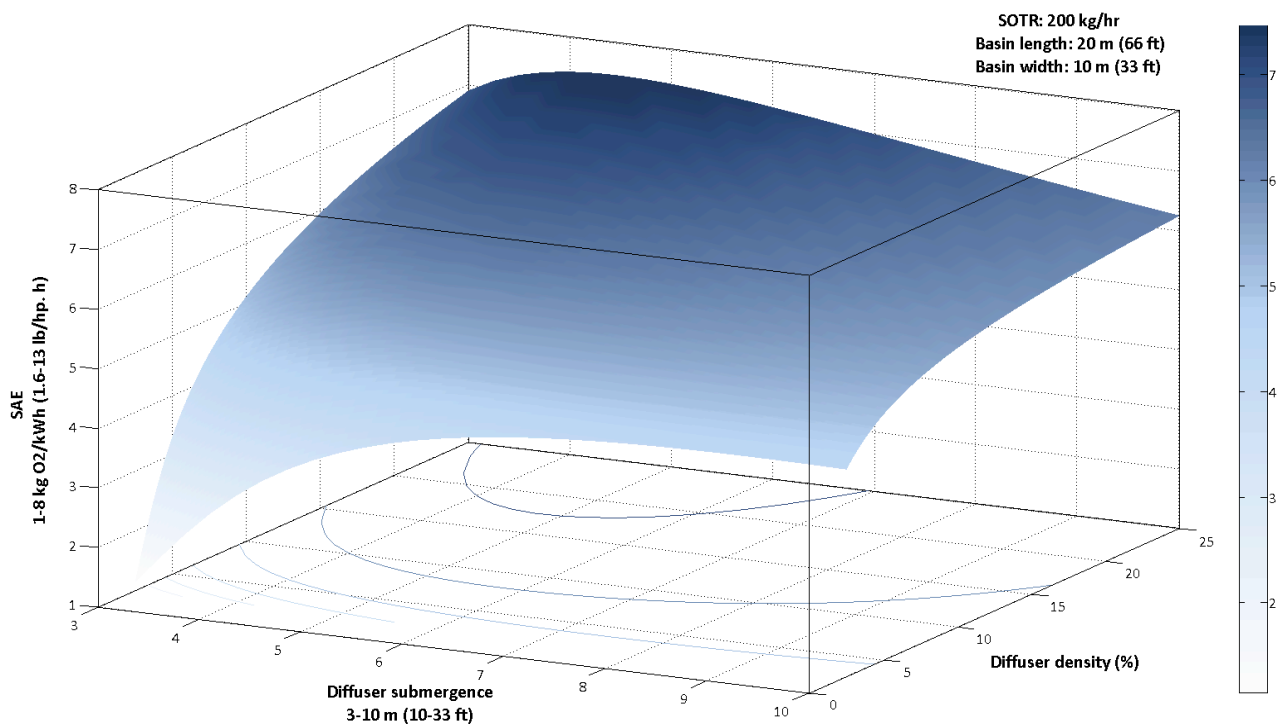
**Figure 1.** Principle of spiral flows. Left: high membrane density fine bubble diffuser system. Right: low density-high flux installation, generating secondary spiral flows causing reduced bubble detention time and oxygen transfer rate.

The response to power requirement of a fine bubble full floor coverage diffuser system can be described conceptually in Figure 2 below. The system as a whole, including air blowers, responds positively by an increase in diffuser density, leading to lower flux and higher SOTE. In what can be described as a positive feed-back response, high SOTE generates lower air flow, pressure and power requirement.



**Figure 2.** Dynamics of the design of a fine bubble diffuser system and the effect on aeration efficiency.

The depth of the aerobic reactor is a vital factor in assessing the oxygen transfer capacity of the aeration system as well as the OTE and the overall SAE. While increasing reactor depth increases the oxygen transfer rate or transfer efficiency SOTE of a bottom diffuser system, its relationship is sub-linear, i.e. SOTE increases slower than linearly versus diffuser submergence. At the same time, system pressure has a nearly linear relationship with diffuser submergence. For a given reactor footprint and oxygen transfer requirement, there exist a power minimum and an SAE optimum. This is portrayed in Figure 3.



**Figure 3.** Optimal diffuser submergence of an aerobic reactor with fine bubble diffused aeration. Example plot under standard conditions according to ASCE (2007) based on Xylem diffuser performance, assuming an overall blower efficiency of 80%.

The positive effects of diffuser density is clearly visible, where the optimal operating point from an energy perspective is a diffuser submergence of 4-5 m (13-16 ft) assuming a constant blower efficiency of 80%. Calculations are based on oxygen transfer performance data of Sanitaire Silver Series II fine bubble diffusers.

The dynamics of the three major factors in aeration system design should be taken into consideration during the engineering and design phase of an activated sludge facility. The optimal design point from an aeration performance perspective varies with the unique characteristics and design of the fine bubble diffuser.

## OXYGEN TRANSFER IN OXIDATION DITCHES

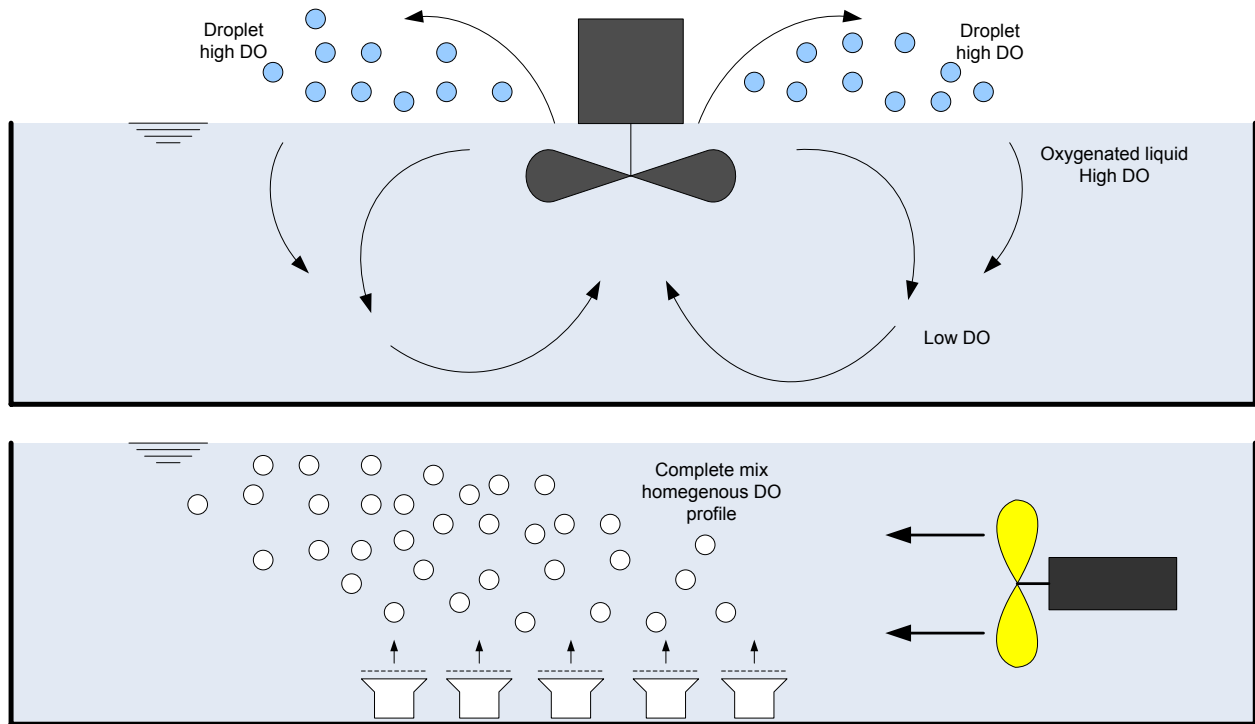
Above discussions pertain mainly to conventional activated sludge processes, however the dynamics of air flux, diffuser density and depth affecting performance are relevant to all variations of the activated sludge process. Oxidation ditches traditionally operate on the basis of supplying oxygen to the biological process in dedicated aeration zones, utilizing simultaneous mechanical generation of horizontal flow to ensure mixing of liquor and transfer of dissolved oxygen to non-aerated zones. Depending on the design of the ditch, non-aerated zones may also provide anoxic conditions for denitrifying bacteria.

### Surface Aerators Versus Fine Bubble Diffused Aeration in Oxidation Ditches

Similar to conventional activated sludge reactors, the oxygenating capabilities of mechanical surface aerators and their SAE should be considered when assessing the power requirements for an oxidation ditch application. Surface aerators rely on producing plumes of droplets above the liquid surface which creates a large water to air surface area for oxygen transfer from the air to the liquid droplets. Oxygen transfer also occurs as air is drawn into the bulk liquid with the mechanical device. The mixing flow pattern in the reactor transfers oxygenated liquid from the surface. Inevitably, a gradient of dissolved oxygen levels forms, where the highest level of dissolved oxygen exists close to the surface and in proximity of the aerating device. In the first generation oxidation ditches, the mixing requirements within an oxidation ditch were satisfied by the aeration device, as vertical or horizontal shaft aerators create a

horizontal flow pattern. Installation of equipment above the liquid surface was seen as an attractive feature of surface aerators.

There may be a number of limitations in such installations, including limited reach of oxygenated liquid in deep tanks, insufficient mixing of liquor, limited turndown capacity, low SAE, and generation of aerosol in the vicinity of the reactor as well as frequent maintenance of rotating parts. The mixing capabilities of such equipment may also limit the horizontal transfer of dissolved oxygen along the lanes of the ditch. Table 2 summarizes features and advantages of surface aerators and diffused aeration. See Figure 4 for the working principles of vertical shaft mechanical aerators and fine bubble diffusers with low speed horizontal mixers.



**Figure 4.** Upper image: vertical shaft surface aerator which oxygenates liquid by generation of plumes of droplets above the surface. Lower image: diffused aeration in combination with submersible low speed mixers, enabling an effective horizontal flow and enhancing the oxygenation of mixed liquor.

Fine bubble diffused aeration offers many advantages to mechanical surface aeration—as discussed previously—in oxidation ditches in particular. General benefits of diffused aeration in combination with submersible mixers include increased SAE (including mixer power), high oxygen transfer rates, independent mixing and aeration devices, completely submersed system with low maintenance needs, and elimination of aerosol formation from rotating parts at the reactor liquid surface.

With independent aeration and mixing devices, fine bubble diffused aeration system not only provide the highest level of OTE, but also provide the capacity to efficiently address a wide range of operating conditions. Independent mixing and aeration offers another level of process control to minimize air flow requirement, adapting blower air flow or control valves against required and observed process parameters such as ammonia-nitrogen and dissolved oxygen concentrations. This level of operational control is restricted with traditional single device serving both aeration and mixing demands.

**Table 2. Features of diffused aeration and surface aeration in oxidation ditches.**

<b>Feature</b>	<b>Diffused aeration</b>	<b>Mechanical surface aerators</b>
SAE	Potentially as high as 7-8 kg O <sub>2</sub> /kWh	Limited to a approximately 2 kg O <sub>2</sub> /kWh
Installation	Diffuser system with piping and blowers. Submersible mixers to generate horizontal flow.	Single unit installation. May require additional stand-alone mixers.
Flexibility in engineering design and capacity	Stand-alone units enable tailor-made solutions which meet oxygen transfer demands.	Limited oxygen transfer variability. Number and size of units is the main flexibility factor.
Installation cost	Depends to a large extent on diffuser density and number of blowers and mixers required. Cost highly related to efficiency.	Relatively low-cost with few additional components. May require additional concrete reinforcements.
Aerosols	Very limited to none.	Common issue due to droplet generation required for oxygen transfer.

### **Combining fine bubble aeration with horizontal flow**

In order to mix liquor in a biological reactor, sufficient thrust must be generated to keep particles in suspension. The use of thrust as a standardized parameter to measure and compare mixer performance is described by ISO (2007). Practically, a certain flow velocity should be maintained throughout an oxidation ditch. The relationship between the required thrust and horizontal flow velocity can be described by equation 3 (Uby, 2012):

$$F \sim k \cdot u^2$$

eq. 3

**Where** F = thrust, N

k = reactor momentum loss factor, -

u = horizontal flow velocity, m/s (ft/s)

For unaerated ditches, a horizontal flow velocity of 0.3 m/s (1 ft/s) most often satisfies particle suspension and mixing of liquor. The loss factor k is a function of tank geometry and obstacles present in the reactor. For oxidation ditches with dedicated aeration zones, the values of both k and u in equation 3 need to be determined as functions of the aeration/mixing horizontal flow effects expanded on below.

Using fine bubble diffused aeration and low speed mixers to generate a horizontal flow around an oxidation ditch presents additional consideration of the momentum losses generated by the vertical rise of bubbles across aerated zones. Proper placement of aeration and mixing equipment is required to ensure optimum performance with respect to mixing and aeration, otherwise spiral flow effects may develop, reducing transfer capacity and efficiency.

Assessment of the ability to produce an even horizontal flow can be done by considering the modified Froude number for such systems. The modified Froude number (Uby, 2012) can be correlated to the total aeration loss factor, where a low loss factor for optimal performance is desired.

$$Fr = \frac{u^2}{gS} \cdot \frac{u}{u_q}$$

eq. 4

**Where** Fr = Froude number, -

u = average cross-section horizontal flow velocity, m/s (ft/s)

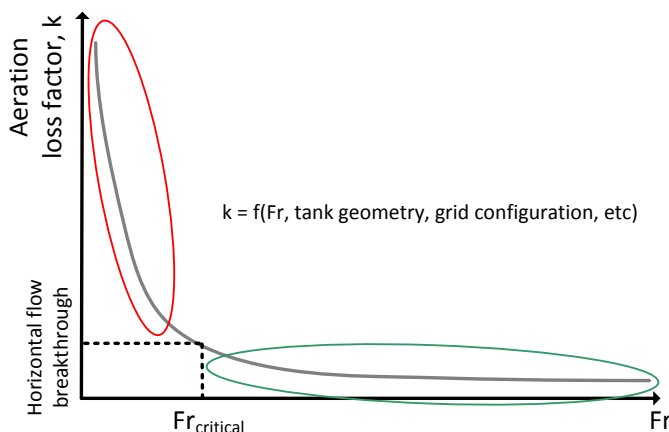
g = acceleration by gravity, 9.8 m/s<sup>2</sup> (32 ft/s<sup>2</sup>)

S = submergence of diffuser, m (ft)

u<sub>q</sub> = air flow per aerated total aerated area, m<sup>3</sup>/m<sup>2</sup>/s (ft<sup>3</sup>/ft<sup>2</sup>/s)

Figure 5 describes in qualitative terms the correlation between the Froude number and the aeration loss factor. For oxidation ditches, a Froude number value estimated using equation 3 should exceed 0.3 (an approximate critical Froude number) to eliminate spiral flows, ensure high oxygen transfer rates and reliable mixing of wastewater (Uby, 2012).

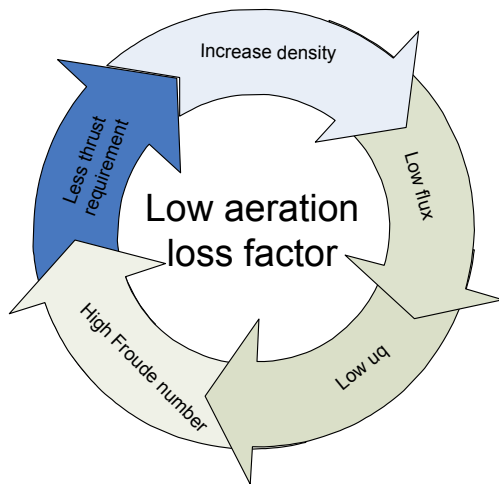
Designing a robust oxidation ditch with stable performance requires a critical Froude number which strikes a proper balance between design depth (relating to S), diffuser flux (relating to u<sub>q</sub>), and mixer thrust (relating to u). The need to establish a critical Froude number relates to the point at which the horizontal thrust produced by submersible mixers breaks through the bubble curtain generated by the diffusers.



**Figure 5.** Depiction of the correlation between the Froude number and the aeration loss factor in horizontal flow-aeration dynamics.

While the aeration loss factor can be implicitly quantified in part by calculation of the Froude number; tank geometry, liquid viscosity, aeration grid layout and mixer positioning also constitute important parameters, as they influence the shape of the aeration loss curve in Figure 5.

The need to appreciate an oxidation ditch as a system with dynamic behavior—whose individual components operate in unison—must be emphasized. Parallel to the pathways of achieving high efficiency aeration systems in general (outlined previously in Figure 2), the aeration-horizontal flow dynamics in oxidation ditches can be described in a similar manner by Figure 6.



**Figure 6.** Achieving low momentum loss caused by aeration in oxidation ditches. A low loss factor is desirable for a well-performing oxidation ditch with low power requirement.

## LESSONS LEARNED

In recent years, significant improvements have been observed at treatment plants which have operated oxidation ditch biological reactors with the use of mechanical surface aerators. Such plants consist of Eunice, LA, South Water Reclamation Facility, FL and Big Gulch, WA. These plants have all replaced mechanical aeration with diffused aeration in combination with submersible low speed mixers, experiencing improved performance and reduced maintenance needs.

### Comparison study – South Water Reclamation Facility, FL

In 2002, South Water Reclamation Facility (SWRF), FL, upgraded one of two identically sized oxidation ditches, installing fine bubble diffused aeration in combination with low speed mixers. The upgrade facilitated an opportunity to compare side-by-side two nutrient removal processes with two fundamentally different aeration-horizontal flow systems as described by Reardon et al (2003).

The two ditches were subject to data collection during the same six months. Xylem Sanitaire fine bubble diffusers and Xylem Flygt mixers were installed in one ditch, designed to achieve both nitrification and denitrification. The other ditch maintained the original vertical/horizontal shaft surface aerators employed to provide both mixing and aeration in a single device. A summary of the performance after the six-month evaluation period is shown in Table 3. The fine bubble ditch received a higher hydraulic load, roughly three times higher, compared to the companion mechanically aerated oxidation ditch. Both lines produced very similar effluent quality. However, the upgraded fine bubble-low speed mixer ditch did exhibit significantly lower power costs per volume of treated wastewater, which was the factor used for normalization of energy comparison.

**Table 3. Summary of performance comparison of the two ditches at South Water Reclamation Facility after six months of testing from 2002-2003 (Reardon et al, 2003).**

Design feature/result	South East reactor	South West reactor
Tank volume, m <sup>3</sup> (ft <sup>3</sup> )	21,405 (755,295)	20,837 (735,243)
Design flow capacity, m <sup>3</sup> /day (MGD)	28,400 (7.5)	77,700 (20.5)
Number of air supply units	5 mechanical surface aerators rated 125 HP	2 air blowers rated at 600 HP
Average power draw, kW (HP)	505 (667)	664 (864)**
Power cost, \$/kWh	\$0.07	
Cost per treated volume of wastewater, \$/km <sup>3</sup> (\$/MG)	432 (114)	204 (54)
aSAE, kg O <sub>2</sub> /kWh (lb O <sub>2</sub> /hp- h)	0.95 (1.6)	1.8 (2.9)**

In Table 3 above aSAE estimation is based on design AOR, measured power uptake and measured alpha factors at both process lines. Alpha at the SE reactor was 0.67 and 0.54 at the SW reactor. Power draw did not include mixer power for the SW reactor.

Note that if an AOR to SOR conversion was to be made using alpha as conversion factors, the South West process would operate at an SAE of approximately 3.3 kg O<sub>2</sub>/kWh (5.4 lb O<sub>2</sub>/hp. h) and the South East process at 1.4 kg O<sub>2</sub>/kWh (2.3 lb O<sub>2</sub>/hp. h), consistent with theoretical tabulated values shown previously in Table 1.

Even though mixer power should be included in the overall energy calculations, the SWRF facility clearly demonstrates the operational advantages that can be made from an energy perspective with a well-working fine bubble system with high oxygenating capacity, without any compromise of the biological process. In fact, a significantly larger biological load could be treated while meeting required effluent targets, with roughly equal operating power.

#### **Creating a low maintenance environment with energy cost saving at Big Gulch, WA**

At Big Gulch WWTP, WA, until 2009, two oxidation ditches were in operation using mechanical brush aerators. The plant experienced maintenance issues concerning the mechanics of the surface aerators in addition to aerosols around the bioprocess basins. To cope with increased influent TSS and BOD loadings, the two ditches were upgraded to operate with a diffused aeration system with automatically dissolved oxygen controlled turbo blowers. Low speed mixers were installed to generate the required horizontal flow (US Environmental Protection Agency, 2010).

Although the intent with the upgrade was primarily to improve operation, reduce maintenance and noise levels, the plant also enjoyed lower power consumption following the upgrades. The diffused aeration upgrade provided an annual energy savings of \$10,000 compared to the four years before the upgrade when mechanical aeration was used.

From a process perspective, the new diffused aeration system, improved performance by reducing the impact of filamentous organisms on sludge settling. Chlorine usage, previously used to control filamentous outbreaks has been reduced with the aeration system upgrade. Fine bubble diffused aeration has provided a much wider control range, enabling the operators to control DO levels during the aerobic phases of the process, along with Oxidation Reduction Potential (ORP) monitoring during the anoxic phases.

The facility has also benefited from the elimination of aerosol previously produced by the brush aerators providing a safer area around the basins.

As a complement study to the South Water Reclamation Facility, Big Gulch showcases operational advantages apart from energy savings alone.

### **Solving performance problems at Eunice Wastewater Treatment Plant**

As discussed previously, oxidation ditch design can be complex with regard to the dynamics of the aeration-horizontal flow. Plants using oxidation ditch technologies should consider installing equipment from suppliers with experience combining low speed mixers and diffused aeration to ensure proper equipment application to provide process and hydraulic performance. The Eunice, LA facility contacted Xylem to investigate the supply of Sanitaire diffused aeration and Flygt low speed submersible mixers to replace the existing aeration and eliminate effluent problems at the site. The previous ceramic diffusers and mixers did not generate the desired process performance over time.

Previously, the facility could not deliver adequate oxygen to maintain the dissolved oxygen levels required for the reduction of ammonia. The highest level of dissolved oxygen was 1.75 mg/L. The system now supplies an average of 5,851 kg standard O<sub>2</sub>/day (12,900 lb/day) to achieve a minimum of 2 mg/L dissolved oxygen. The mixer upgrade provided a healthy 0.3 m/s (1 ft/s) horizontal flow velocity, producing a clear effluent with BOD, ammonia and suspended solids concentrations well below plant permit limits (London, 2010).

### **TAKING PROCESS AND AERATION PERFORMANCE TO THE NEXT LEVEL—ADVANTAGES OF HIGH DENSITY, LOW FLUX DIFFUSER INSTALLATIONS AND IMPROVED MIXER HYDRAULICS**

Taking into account the positive effects of low flux diffuser systems for suspended growth aerobic biological reactors in general, fine bubble high density diffusers offer another choice along with disc diffusers to satisfy oxidation ditch aeration needs. Increasing diffuser floor density not only positively influences SOTE and SAE, but also contributes to high Froude number (and low aeration loss factor due to a low  $uq$ ) as can be derived from equation 4.

Installations with HDLF diffusers may favor the development of a homogeneous horizontal flow throughout the ditch due to significant reduction of the aeration loss factor. Figure 7 shows HDLF diffusers installed at a membrane density of 40%, making possible a low air flux, effectively reducing mixer power as well as enhancing OTE and SAE when compared to an equivalent installation with lower diffuser density.



**Figure 7.** Left: example of an installation of Sanitaire (a Xylem brand) Gold Series HDLF diffusers on a liftable grid with a 40% diffuser density. Right: single Gold Series diffuser.

For ditches with limited possibilities—for example due to available footprint—of achieving desired basin depth or diffuser density to reach a critical Froude number for proper horizontal flow, HDLF diffusers are viable alternatives.

Steady mixer hydraulics product development has yielded new low speed mid-size mixers with high efficiency with lower propeller diameter compared to large low-speed submersible mixers. For example shallow or narrow oxidation ditch channels can still take advantage of diffused aeration in combination with submersible low speed mixers with

maintained high SAE and capacity, without resorting to a mechanical surface aeration installation. Figure 8 displays a comparison of 1.2 m (3.9 ft) mid-size and 1.4-2.5 m (4.6-8.2 ft) large low speed submersible mixers, suitable for oxidation ditch designs.



**Figure 8.** Left: mid-size low speed mixer suitable for oxidation ditches where reactor geometry does not allow for large, low speed mixers (Xylem Inc., 2012a). Right: large, low speed mixer highly suitable for oxidation ditches, capable of high thrust at low power input (Xylem Inc., 2012b).

Thus, the development of mid-size, high thrust and efficiency propellers provide design flexibility even for ditches less than 3 m (10 ft) deep.

## SUMMARY AND CONCLUSIONS

Two viable alternatives for aerating biological reactors in municipal water resource recovery facilities often stand side by side: mechanical surface aerators and fine bubble diffused aeration. Mechanical surface aerators are often found in oxidation ditches but lack many of the features required to provide low operating cost with optimized aeration efficiency while maximizing oxygen transfer capacity without compromising mixing. Diffused aeration is an engineered solution which requires insight into the factors affecting the degree of oxygen transfer for a given reactor geometry and diffuser configuration. However, with experience, such installations offer tangible advantages to mechanical surface aeration including high aeration efficiency, low maintenance, a safer working environment, and increased process control flexibility.

Oxidation ditches present additional challenges in terms of achieving an adequate horizontal flow throughout the reactor. Highlighted in this study are examples where Xylem has successfully incorporated diffused aeration systems with low speed horizontal flow mixers to lower operational costs and at the same time improve effluent quality along with reduced equipment maintenance. It has been demonstrated with the proper engineering experience, diffused aeration and submersible low speed mixers can provide increased treatment capacity, improved energy efficiency, and operational flexibility when compared to mechanical surface aerators.

Due to the nature of the dynamics of the aeration-horizontal flow phenomenon, the use of low flux, HDLF diffusers has the ability to further improve oxygen transfer efficiency and mixer thrust requirement without compromising effluent quality. Further, as an alternative to large, low speed mixers, the next generation of mid-size mixers may offer extended design flexibility.

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