

MODELING WASTEWATER AERATION SYSTEMS TO DISCOVER ENERGY SAVINGS OPPORTUNITIES

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Introduction

Aeration systems for conventional wastewater activated sludge plants typically account for 45 to 60% of a treatment facility's total energy use. The ability to define what improvements will be most cost effective begins with understanding how to create a simplified model of the system.

The equipment used for wastewater aeration is required for the biological process and also to provide mixing to keep solids suspended for more effective treatment. Although there are many types of aeration systems, the two basic methods of aerating wastewater are through mechanical surface aeration to entrain air into the wastewater by agitation, or by introducing air or pure oxygen with submerged diffusers.

When facilities are interested in improving aeration system efficiency to reduce energy costs, the first thought is typically "fine bubble aeration." While this is an excellent way to improve the oxygen transfer efficiency for some aeration systems, many other considerations should be reviewed to understand how each part of the aeration process impacts energy use and the effect it may have on other facility processes.

The focus of this paper is to develop a simple baseline model of a municipal wastewater treatment facilities aeration system, in order to understand the energy savings impact of various operational strategies and equipment selection. The model does not account for interfering agents (such as surfactants) that may be encountered in industrial flows which can cause a decrease in aeration system oxygen transfer, and does not attempt to provide a life cycle cost analysis that reviews equipment life, maintenance costs, or the impact on sludge disposal costs. However, where appropriate, some general discussion of these considerations are presented. Although the steps outlined provide for data collection on a daily basis, monthly averages can also be used. The goal of the model is to identify how equipment improvements and operational adjustments will impact the efficiency of the aeration process.

Treatment Prior to Aeration

Before a discussion of specific opportunities in the aeration process, primary treatment efficiency serves some attention. Improving BOD removal in the primaries is one of the most underutilized methods of reducing secondary treatment aeration system energy use. Making improvements in this process has been one of the most cost effective ways to remove BOD and TSS prior to investing in new aeration equipment. The Portland, Maine POTW provides a good example where this was discovered. Dye tests revealed that improving the flow split to multiple clarifiers, and installing baffles to reduce clarifier short circuiting would improve BOD removal significantly. This, in turn, reduced the BOD load and oxygen demands on the aeration system and maximized the cost effectiveness of aeration system efficiency improvements.

Aeration System Process

One of the variables that can be optimized to reduce energy use is controlling the solids retention time (SRT) of the process. Maintaining a high or low SRT typically has a corresponding effect on the amount of excess sludge that must be wasted from the process and the energy use of the aeration system. If a facility is not required to nitrify, and sludge disposal costs are not high, reducing the SRT can be cost effective by lowering the mixed liquor suspended solids or reducing the number of aeration tanks in service.

Many facilities are required to meet effluent ammonia nitrogen ($\text{NH}_4^+\text{-N}$), or total Kjeldahl nitrogen (TKN) limitations for their discharge permits and must operate their aeration systems carefully to ensure a certain level of nitrification occurs. This includes maintaining an adequate SRT, and understanding the effect that temperature, dissolved oxygen levels and pH have on nitrification. Unfortunately, during nitrification, oxygen demand increases substantially.

One method of reducing energy use for facilities required to nitrify is to create an anoxic zone at the head end of the aeration basin. This is best applied at extended aeration plants or conventional activated sludge facilities. For this process, an oxygen-deficient zone (typically 15% of the aeration tank volume) is created to allow the activated sludge bacteria to use the nitrate to oxidize waste BOD. From this process, nitrogen gas is created as denitrification occurs.

For facilities with diffused aeration systems, the anoxic zone is typically created by reducing the air flow significantly to the anoxic zone diffusers to maintain just enough air flow for mixing. Several facilities have found that mixing can be accomplished more efficiently in this zone by using submerged or floating mixers.

Aeration System Equipment

The equipment used to deliver oxygen to the aeration system is typically provided by surface mechanical type aerators or diffused aeration systems. Some common types of mechanical surface aeration equipment include low speed mechanical aerators, direct drive surface aerators, and brush type surface aerators.

Diffused aeration systems include a low pressure, high volume air compressor (blower), air piping system, and diffusers that break the air into bubbles as they are dispersed through the aeration tank. The most commonly used blowers are positive displacement type blowers, and centrifugal blowers (single and multi-stage).

Some aeration equipment combines diffusers with mechanical aerators. Submerged turbine aerators use sparger rings to deliver diffused air below mechanical mixers. As the bubbles rise, the mixers shear the coarse bubbles and provide mixing as well.

The diffusion of air can be accomplished with several types of diffusers. Typical clean water oxygen transfer rates are shown in Table 1.

Table 1. Typical Clean Water Oxygen Transfer Rates (EPA 1984)

Diffuser Type and Placement	Oxygen Transfer Rate lb O ₂ /hp-hr
Course Bubble Diffusers ¹	2.0
Fine Bubble Diffusers ²	6.5
Surface Mechanical Aerators	3.0
Submerged Turbine Aerators ³	2.0
Jet Aerators ⁴	2.8

¹ For 2.7 - 3.6 m (9-12 feet) submergence

² For 18 - 26 w/m³ (0.7-1.0 hp-hr/100 ft³)

³ Includes both blower and mixer horsepower

⁴ Includes both blower and pump horsepower

Without a comprehensive model of the aeration system, energy savings calculations comparing course with fine bubble aeration systems are often skewed by not including the increased back pressure that occurs in fine bubble systems, or taking credit for improved control of dissolved oxygen levels as part of a diffuser upgrade. This can be addressed by separating the calculations for each of these improvements.

As part of the calculation process of comparing aeration system equipment, the relative rate of oxygen transfer in wastewater compared to clean water must be established (alpha value). Typical alpha values are shown in Table 2.

Table 2. Typical Alpha Values

Aeration System	Typical Alpha (α)
Course Bubble Diffusers	0.80
Fine Bubble Diffusers	0.45
Jet Aeration	0.75
Surface Mechanical Aerators	0.85
Submerged Turbines	0.85

The value relating oxygen saturation in wastewater compared to clean water is referred to as the beta value (β). For municipal wastewater, 0.95 to 1.0 is typically used (EPA 1989).

With the focus on fine bubble diffused aeration systems to improve aeration system efficiency, the system blower(s) is often a secondary consideration that is not given enough attention. All too often, oversized blowers are installed that must be operated at less than 50% of their designed

capacity using variable speed drives or throttling air flows just to maintain a DO level in the 4 to 5 mg/l (ideal range is 1.5 to 2.0 mg/l). The inefficiency of operating an aeration system at high DO levels is compounded by the poor mechanical efficiency of some blowers at reduced outputs.

A comparison of guaranteed shaft horsepower values between blower manufacturers at specified humidity, temperature, and turn down air flows, reveals some surprising results. While some facilities may feel that a positive displacement blower and a variable speed drive provides an efficient system at reduced air flows, comparing the energy use of this equipment with an efficient single stage centrifugal blower controlled with damper controls can provide impressive savings.

Comparing manufacturer’s guaranteed shaft brake horsepower values can be challenging as well. The most accurate method is with the ASME Power Test Code PTC-9 for positive displacement blowers, and ASME PTC-10 for centrifugal blowers. This testing procedure uses a calibrated torque meter to measure the compressor/gearbox shaft input horsepower. Alternative testing methods that use heat balances may not provide accurate results.

Another important function of the aeration equipment is to provide adequate mixing in the tanks to prevent solids from settling. This is an important aspect that is often overlooked when aeration systems are reviewed for energy saving opportunities. It is typical for many municipal wastewater treatment facilities to have BOD load be the predominant factor for the aeration system to satisfy during the day, but when BOD loads decrease during the late evening hours, adequate mixing in the tank may be the controlling energy requirement. Table 3. shows typical minimum mixing values for aeration tanks (EPA 1989, M&E 1991).

Table 3. Typical Aeration Tank Mixing Requirements

Type of Aeration System	Mixing Requirement
Course Bubble Diffused Aeration	20 to 30 scfm/1000 cu.ft.
Fine Bubble Diffused Aeration	7 to 10 scfm / 1000 cu.ft.
Mechanical Surface Aeration	0.6 to 1.15 hp/1000 cu.ft.

Some facilities have successfully used a combination of high efficiency mixers (.23 hp/1000 ft³) with aeration equipment to optimize their aeration process. The mixers can be used during periods when mixing energy requirements control to maximize treatment efficiency while minimizing energy demand. This hybrid system is currently being used successfully at the Anson-Madison Wastewater Treatment Facility in Madison, Maine.

Aeration Control Systems

Although the type of aeration system is important to deliver air as efficiently as possible, *one of the single greatest factors that can provide the most cost effective energy savings impact for a facility is applying an automatic control system.* For aeration systems, dissolved oxygen probes and analyzers are the most commonly used instruments to measure the level of dissolved oxygen in the wastewater and provide a variable signal to adjust air flow, tank level (using adjustable weirs) or mechanical aerator speed.

Reliability, maintenance issues and calibration requirements have been a concern with dissolved oxygen (DO) probes. Although the reliability of DO probes has improved substantially over the last 10 years, the probes must still be cleaned periodically to ensure accurate readings. Even with the maintenance drawbacks, the ability to automatically control high energy aeration equipment is one of the most effective methods of reducing aeration energy use.

The ability to immediately identify the energy savings impact of taking an average DO level of 3.0 to 4.0 mg/l (typical for many facilities that do not have automatic controls) and maintain a consistent 2.0 mg/l can easily be done with an aeration model to understand the cost effectiveness of these type of controls.

Developing a Simple Model

Up to this point we have provided a general discussion of aeration systems and reviewed the minimal data requirements for determining the energy savings impact of aeration system improvements. The values and assumptions to be used in the model are shown below in Table 4.

Table 4. Calculation Values and Assumptions

<u>Values</u>	<u>Definition</u>	<u>Source</u>
α = (see Table 2)	Ratio of oxygen transfer efficiency (OTE) in wastewater to OTE in tap water. This parameter accounts for the effects of aeration type, basin geometry, degree of mixing, and the wastewater characteristics such as the presence of surfactants.	1, 2
β = 0.95	$C_s(\text{wastewater})/C_s(\text{tap water})$. This term corrects for constituents in the wastewater which impact the solubility of oxygen.	1, 2
Θ = 1.024	Arrhenius constant- used to correct for the effects of temperature.	1
e = 0.75	Blower efficiency for diffused aeration systems (typ. range 0.7-0.9)	1
Alt. (ft) = 200	Altitude above mean sea-level	
$BOD_{in}(\text{mg/L})$ = 220	Biochemical oxygen demand influent for a typical medium strength municipal wastewater flow.	1
$BOD_{ef}(\text{mg/L})$ = 20	Biochemical oxygen demand (assume 20 mg/L)	

Con.	= 1.0	Pounds of oxygen required per pound of BOD removed. Value is dependent upon the SRT and temperature: Generally, the higher the SRT/temperature, the higher the ratio (up to ≈1.5).	
Con.N	= 4.57	Pounds of oxygen required per pound of TKN oxidized to nitrate.	
C _{s,20}	= 9.02	Oxygen saturation concentration for tap water at 20°C	1
C _{s,T}	=	Oxygen saturation concentration corrected for altitude and temperature	1
C _w (mg/L)	= 3.0	Operating dissolved oxygen concentration. highly variable from plant to plant, 2-4 mg/L, is the typical range.	1
Dynamic Pres.	= 2.0 (lb _f /in ²)	Headloss associated with the piping and diffuser for diffused aeration system. Dynamic pressure is a function of the type of piping, length, diameter, and tortuosity (bends, elbows, etc.) of the piping and the type of diffuser being employed.	
H (ft)	= 14	Depth of submergence for diffused aeration systems (static head on diffusers). In general, greater depth results in greater transfer efficiency.	
Nit. (%)	= 50 or 0	Percent nitrification in WWTP varies as a function of season. For model, assume 50% nitrification in summer and none in the winter.	
OTR	=	Oxygen transfer rate under process conditions	
LOTR	= 2.5	Standard oxygen transfer rate in clean water at 20 degrees C and zero dissolved oxygen (mechanical aeration calculations)	
FOTR	=	Field oxygen transfer rate (mechanical aeration calculations)	
Q (MGD)	= 1	Municipal waste water flow in millions of gallons per day	
SOTE	= 0.28	Standard oxygen transfer efficiency in clean water (e.g., 28% of O ₂ actually dissolves into water). SOTE is very dependent upon the depth of submergence and the type of diffuser (diffused aeration systems)	1
SRT (d)	= 8	Solids retention time in days. SRT represent the average age of the microorganisms in the system.	
T (C)	=	Outside temperature value in degrees C	
TKN _{in} (mg/L)	= 40	Total Kjeldhal Nitrogen: Concentration of nitrogen for a typical medium strength municipal wastewater.	1

Sample Calculations

The key equations used in the model that will help quantify energy savings are as follows:

First calculate the amount of oxygen required for BOD oxidation in aeration basins (lb/d):

$$O_{\text{req.}}(\text{lb/d})_{\text{BOD}} = (\text{BOD}_{\text{in}} - \text{BOD}_{\text{ef}}) \otimes 8.34 \otimes \text{Con.} \otimes Q$$

$$O_{\text{req.}}(\text{lb/d})_{\text{BOD}} = 1,668$$

$$\underline{\text{OTR}(\text{lb/hr})_{\text{BOD}} = 69.5}$$

Next, calculate the amount of oxygen required for 50% nitrification in the summer (lb/d):

$$\text{O}_{\text{req.}}(\text{lb/d})_{\text{TKN}} = (\text{TKN}_{\text{in}} - \text{TKN}_{\text{ef}}) \otimes 8.34 \otimes \text{Con.N} \otimes Q$$

$$\text{O}_{\text{req.}}(\text{lb/d})_{\text{TKN}} = 762.3$$

$$\underline{\text{OTR}(\text{lb/hr})_{\text{TKN}} = 31.8}$$

Mechanical Aeration Systems

Calculate the field oxygen transfer rate (FOTR) of the mechanical aeration system. This equation corrects for the effects of surfactants, temperature, salinity, etc.

Example for Summer Operation: Temp. = 25 °C therefore $C_{s,T} = 8.19$

1

$$\text{FOTR} = \text{LabOTR} \otimes \left(\frac{\beta \otimes C_{s,T} - C_w}{C_{s,20}} \right) \otimes \alpha \otimes (\Theta^{(T-20)})$$

Summer: $\underline{\text{FOTR}(\text{lb O}_2/\text{hp-hr}) = 1.27}$

Now calculate the horsepower required to meet the OTR

The power requirements are as follows:

Summer: $\underline{\text{hp} = \text{OTR}/\text{FOTR} = (69.5 + 31.8)/1.27 = 80}$

Diffused Aeration Systems

Convert the total pounds of oxygen per day into standard oxygen transfer rate (SOTR). This equation corrects for the effects of surfactants, temperature, salinity, membrane fouling, etc.

Summer: Temp. = 25 °C therefore $C_{s,T} = 8.19$

1

$$\text{SOTR} = \frac{\text{OTR}}{\left(\frac{\beta \otimes C_{s,T} - C_w}{C_{s,20}} \right) \otimes \alpha F \otimes (\Theta^{(T-20)})}$$

Summer: $\underline{SOTR (lb O_2/hr) = 378}$

Next convert the SOTR to standard cubic feet per minute of air required (SCFM):

$$SCFM = \frac{SOTR}{60 \otimes \rho_{air} \otimes SOTE \otimes 0.23}$$

Summer: $\rho_{air} = 0.0769 \text{ lb/ft}^3$ $\underline{SCFM = 1,272}$

Note: The density of air was calculated using $pV = nRT$ with the pressure being corrected for the elevation (see Ref. 1 pp. 1249). The constants 60 and 0.23 represent the number of minutes per hour and the lbs of oxygen per pound of air, respectively.

Now that we have the SCFM required, we need to calculate the horsepower required for the blower by calculating the power requirement for adiabatic compression (1):

$$P_w = \frac{WRT_1}{550 \otimes n \otimes e} \left[\left(\frac{p_2}{p_1} \right)^{0.283} - 1 \right]$$

where

P_w = power requirement of each blower (hp)

W = mass flowrate of air (lb/s)

R = engineering gas constant for air 53.3 (ft-lb/(lb air)°R)

T_1 = absolute inlet temperature (°R = 460 + °F)

p_1 = absolute inlet pressure (lb_f/in²)

p_2 = absolute outlet pressure (lb_f/in²)

n = 0.283 for air

550 = ft-lb/s-hp

e = efficiency

In order to do this, we must first calculate the weight of the flow of air and the absolute inlet and outlet pressures for the blower.

$W = SCFM \otimes \rho_{air} \otimes 1/60$ (converts SCFM to lb/s)

$p_2 = \text{absolute outlet pressure (lb}_f\text{/in}^2\text{)} = \text{static pressure} + \text{dynamic pressure} + \text{atmospheric}$

Static pressure = pressure applied to diffuser due to the depth of submergence.

Static pressure = 14 ft-water \otimes 33.7 ft-water/atm \otimes 14.7 lb_f-atm/in² = 6.1

Dynamic pressure = 2 pressure loss associated with piping and diffuser.

Summer: $W = 1.630$ $p_1 = 14.7$ and $p_2 = 6.1 + 2 + 14.7 = 22.8$

The power requirements are as follows:

$$\text{Summer: } \underline{P_w(\text{hp}) = 53}$$

To convert the hp to kW, multiply by 0.746 kW/hp and divide by electrical system efficiencies (motor, variable speed drive, etc.). To convert to electrical costs (\$/d), multiply the kW answer by 24 (hr/d) \otimes kW cost (\$kW/hr).

Example Aeration System Model

Based on the assumptions listed above, and the data collected, a spreadsheet format can be developed. A sample model based on the above calculations is shown on the following page.

(insert spreadsheet model)

Summary

The model presented is the first step in discovering aeration system energy savings. Additional columns can be added to compare the impact of changing the SRT, creating an anoxic zone, or comparing blower efficiencies at different humidity and temperature conditions.

Variations of this spreadsheet model have been used at many municipal wastewater treatment facilities to identify cost effective improvements for aeration systems. Savings of 30 to 60% have been identified through this modeling process saving facilities hundreds of thousands of dollars annually.

References:

1. USEPA., (1989), "Design Manual - Fine Pore Aeration Systems", Center for Environmental Research, Cincinnati, Ohio
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3. Hunt, B., (1996), "Fine Bubble", "Mechanical Aeration" Woodard & Curran
4. Mitchell, B., (1990), "A Practical Guide to Energy Conservation Measures in Water Quality Systems", University of Florida TREEO Center, Gainesville, Florida