FACT SHEET

Liquid Stream Fundamentals: Aeration Design

This fact sheet covers an overview of diffused and mechanical aeration, basic concepts of aeration design, the parameters and correction factors utilized in aeration design calculations, and aeration design considerations as well as solutions.

Introduction

Biological treatment of organic material and ammonia requires ample oxygen to facilitate degradation and removal. However, minimal ***Dissolved Oxygen (DO)*** is typically present in raw wastewater, and must be added to the treatment process to enhance and facilitate biological removal of soluble organic material and ammonia. ***Water Resource Recovery Facilities (WRRFs)*** rely on aeration systems to transfer oxygen from a gaseous state to a dissolved liquid form that is available to support biological treatment. Aeration can be provided through mechanical agitation of the liquid surface to entrain DO in the aeration tanks (mechanical aeration) or through introducing oxygen into the aeration tanks through porous devices (diffused aeration). Aeration systems are designed to increase the air-water interface within a process liquid, allowing for sufficient oxygen transfer required to support the biological processes.

Mechanical aeration consists of motor-driven impellers, propeller aspirators, or rotors that generally operate at the liquid surface to provide DO within the aeration tanks. The impeller and rotor transfer oxygen by mixing the liquid surface while the propeller aspirator injects atmospheric air into the liquid. The equipment used depends on which configuration was utilized for the treatment process. There are four general configurations for mechanical aeration systems: radial flow low speed, axial flow high speed, horizontal rotors, and aspirating devices. Radial flow low speed and axial flow high speed utilize impellers that can be designed at the liquid surface or submerged at varying depths (see Figures 1 and 2). Horizontal rotors utilize horizontal impellers (rotors) to agitate the liquid surface and deliver oxygen to the aeration tanks (see Figure 3). Aspirating devices utilize a propeller aspirator which can be positioned at various angles to reach distinct levels for aeration mixing (see Figure 4). The ***Standard Aeration Efficiency (SAE)*** of each configuration is dependent upon the design of the equipment used (impeller, rotor, or propeller aspirator), tank geometry, effects of adjacent walls, input power to tank volume, and various other factors [1].

Figure 1—Radial flow low speed surface aerator [2].

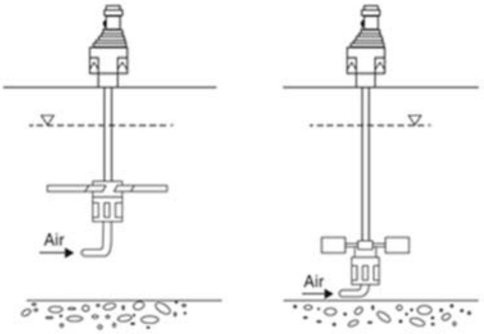

Figure 2—Axial flow submerged turbine aerator (left) and radial flow submerged turbine aerator (right) [1].

Figure 3. Horizontal rotor [1][2].

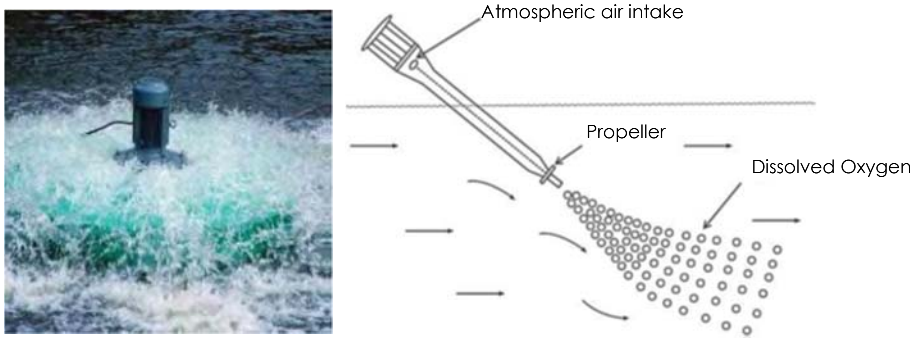

Figure 4. Aspirating device [1][2].

Diffused aeration systems typically consist of mechanical equipment including blowers, air piping and diffusers, that work in conjunction with instrumentation and controls to deliver oxygen as required to support the biological processes. Ambient air is compressed and introduced via submerged diffusers to distribute gaseous air bubbles in the process liquid (see Figures 5 and 6). Fine pore diffusers create smaller bubbles which maximize the air-water interface, and subsequently allow for greater oxygen transfer from the air to the liquid. Once in liquid form, the oxygen is available for use by the biological process. Refer to the *Aeration Diffuser Fundamentals* and the *Aeration Blower Fundamentals* Fact Sheets for additional information regarding the mechanical components that comprise diffused aeration systems.

Figure 5. Coarse bubble diffuser 0.2 – 0.5in. in diameter [2]

Atmospheric air is commonly used for both mechanical and diffused aeration purposes at WRRFs, as it is an abundant, easily accessible resource. Ambient, atmospheric air, is comprised of approximately 21% oxygen (depending on the altitude). Alternatively, pure oxygen, or ***high-purity oxygen (HPO)*** can also be used for aeration; however, considering the operations and maintenance costs of oxygen generation systems and/or commercially available bulk oxygen, the use of HPO for aeration is less common [1].

WRRFs may also draw foul air from the headspace of process tanks or from odorous buildings such as preliminary treatment facilities for odor control, and use that air for aeration of biological processes. Odorous air, however, contains compounds that could potentially lead to corrosion of aeration equipment, and if odorous air is used for aeration, careful consideration for compatible materials must be included in the selection and design of aeration equipment.

Figure 6. Fine bubble diffuser 0.04 – 0.1in. in diameter [2]

Aeration System Design

Design of aeration systems generally includes selecting equipment and developing controls that will allow for the delivery of oxygen as required to support the biological treatment system. The first step in designing an aeration system is to determine the oxygen demand. Although process model simulations aid in determining oxygen demand and aeration requirements, it is important to understand the factors that influence oxygen demand and how oxygen demand is calculated.

The amount of air required to support the biological process is also known as the ***Actual Oxygen Requirement (AOR)***, and is given in terms of mass per time (i.e. lbs O_2/day). The following considerations factor into calculation of the AOR:

- ***Design Flows and Loads.*** Establishing the correct flow and load criteria is imperative to the success of the aeration system design. In general, the aeration system must be capable of providing sufficient oxygen under minimum, average and peak demand conditions. Design guidelines recommend accounting for the 24-hour demand of the average day of the peak month when calculating the maximum aeration requirements [1].

- ***Requirements for Carbonaceous Biochemical Oxygen Demand (cBOD) Removal.*** The mass of oxygen required to satisfy carbonaceous oxidation can be approximated for preliminary design assuming a range of 0.9 to 1.3 lb O_2 is required per pound of cBOD removed [3]. The amount of oxygen per mass cBOD removed is dependent on the ***Solids Retention Time (SRT)*** of the process, and processes operated at a longer SRT require more oxygen per mass of cBOD due to endogenous respiration. Equation 12.8 in WEF MOP 8 or Figure 5-4 in the USEPA Fine Pore Aeration Design Manual can be used to estimate the carbonaceous oxygen demand applied to actual aeration system design [1][4]. The reaction of carbonaceous oxidation and removal can be found below [5]:
  Oxidation and synthesis:

  $$COHNS + O_2 + nutrients \rightarrow CO_2 + NH_3 + C_5H_7NO_2 + other\ end\ products$$

  Endogenous respiration:

  $$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + energy$$

- ***Requirements for Total Nitrogen Reduction.*** Oxygen demand to satisfy nitrification needs to be considered in addition to the oxygen demand required for carbonaceous oxidation for systems which provide ammonia removal or otherwise nitrify. In general, 4.6 lb of O_2 is required per pound of ammonia oxidized to nitrate [1]. Equation 12.14 of WEF MOP 8 should be used to calculate the oxygen demand required for nitrification. The reaction for oxidation of ammonia to nitrate can be found below:

  $$NH_4^+ \rightarrow 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

  $$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

  $$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

Once the AOR is calculated, the ***Standard Oxygen Requirement (SOR)*** can be estimated. The SOR is the amount of oxygen that needs to be transferred to meet the AOR after adjusting for the environmental conditions within the aeration tank. The SOR value is used to determine the air demand required to deliver sufficient oxygen to the process liquid. The air demand, given in terms of ***standard cubic feet per minute (scfm)***, is calculated by accounting for the specific weight of air at standard temperature, as well as the mass fraction of oxygen in air.

Additionally, the ***Standard Oxygen Transfer Efficiency (SOTE)*** of the aeration equipment must be applied to the air demand calculation. The SOTE varies depending on the aeration equipment as well as the air flux applied to the diffuser, with fine bubble diffusers exhibiting higher SOTE values (~2%/ft submergence) compared with coarse bubble diffusers (< 1%/ft submergence) and jet aerators (between < 1%/ft and 2%/ft submergence) [1].

Air demand calculations must also account for the quantity of air required to maintain biomass in suspension. The volume of air required to provide sufficient mixing depends on a variety of factors, including the tank geometry and the biomass concentration. The tank geometry is a key factor to consider because typically the back of the aeration tank receives a limited amount of mixing, especially if a tapered grid system is utilized. In suspended growth aeration systems, the air demand for mixing is typically less than that required for oxygen transfer to support biological processes. In fixed growth and ***Integrated Fixed-Film Activated Sludge (IFAS)*** biological processes, mixing requirements often exceed process aeration requirements due to the fixed or floating media added to the ***Mixed Liquor Suspended Solids (MLSS)*** that promotes additional biological growth. However, the air demand requirements for mixing should still be compared with the air demands for oxygen transfer across all of the zones of an aeration tank to ensure that sufficient mixing air is provided.

The ***Standard Oxygen Transfer Rate (SOTR)*** is the rate at which the SOR is transferred in tap water at 20°C and zero DO. The **Actual Oxygen Transfer Rate (AOTR or OTR_f)** is the rate at which AOR is transferred under field conditions. A variety of factors influence the OTR_f, and the quantity of oxygen delivered to a process fluid must exceed the AOR value to account for the reduced transfer efficiency in process water versus standard tap water. To determine the OTR_f, SOTR must be calculated first using Eq. 12.30 from WEF MOP 8.

$$SOTR = V\frac{\sum_{i=1}^{n} K_L a_{20i} C^*_{\infty 20i}}{n}$$

$K_L a_{20}$ = sampling point value of $K_L a$ (volumetric mass-transfer coefficient) corrected to 20°C, time^{-1}

$C^*_{\infty 20}$ = sampling point value of steady-state dissolved-oxygen saturation concentration corrected to 20°C, mass/volume

C^* = equilibrium spatial average dissolved-oxygen saturation concentration, mass/volume

V = aeration tank volume, volume

n = sampling point

Since many of the factors that influence the OTR_f depend on the type of aeration equipment to be implemented, a general understanding of the aeration system equipment should be established prior to calculating the OTR_f. Table 1 provides SOTR ranges for a variety aeration equipment.

***Diffused Aeration Devices**	**Standard Transfer Rate (lb O_2 / hp*h)**
Fine Bubble	2.0 – 3.3 (1.2-2.0)
Medium Bubble	1.6 – 2.6 (1.0-1.6)
Coarse Bubble	1.0 – 2.0 (0.6-1.2)
Tubular System or Static Tube	2.0 – 2.6 (1.2-1.6)
Jet	2.0 – 4.0 (1.2-2.4)
Aspirator Jet	2.5 – 4.0 (1.5-2.5)
U-tube	2.1 – 4.0 (1.3-2.4)
Mechanical Aerators	
Surface low-speed	2.5-3.5
Surface low-speed with draft tub	2.0-4.6
Surface high-speed	1.8-2.3
Submerged turbine with draft tube	2.0-3.3
Submerged turbine	1.8-3.5
Submerged turbine with sparger	2.0-3.3
Horizontal rotor	1.5-3.6

Table 1 – Aeration Equipment vs SOTR

****Values in brackets are directly from the reference which was provided in kg O_2/kW*h. For consistency purposes values were converted to lb O_2/hp*h [5][6].***

In order to account for field conditions, multiple correction factors are applied to the SOTR to calculate the OTR_f. Table 2 provides a summary of the correction factors used in oxygen-transfer to account for non-standard conditions. Eq. 12.32 from WEF Mop 8 shows the calculation for OTR_f and how the correction factors are applied.

$$OTR_f = SOTR\alpha F\theta^{T-20}\frac{(\tau\beta\Omega C^*_{20} - C)}{C^*_{20}}$$

OTR_f = oxygen-transfer rate estimated for the system operating under process conditions, mass/time

SOTR = standard oxygen- transfer rate of new diffuser, mass/time

C^*_{20} = steady-state value of dissolved-oxygen saturation at infinite time at 20°C and a barometric pressure of 100kPa (1.0 atm), mass/length^3

C= average water process volume dissolved-oxygen concentration, mass/length^3

Correction Factor	Name	Description	Typical Value
α	Wastewater Correction Factor for Oxygen Transfer	The α ("alpha") factor adjusts the oxygen transfer rate to account for variations in wastewater characteristics, aeration tank layout, and aeration system equipment. Aeration equipment, such as diffusers, are typically tested in clean water to determine the oxygen transfer rate and efficiency of specific equipment. Since the oxygen transfer efficiency is greater in clean water, the α factor is applied to account for lower transfer efficiency in process water (i.e. wastewater). Values for α range from approximately 0.3 to 1.0 [3], depending on the type of aeration equipment used (see Table 1). The α factor applied to systems with diffused aeration is typically on the low end of the range, while the α factor applied to mechanical aeration equipment is typically on the higher end of the range.	0.3-1.0
F	Fouling Factor	The fouling factor accounts for the loss of oxygen transfer efficiency that results from buildup or scaling of biological and/or chemical film or deposits on the surface of aeration equipment. Fouling is most commonly experienced on the surface of fine-pore diffusers. The typical fouling factor ranges from approximately 0.5 to 1.0 [1] for fine-pore diffusers. Mechanical aeration systems or coarse bubble diffusers typically have a fouling factor of 1.0 due to their resistance to fouling.	0.5-1.0
αF	Combination of Alpha and Fouling Factors	When selecting an α factor, potential fouling should be considered. Therefore, α is then referred to as αF (alpha-F). αF is site specific and ranges widely from 0.11 – 0.79 with a mean of < 0.5 [5].	0.11-0.79
β	Wastewater Correction Factor for Oxygen Solubility	The solubility of oxygen in wastewater depends on the concentration of salts and particulates in the process liquid. The β correction factor accounts for the reduction in oxygen transfer efficiency that results from the presence of these constituents in the wastewater. A typical β factor ranges from 0.95 to 0.98 [3].	0.95-0.98
θ	Temperature Correction Factor for Oxygen Transfer	Accounts for variations in oxygen transfer efficiency as a result of the process liquid temperature. The typical temperature correction factor applied to the SOTR calculation is 1.024 [1].	1.024
τ	Temperature Correction Factor for Oxygen Saturation	The τ value allows for a correction of oxygen transfer efficiency to account for fluctuations in oxygen saturation concentration that result from variation of wastewater temperature. τ is calculated by dividing the oxygen saturation at the current temperature by the oxygen saturation at 20°C. DO saturation values used to calculate τ are typically found in reference materials such as Metcalf & Eddy and can range from 0.7 – 1.6.	0.7 – 1.6
Ω	Pressure Correction Factor for Oxygen Saturation	The Ω factor accounts for variations in oxygen transfer efficiency that result from dissolved oxygen saturation as a result of atmospheric air pressure. Ω is calculated by dividing the barometric pressure at the site by the standard atmospheric pressure. The barometric pressure is a function of average elevation and temperature compared to standard pressure [1].	$\frac{P_b}{14.7\ psi}$
DO	Design Dissolved Oxygen Concentration	Aeration systems are designed to maintain a specific DO concentration in the process fluid. The design DO typically ranges from 0.5 mg/L to 2.0 mg/L, depending on the flow and load conditions and the process employed. Under low and average load conditions, Aeration systems have historically been designed to maintain DO concentrations around 2 mg/L. Lower DO concentrations (i.e. 0.5 mg/L) during peak load conditions are generally acceptable, but may lead to system upset such as film and bacteria growth [1]. Advanced aeration control, allowing operation at lower DO concentrations, is becoming more prevalent.	0.5-2.0 (mass/length^3)

Table 2 – Summary of Correction Factors used in Oxygen-Transfer Equation

Design Considerations

Efficiency of aeration systems is a major consideration in design, as aeration systems typically account for the largest energy draw and consumption at WRRFs. Considering that flows and loads vary both seasonally and diurnally, aeration systems must be designed to meet the demand of a wide variety of conditions. Designing for maximum flows and loads to account for worst case conditions, however, leads to the over-sizing of equipment with the inability to turndown to meet actual demands, and results in wasted energy and potential process upset. A variety of solutions exist to prevent over-design of aeration equipment and optimize energy consumption. Such solutions include:

- Provide blowers of varying sizes and with different turndown capabilities. Larger blowers can operate to deliver air under high flow and load conditions, and turn off when peak conditions subside. Smaller blowers can then take over operation during low and/or average flow and load conditions. Newer variable speed blowers provide flexibility under varying conditions.
- Provide flexible zones in the aeration tanks that can alternate between aerobic and anaerobic/anoxic conditions. Operate the flexible zones in aerobic conditions as needed to meet peak flow and load demands, or to meet increased aeration demands as a result of seasonal temperature variations. Mixing must be provided when the zones are operated in anaerobic/anoxic mode.
- Provide control strategies that adjust blower output to meet oxygen demands for real-time conditions. Refer to the Blower Fundamental fact-sheet for a list of control strategies that help to optimize oxygen addition and energy consumption.

The configuration of the biological reactor should also be considered in designing and sizing aeration equipment. For reactors that utilize influent wastewater as a carbon source (i.e. step-feed or modified Ludzak-Ettinger) a denitrification credit can be applied to the AOR calculation to ultimately reduce the air quantity requirements. In general, 2.9 lbs of oxygen per pound of nitrate reduced to nitrogen gas can be offset from the AOR and subtracted from the overall oxygen demand. This denitrification credit helps to reduce the overall demand and energy consumption of the aeration system.

Conclusion

Within a WRRF aeration systems are designed to increase the air-water interface within a process liquid, allowing for sufficient oxygen transfer to support biological treatment. The air-water interface is increased by introducing oxygen to the process liquid through diffusion or mechanical agitation of the liquid surface. The first step in aeration design is to determine the AOR which requires an understanding of the different factors that influence it: flows and loads, requirements for cBOD oxidation and removal, and requirements for total nitrogen reduction. After the AOR is determined, the SOR is estimated by accounting for specific weight of air at standard temperature as well as mass fraction of oxygen in the air. The estimated SOR value is then used to calculate the air demand required to deliver oxygen to the process liquid. Energy consumption is the main design consideration for aeration systems due to over-designing for peak seasonal flows which results in wasted energy throughout the rest of the year. To ensure the aeration design is energy efficient, the following factors should be implemented: design using varying blower sizes or provide VFDs where applicable, provide flexible zones that alternate between aerobic and anoxic conditions, provide control strategies that adjust blower outputs, and the design configuration of the biological reactor.

References

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Acknowledgments

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