STUDYING THE OXYGEN REQUIREMENT FOR AERATION SYSTEMS IN WASTEWATER TREATMENT PLANTS

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ABSTRACT
Aeration system is an essential part of wastewater plants. Aeration system represents the major energy consuming element in the wastewater treatment plants. Mathematical model is developed to calculate the energy usage for the diffusion and mechanical aeration systems. To evaluate the model parameters, oxygen transfer in clean water was studied. The model parameters were estimated using non-linear regression method. The model can be used to predict the oxygen and energy requirements for diffused-air and mechanical aeration systems. For 1000 m³/day, the size of aeration system will be 10.6 kW using mechanical aeration system or 31.3 kW using diffused aeration system. The calculation indicated that using diffused aeration system will increase energy requirements by more than 200%. However, the calculation is only valid for the system under study. The article represents a simplified mathematical model to estimate the energy requirements for the mechanical and diffused aeration systems.

Keywords: oxygen requirement, aeration systems, wastewater treatment, energy.

INTRODUCTION
Water and wastewater treatment and recycling is an emerging need for the world sustainable development. Aeration is essential process in water and wastewater treatment units [1, 2]. Aeration systems provide oxygen required for wastewater treatment and induce mixing between living medium and oxygenated water [3]. Blowers are used in aeration process during nitrification and de-nitrification processes. The most common blowers in aeration are centrifugal blowers and positive displacement blowers [1, 4, 5].

Energy consumption during aeration is relatively high especially during activated sludge process. The aeration process is important to increase the effectiveness of the wastewater treatment through better mixing which keeps the solid in suspended form [1, 6]. Two aeration methods are commonly used in treatment units including submerged diffusers which introduces air/oxygen into water/wastewater and mechanical surface aeration which entrains air into water/wastewater [1, 7].

Mechanical surface aeration can be achieved using direct drive surface aerators, low speed mechanical aerators, and brush type surface aerators [8]. Submerged diffuser aeration systems involve air piping system, a low pressure air compressor, blowers (high volume air compressor), and diffusers [9]. Aeration equipment may combine diffusers and mechanical aerators like submerged turbine aerators [3, 9].

Fine bubble aeration is an improved novel aeration method implemented recently in several treatment units which can improve better oxygen transfer efficiency [10]. However, different factors must be considered when treatment facility is upgraded. Improving/replacing aeration system will affect the energy use of the treatment facility which may affect other units’ operation and energy requirements [10, 11].

To predict the system behaviour accurately, the aeration system should be studied under actual operating conditions to minimize the error in design and energy calculation [6]. Air flowrate and aeration system are affected by the quality of sludge, the wastewater nature, biological and hydraulic operating conditions [6, 12]. Tank re-oxygenation is one of the most common methods for measuring oxygen requirement for treating wastewater [13].

Reducing energy consumption during aeration step is important to minimize the energy requirements of the water/wastewater treatment unit [14]. To achieve a considerable reduction in energy needs, the aeration process energy needs will be studied by developing a model to predict the energy requirements for several aeration devices. The developed model is intended to provide a numerical basis for evaluating different aeration systems considering low energy cost and better performance. The model is expected to help in developing sustainable water treatment technologies by reducing energy required for aeration.

AERATION SYSTEM PROCESS
The solid retention time (SRT) can be used to optimized to minimize energy requirements and the amount of excess sludge [15, 16]. Lower SRT can be achieved economically by minimizing the number of aeration tanks or reducing mixed liquor suspended solids [10-16]. If a certain level of nitrification is imposed on the facility, the aeration system must be operated carefully to ensure that the ammonia nitrogen (NH₄⁺-N), or total Kjeldahl nitrogen (TKN) in the effluent meets the environmental specifications [1].

The nitrification process is affected by pH, temperature, and dissolved oxygen levels which require maintaining an effective SRT [16, 17]. The nitrification process may impose an increased oxygen demand since
nitrogen is produced as a result of nitrification. The energy requirement of aeration during nitrification can be reduced by creating an anoxic zone to improve the performance of the activated sludge bacteria to oxidize waste BOD$_5$ [16-18]. Shown in Figure-1 activated sludge wastewater treatment process flow diagram.

Figure-1. Activated sludge wastewater treatment process flow diagram.

**MODEL EQUATIONS**

The energy requirements for aeration system in wastewater activated sludge units can be calculated as follows:

**Oxygen Transfer Rate (OTR):**

The dissolved oxygen concentration over time can be described using a simple mass transfer equation. The OTR is the amount of oxygen required in (kg/hr) required for the aeration, assuming a constant level of oxygen is maintained [1, 9 and 19]:

$$ OTR = k_L a (DO_{sat} - DO) V $$

Where:

- $k_L a$: Liquid-side mass transfer coefficient, a function of the aeration system and the tank geometry (h$^{-1}$)
- $DO_{sat}$: The dissolved oxygen concentration at saturation with no reactions in water (kgO$_2$/m$^3$),
- $DO$: The dissolved oxygen concentration in water (kgO$_2$/m$^3$),
- $V$: Activation tank volume (m$^3$)

In addition, the OTR can be calculated from the following modified equation [1, 9, and 19]:

$$ OTR = \alpha * k_L a (\beta * DO_{sat} - DO) V $$

Where:

- $\alpha$: The ratio of oxygen transfer efficiency (OTE) in wastewater to OTE in tap water, defined mathematically as the ratio of process to clean water conditions. It is an oxygen transfer correction factor for waste.
- $\beta$: A design factors to take into account the effect of the wastewater characteristics, basin geometry, aeration type, the degree of mixing.

$\alpha$ can be determined from the following equation [1, 9, and 19]:

$$ \alpha = \frac{(k_L a)_{process water}}{(k_L a)_{clean water}} $$

$\beta$ accounts for the effect of constituents in wastewater on oxygen solubility [1, 9, 19].

$$ \beta = \frac{C_s (waste \ water)}{C_s (tap \ water)} \approx 0.95 $$

$C_s$: Oxygen saturation concentration

**Determination of $k_L a$:**

$k_L a$ can be determined from the following mass transfer model [1, 9, 19]:

$$ \frac{C_s - C_t}{C_s - C_0} = \frac{e^{-(k_L a) t}}{1} $$

Where:

- $C_s$: Concentration in equilibrium with gas, mg/L
- $C_t$: Concentration in liquid bulk phase at time t, mg/L
- $C_0$: Initial concentration, mg/L

The water sample was treated with sodium sulfite to remove oxygen. Then, the water was de-oxygenated close to saturation level. The data was analysed using equation 4 to estimate the mass transfer coefficient $k_L a$ using non-linear regression method. Using a surface aeration test, the following dissolved Oxygen concentration was observed. The water temperature was 17°C: $C_s$ at 17°C, mg/L: 9.65 mg/L

![Table-1. Typical $\alpha$ values [1, 19]](image-url)
conditions including salinity, temperature and geometry. The actual amount of oxygen required (AOTR) can be calculated from the following equation [1, 9 and 19]:

$$AOTR = SOTR \left( \frac{\beta \cdot C_{T,H} - C_W}{C_{s,20}} \right) \cdot \alpha \cdot \Theta^{(r-20)} (F)$$

Where:

- $AOTR$: Actual oxygen transfer rate under field conditions, kg O$_2$/h
- $SOTR$: Standard oxygen transfer rate at 20°C and zero dissolved oxygen, kg O$_2$/h
- $\beta$: Salinity-surface tension corrosion factor (0.95-0.98)
- $\Theta$: A constant used to correct for the effects of temperature (around 1.024)
- $C_W$: The operating dissolved oxygen concentration, 2-4 mg/L
- $C_{s,20}$: Oxygen saturation concentration dissolved in clean water at 20°C and 1 atm, mg/L
- $F$: Fouling factor, typically between 0.69-0.9, to account for air diffusers internal and external fouling
- $\alpha$: Oxygen transfer correction factor, Table-1
- $C_{T,H}$: The average oxygen saturation concentration dissolved in clean water in the aeration tank at altitude H and temperature T, mg/L

$$C_{T,H} = \frac{1}{2} C_{s,T,H} \left( \frac{P_d}{P_{atm,H}} + \frac{O_t}{2T} \right)$$

$C_{s,T,H}$: The oxygen saturation concentration at temperature T and altitude H in clean water, mg/L
- $P_d$: Pressure measured at the air release depth, kPa
- $P_{atm,H}$: Atmospheric pressure at altitude H, kPa
- $O_t$: The oxygen (%) leaving the tank, (18-20%)

For surface aerators for $C_{T,H} = C_{s,T,H}$

If the biological oxygen uptake is not considered:

$$C_{T,H} = \frac{1}{2} C_{s,T,H} \left( \frac{P_{atm,H} + P_{middepth}}{P_{atm,H}} \right)$$

$P_{middepth}$: Pressure as a result of water column at a medium depth above point of air release, kPa

According to the experimental results:

- $AOTR = 10.6$ kg O$_2$/h

**Oxygen Amount Required for BOD and Nitrification:**

The amount of oxygen required for oxidizing BOD during aeration step (kg/day) [1, 19]:

$$O_{req}(kg/day)_{BOD} = (BOD_{in} - BOD_{out}) \cdot r_{O_2} \cdot Q$$

where:

- $O_{req}(kg/day)_{BOD}$: Oxygen required for oxidizing BOD during aeration step (kg/day)
- $BOD_{in}$: Influent BOD (mg/L)
- $BOD_{out}$: Effluent BOD (mg/L)
- $r_{O_2}$: Oxygen transfer efficiency
- $Q$: Flow rate (L/day)
Where:

\( r_{O_2} \) The ratio of kilograms of oxygen required per kilograms of BOD\(_5\) removed (usually between 1-1.5) the higher the SRT/temperature, the higher the \( r_{O_2} \).

\( BOD_{in} \) The inlet biochemical oxygen demand concentration, kg/L.

\( BOD_{out} \) The outlet biochemical oxygen demand concentration (assumed 20E-6kg/L).

\( Q \) Wastewater flow in liters per day (L/day).

Assuming a flow rate of 1000 m\(^3\)/day, and \( BOD_{in} \) of (570E-6kg/L).

\[ O_{req} = 688 \text{ kg/day} \]

The amount of oxygen required for 50% nitrification (kg/day) [1, 19]:

\[ O_{req} = \left(\frac{1b}{day}\right)_{TKN} = \left( TKN_{in} - TKN_{out} \right) \cdot r_{NO_2} \cdot Q \]

\( r_{NO_2} \) The ratio of kilograms of oxygen required per kilograms of TKN oxidized to nitrate (usually 4.75).

\( TKN_{in} \) (Total Kjedhal Nitrogen): The inlet concentration of nitrogen (usually 40E-6kg/L).

\( TKN_{out} \) The outlet concentration of nitrogen (usually 20E-6kg/L).

\[ O_{req,TKN} = 95 \text{ kg/day} \]

Total req. \( O_2 \) = 783 kg/day

**MECHANICAL AERATION SYSTEMS**

The mechanical aeration system performance is measured in terms of the transfer rate of oxygen expressed in kg\(O_2\)/kw.hr at standard conditions (20°C, dissolved oxygen of 0 gm/L, and using tap water). The mechanical aerators oxygen transfer rate may vary between 1.2-2.4 kg\(O_2\)/kw.hr. The following equation can be used to calculate the oxygen transfer rate for the mechanical aeration systems.

The field oxygen transfer rate (FOTR) in the mechanical aeration system (kg\(O_2\)/kw.hr) can be calculated using the following equation [1, 9, 19]:

\[ FOTR = LOTR \left( \frac{\beta \cdot C_{s,T} - C_W}{9.17} \right) \cdot \alpha \cdot \Theta^{-20} \]

Where:

\( LOTR \) The standard oxygen transfer rate in clean water at 20°C and zero dissolved oxygen, kg\(O_2\)/kw.hr, Table 3 [1].

\( C_W \): The operating dissolved oxygen concentration, 2-4 mg/L.

\( \Theta \) A constant used to correct for the effects of temperature (around 1.024)

\( \beta \) Salinity-surface tension corrosion factor (0.95-0.98)

\( T \) Temperature, °C

\( C_{s,T} \) Saturation concentration of oxygen at given temperature and altitude for tap water (Appendix D [1]), mg/L.

\[ AOTR = 1 \text{ kg}O_2/kW.hr \]

The power requirements in horsepower can be calculated as follows [1, 9, 19]:

\[ P_w = AOTR / FOTR \]

\[ P_w = 10.6 \text{ kW} \]

The aerator size is 10.6 kW

**Diffused Aeration Systems:**

The required blower horsepower can be calculated using the following equation assuming adiabatic compression [1, 9, 19]:

\[ P_w = \frac{WRT_1}{29.7 \cdot n \cdot e} \left( \frac{P_2}{P_1} \right)^{0.283} - 1 \]

Where,

\( P_w \): Blower power requirement, kW

\( W \): Mass flowrate of air (kg/s) (0.683 kg/s)

<table>
<thead>
<tr>
<th>Aeration systems</th>
<th>Transfer rate, kg(O_2)/kW.h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface low-speed</td>
<td>1.3-2.1</td>
</tr>
<tr>
<td>Surface high-speed</td>
<td>1.1-1.4</td>
</tr>
<tr>
<td>Surface high-speed with draft tube</td>
<td>1.2-2.0</td>
</tr>
<tr>
<td>Submerged turbine with draft tube</td>
<td>1.2-2.0</td>
</tr>
<tr>
<td>Submerged turbine with sparger</td>
<td>1.2-2.0</td>
</tr>
<tr>
<td>Horizontal rotor</td>
<td>1.3-2.1</td>
</tr>
</tbody>
</table>

\[ P_w = \frac{WRT_1}{29.7 \cdot n \cdot e} \left( \frac{P_2}{P_1} \right)^{0.283} - 1 \]
The weight of the flow of air can be calculated using the following equation [1, 9, 19]:

\[ W = \text{Flowrate} \left( \frac{m^3}{s} \right) \times \rho_{\text{air}} \left( \frac{kg}{m^3} \right) \]

where:

- \( W \) is the weight of the flow of air.
- \( \text{Flowrate} \) is the flow rate of air in cubic meters per second (m\(^3\)/s).
- \( \rho_{\text{air}} \) is the density of air in kilograms per cubic meter (kg/m\(^3\)).

\[ R : \quad \text{Gas constant, 8.314 kJ/kmol/K} \]

\[ T_i : \quad \text{Inlet temperature, K} \]

\[ P_i : \quad \text{Absolute inlet pressure, atm} \]

\[ P_o : \quad \text{Absolute outlet pressure, atm} \]

**Oxygen Transfer Efficiency in Clean Water (OTE):**

The oxygen transfer efficiency for subsurface or diffused aeration systems can be expressed as follows [1, 9, 19]:

\[ OTE = \frac{O_{2,\text{out}} - O_{2,\text{in}}}{O_{2,\text{in}}} \]

where:

- \( O_{2,\text{in}} \) and \( O_{2,\text{out}} \) are the oxygen mass flow rates in the clean water.

\[ OTE \] is the efficiency of oxygen transfer in clean water (usually 28%), it is a function of diffuser type, aeration system, and the depth of submergence.

\[ \rho_{\text{air}} \] is the air density (1.204 kg/m\(^3\)).

**Aeration Efficiency in Clean Water (AE):**

The aeration efficiency is the mass of oxygen transferred per unit of power input, equal to the OTR divided by the power input [1, 9, 19]:

\[ AE = \frac{OTR}{P} \]

where:

- \( P \) is the power drawn.

**CONCLUSIONS**

The mathematical model can be used efficiently to predict and reduce the energy usage for aeration systems. The model represents a simplified description of the aeration systems. Aeration systems are used to supply oxygen for wastewater treatment facilities. Standard methods were used to evaluate the oxygen transfer behaviour in tape water. The model describes the aeration process to predict the energy requirement for different aeration systems. Laboratory experimental results were used to fit the model parameters using non-linear regression methods. Our calculation has showed that the mechanical aeration is more energy efficient compared to diffused aeration systems.

**REFERENCES**


