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# ANALYSIS OF OXYGEN REQUIREMENTS AND TRANSFER EFFICIENCY IN A WASTEWATER TREATMENT PLANT

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***Abstract-* To determine the oxygen transfer efficiency of an aerator in clean water the following procedure is used. Residual dissolved oxygen is removed from the liquid by adding sodium sulphite and a catalyst (cobalt chloride). Aeration is started and the rate of oxygenation of the liquid is measured by recording the DO at regular intervals. The oxygen transfer coefficient ($K_{La}$) may then be determined. The oxygen transfer coefficient is affected by the following factors: temperature: mixing intensity, tank geometry and characteristics of the water.**

***Keywords –*** oxygen transfer, air supply, aeration equipment, diffuser, DO, $K_{La}$

## I. 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. Oxygen (dissolved in the mixed liquor) is required for respiration by the microorganisms in the aeration tank. The activated sludge process depends on the activity of these aerobic micro-organisms and consequently, accurate control of oxygen in the aeration tank is vital [5].

Most aeration equipment is of proprietary manufacture and is constantly being upgraded and refined. Although there are many types of aeration systems, oxygen is supplied by three basic methods as illustrated in figure 1, 2 and 3.

Mechanical agitation of the wastewater promoting the entrapment of air from the atmosphere, submerged diffusion using air blowers, combinations of mechanical and diffused systems.

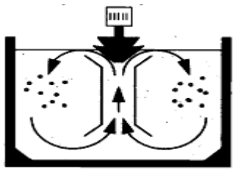

Fig. 1 Mechanical surface aerator with (or without) draft tube

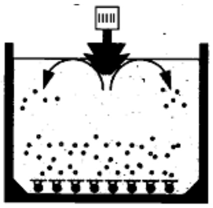

Fig. 2 Combined surface mixing and submerged diffuse aeration

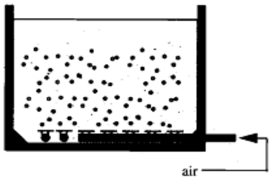

Fig .3 Submerged air diffusion –side view and end of laterals

Diffused air systems use diffusers which break the air stream into bubbles.

Diffusers are traditionally divided into coarse and fine bubble systems; theoretically, the finer the bubble the greater is the oxygen mass transfer.

These units are divided into three categories: porous or fine pore diffusers; non-porous diffusers; and other devices such as jet aerators, aspirating aerators and u-tubes.

The transfer of oxygen to the wastewater depends on factors such as: the type, size and shape of the diffuser; the air flow-rate; the depth of submergence; and the geometry of the tank.

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## II. AIR SUPPLY

An adequate design of the aeration system is of course the pre-requisite for an energy efficient aeration. There are two principally important parts, the compressor and the diffuser system. The compressor has to allow for variable air flow rates, which is crucial for any control of the dissolved oxygen. A diffuser system that forms fine bubbles in the water is more energy efficient than a coarse bubble system. There is a basic physical reason for this. The rate of the mass transfer of gaseous oxygen to DO depends on the relation between the surface area and the volume of the air bubbles, as 1/r, where r is the bubble diameter. So, if the diameter of a bubble is halved then the ratio of surface to volume will double. The contact time between the air bubbles and the water is also important. Small bubbles rise more slowly than large bubbles and have longer contact time.

Many activated sludge systems look like a long tank or are designed as a series of tanks. As the wastewater enters the biological reactor the organic matter concentration is relatively high, figure 4 and 5. The microorganisms will be active and growing and the oxygen demand is high. As the water flows towards the outlet of the tanks the organic matter has been consumed and the resulting oxygen consumption is low. It is still common that there is a uniform air supply along the tank. This means that the DO concentration is low at the inlet and quite high at the outlet, as illustrated in figure 4.

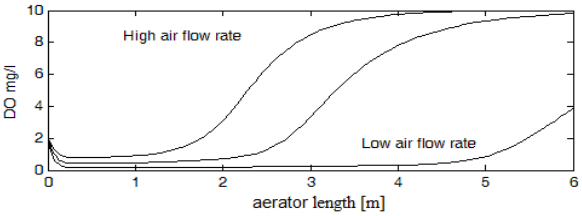

Fig. 4 The DO profile in a plug-flow reactor for carbon removal with uniform airflow distribution. The upper figure shows the DO profile (mg/l) for different air flows [4]

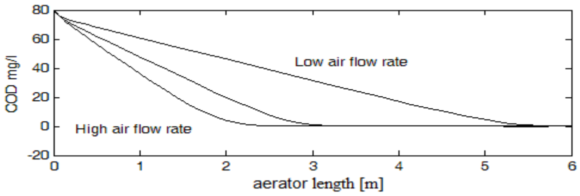

Fig. 5 The lo wer figure depicts the corresponding carbon concentration COD (mg/l) decrease along the plug flow reactor [4]

Normally the microorganisms require around 1-3 mg/l of DO. As figure 4 and 5 illustrates a lot of excess oxygen is supplied towards the outlet of the tank. This results in energy waste. The situation is similar for nitrification systems. The organic matter is consumed mainly by so called heterotrophic organisms, while the ammonium nitrogen is oxidized to nitrate via autotrophic organisms. The DO requirement is larger for the utotrophic organisms. They are slower than the heterotrophic ones, which means that ammonium is removed slower than the organic matter.

This is illustrated in figure 6 and 7. Just before the middle of the reactor the DO concentration rises quickly. This is an indicator that the organic matter has been consumed. The ammonium still is getting oxidized and continues to consume oxygen along the reactor. At the outlet all ammonium has been oxidized into nitrate.

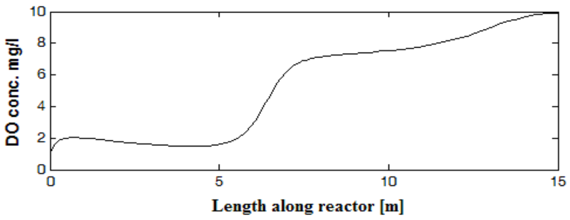

Fig. 6 The DO profile in a plug-flow reactor for carbon removal combined with nitrification. The airflow distribution is uniform. The upper figure shows the DO profile (mg/l) [4]

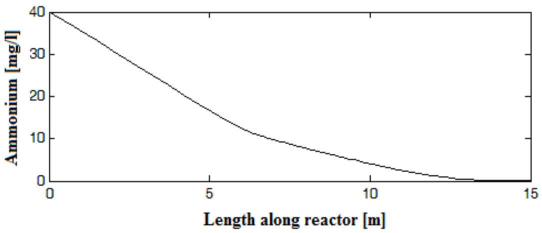

Fig. 7 The lower figure depicts the corresponding ammonium concentration decrease along the plug flow reactor [4]

## III. OXYGEN TRANSFER

In many cases too much or too little oxygen in aeration tank is undessirable for different reasons. Too much oxygen adds unnecessary cost, to increased power consumption and too little can decrease the metabolism of the microorganisms and the efficiency of the process [1].

The theoretical oxygen requirement can be calculated by assuming that the biodegradable matter is converted to carbon dioxide, water and energy.

It is possible to estimate the exact oxygen requirement by writing down a balanced equation:

$$C_6H_{12}O_6+6O_2 \rightarrow 6CO_2+6H_2O \quad (1)$$

In reality however, such theoretical calculations become complex because of the diversity of the chemical compounds found in wastewater.

If nitrification is required, then the oxygen demand for the convention of ammonia to nitrate must be taken into account.

$$\begin{aligned} &2NH_4^+ + 3O_2 + nitrifyingbacteria \rightarrow \\ &2NO_2^+ + 4H^+ + 2H_2O \end{aligned} \quad (2)$$

$$2NO_2 + O_2 + nitrifyingbacteria \rightarrow 2NO_3 \quad (3)$$

Aeration equipment is compared by the amount of oxygen transferred per unit of air introduced to the wastewater under standard operating conditions expressed as $kgO_2$/kWh.

The oxygen transfer rate of selected aeration systems is presented in table1.

Residual dissolved oxygen is removed from the liquid by adding sodium sulphite and a catalyst (cobalt chloride). Aeration is started and the rate of oxygenation of the liquid is measured by recording the DO at regular intervals. The oxygen transfer coefficient ($K_{La}$) may then be determined [6].

**TABLE 1 Typical performance data for selected aeration devices**

| Aeration device | Oxygen transfer rate, kgO$_2$/kWh |
|---|---|
| Fine bubble diffusers | 2,0-2,5 |
| Coarse bubble diffusers | 0,8-1,2 |
| Vertical shaft aerators | up to 2,0 |
| Horizontal shaft aerators | up to 2,0 |

The test method involves the removal of dissolved oxygen (DO) from a known volume of water by the addition of sodium sulfite followed by re-oxygenation to near the saturation level. The DO of the water volume is monitored during the re-aeration period by measuring DO concentration at several different points.

The basic equation describing the rate at which oxygen is absorbed by water is:

$$\frac{dc}{dt} = K_{La} \cdot (C_{st} - C_t) \quad (4)$$

where:

$\frac{dc}{dt} =$ transfer rate of oxygen to the water (mg/l.t);

$C_t =$ concentration of oxygen in the water at time (t), (mg/l);

$C_{st}$ = saturation, or equilibrium, concentration of oxygen in water with respect to air in bubble at mean depth, (mg/l);

t = the time.

The difference ($C_{st} - C_t$) between saturation value and actual concentration of oxygen (C) in the body of the liquid phase is usually called oxygen deficit. The oxygen transfer rate is determined by integrating of this equation.

From equation (5), the initial oxygen uptake rate at $C_t = 0$, is:

$$\frac{dc}{dt} = OC = K_{La} \cdot (C_{st}) \quad (5)$$

where:

OC = the oxygen transfer capacity of the system, (grO$_2$/m$^3$ water.h).

The fraction of oxygen transferred to the water, to pass one-meter cubic of air is expressed as oxygenation efficiency (E) of the diffuser system, which can be written as:

$$E = \frac{OC \cdot H}{I} \quad (6)$$

where:

H = the liquid depth in the tank in meters.

I= the aeration intensity, or volumetric air flux per unit area of tank surface.

The solubility of oxygen in water is temperature dependent, as:

$$K_{La(T)} = K_{La(20°C)} \cdot \Theta^{T-20} \quad (7)$$

where: $\Theta$ is a temperature correction factor typically taken as 1,024 for aeration devices and T is the temperature at which the test is carried out.

Mass transfer coefficients are usually measured in clean water which does not have the same surface tension as wastewater. Two coefficients are used to compensate for the difference between measured and actual values. These are the $\alpha$ and $\beta$ values [3].

$$\alpha = \frac{K_{La(wastewater)}}{K_{La(tapwater)}} \quad (8)$$

The $\alpha$ value is used to compensate between the measured and actual values of $K_{La}$ with regard to surface tension, tank geometry and mixing intensity.

Typical $\alpha$ values for diffused and surface aerators are in the range of 0,4-0,8 and 0,6-1,2 respectively. These values are related to the design of the tank used during the test procedure.

$\beta$-values are used to account for the differences in the solubility of oxygen to constituents in the wastewater. The presence of salts, particulates and detergents may affect the oxygen transfer rate. The factor is:

$$\beta = \frac{C_{S20(wastewater)}}{C_{S20(tapwater)}} \quad (9)$$

where: $C_{S20}$ is the saturation concentration of oxygen at 20 °C. Values may vary from 0,7 to 0,98 with a value of 0,95 being commonly used.

## IV. CALCULATIONS TO EVALUATE AERATION PERFORMANCE

To evaluate aeration device performance there is need for using the standard method for oxygen transfer measurements and it can be applied for all types of aeration systems. First of all the aeration product should be set in a tank containing clean tap water. Two chemicals should be added to the water while the product is operating which decreases the dissolved oxygen concentration until it reaches almost zero. After a while, the concentration rises to the dissolved oxygen saturation concentration, $C_{ss}$, which is a value of how much oxygen that can be dissolved in water. This period is called re-oxygenation. The dissolved oxygen concentration should be measured during the whole re-oxygenation by probes.

They are placed in the tank to represent the total water volume. If there is a small plume with air bubbles, the probes should be positioned in different places in the tank. The measured data should be the dissolved oxygen concentration over time.

Other parameters like air flow and temperatures have to be measured and included in later calculations. Some of them have to be measured both before and after the chemical additions.

When the oxygen transfer measurements are finished it is possible to analyze the data.

Data from the re-oxygenation should be truncated where the lowest concentration should be lower than 20% of $C_{ss}$ and the highest concentration should be at least 98% of $C_{ss}$.

After the truncation, the data with dissolved oxygen concentration over time should be analyzed according to the standard model.

The standard model consists of a mass balance equation which describes the dissolved oxygen concentration in water at various times. It can also be seen as a box with water and air bubbles. The oxygen is transferred to the water by a mass transfer coefficient, $K_{La}$, which describes how fast the oxygen is transferred to be dissolved in water. That coefficient includes the total oxygen transfer both from the air bubbles and at the water surface [2].

1. Standard oxygen transfer rate (SOTR)

The standard oxygen transfer rate (SOTR) describes the rate of oxygen transfer at time zero (equation 10). For standard conditions, the dissolved oxygen concentration is assumed to be zero at time zero. SOTR is determined by the estimated parameters $K_{La}$ and $C_{ss}$ and the total water volume and is expressed as mass per time.

$$SOTR = \frac{V}{n} \cdot \sum_{i=1}^{n} K_L a_{20i} \cdot C_{SS\_20i} \qquad (10)$$

where:
V = water volume ($m^3$)
n = number of dissolved oxygen probes
$K_L a_{20i}$ = volumetric mass transfer coefficient at standard conditions for measurement probe i (temperature 20°C and pressure 1atm) ($min^{-1}$)
$C_{ss\_20i}$ = dissolved oxygen saturation concentration at standard conditions for measurement probe i (temperature 20°C and pressure 1atm) (mg/l).

2. Standard aeration efficiency (SAE)

Standard aeration efficiency (SAE) is expressed as the oxygen transfer per unit power input (equation 11). SAE is determined by SOTR and the power input. SAE is expressed as mass transfer per power unit.

$$SAE = \frac{SOTR}{Powerinput} \qquad (11)$$

where:
SOTR = standard oxygen transfer rate (kg/h)
Power input = aeration power (W)

3. Standard oxygen transfer efficiency (SOTE)

Standard oxygen transfer efficiency (SOTE) describes how much of the injected oxygen that becomes dissolved in water and is expressed in percent (equation 12). SOTE is determined by the SOTR and the injected flow of oxygen.

$$SOTE = \frac{SORT}{W_{O_2}} \cdot 100 \qquad (12)$$

where:
SOTR = standard oxygen transfer rate (kg/h)
$W_{O2}$ = oxygen mass flow (kg/h)

All parameters are expressed as standard parameters which are defined for a water temperature of 20°C and ambient air pressure of 1atm.

## V. CONCLUSIONS

Aeration is a critical operation in most wastewater treatment. It is a major energy consumer, therefore aeration control is important. Aeration control aims not only at energy savings but will guarantee that the microorganisms are adequately supplied with oxygen at all times. A variable setpoint (DO concentration) is made possible by ammonium measurements. Further energy reduction can be obtained by allowing variable air pressure in the system.

For good performance the rate of supply of dissolved oxygen should be equal to the rate of oxygen consumption exerted by the mixed liquor under any given set of circumstances.

In diffused air systems bubbles are distributed from diffusers at the base of the reactor. Oxygen transfer takes place from the rising bubbles to the mixed liquor to supply the oxygen requirements for the biological process.

The standard method for oxygen transfer measurements which is used today seemed to be fairly good and reasonable considering usability. The standard model does not describe the whole aeration process, but if it is used for all aeration systems it is possible to get comparable results.

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