OXYGEN TRANSFER EFFICIENCY IN FINE BUBBLE DIFFUSED AERATION - FACTORY TESTING

Irina BRATU[1]

The present paper analyses and tests the standard oxygen transfer efficiency (SOTE) of a diffused air aeration system with fine bubble disc diffusers. The proposed diffuser density was required to demonstrate an oxygen transfer efficiency of approximately 38% at an aeration depth of 6.20m. The tests were conducted according to ASCE Standard, Measurement of Oxygen Transfer in Clean Water, 2006.. The test method is based on removal of Dissolved Oxygen (DO) from the water by adding chemicals, followed by reaeration to the saturation level. The dissolved oxygen is measured by using four (4) DO probes placed at several water depths, to best represent the water contents. The purpose of this research is to compare theoretical design calculations with actual on site operation of the aeration system. The test results were able to prove that the measured values exceeed the guaranteed performance values

Keywords: wastewater treatment, diffused aeration, pneumatic diffusers, activated sludge process, oxygen transfer efficiency

1. Introduction

The activated sludge treatment process is a treatment process for municipal and/or industrial wastewater, commonly referred to as "effluent", using bacteria (for the degradation of biodegradable organic substances) and air (oxygen for aerobic bacteria). Activated sludge is defined as a mixture of microorganisms and suspended solids. Bacterial culture is grown in the treatment process to break down the organic matter into carbon dioxide, water and other inorganic compounds. [1]

There are many variations of activated sludge processes, including variations in the aeration method. Dissolving oxygen is achieved by aerating the sludge, which allows organic matter (BOD - Biochemical oxygen demand) to be used by bacteria. Dissolved oxygen in the water allows bacteria to use nutrients (BOD) and converts ammonia into nitrate.

Aeration is essential to the efficiency of any activated sludge treatment process. The optimal amount of air, at the right time, ensures success of the process. The level of dissolved oxygen determines operation efficiency and influences treatment process results. [2]

The Standard Oxygen Transfer Efficiency (SOTE) is the basic parameter characterizing the diffusers. SOTE is defined as percentage of oxygen in an injected gas flow, dissolved under standard conditions of temperature (20^0C), pressure (1.013 hPa), clean water (α, β=1), gas rate and DO concentration. The values are

[1] PhD Student, Faculty of Power Engineering, National University of Science and Technology POLITEHNICA Bucharest, Romania, e-mail: Irina.bratu@waterengineering.ro

usually determined under laboratory conditions, the actual values in wastewater can be different. Therefore, a Wastewater Treatment Plant operator should verify the SOTE experimentally. [2]

OTE (Oxygen Transfer Efficiency) in fine-bubble diffuser aeration depends on a variety of factors [3]:

- Suspended solids contained in wastewater and activated sludge – for SOTE factory testing it is important to know the TDS (Total Dissolved Solids) value for the testing. As per ASCE (American Society of Civil Engineers), this value is between 1000 mg/l and 2000 mg/l
- Water temperature, measured in ^{0}C – the oxygen solubility decreases as the temperature increases; also, the water temperature influences the oscillation intensity of the bubble.
- SOTE – Standard oxygen Transfer Efficiency, measured in %/m
- Dissolved Oxygen concentration, measured in gO_2/m^3 – influences the growth of the microorganisms
- Aeration depth, measured in m – at higher aeration depths the diffusion period oh the oxygen from the air bubbles is longer, which increases the oxygen transfer
- Airflow/ diffuser unit, measured in Nm^3/h – as the airflow/ diffuser unit increases, the OTE decreases due to the creation of larger bubbles. The larger the bubbles, the higher the collisions and the surface for oxygen transfer is lower.
- Diffuser fowling – reduces the OTE and increases the head-loss pressure.

The following article analyzes the efficiency of oxygen transfer by factory testing using an aeration system with pneumatic oxygenation equipment, with given, fixed values for the above-mentioned factors. All tests were conducted at the laboratories of Environmental Dynamics International. Factory clean water oxygen transfer testing was conducted in conformance with the ASCE Standard, Measurement of Oxygen Transfer in Clean Water, 2006 [4]. Performance tests were conducted at the design aeration conditions, presented in Chapter 2.3. Test program scope (Table 1, Table 2).

2. Methodology and equipment

Clean water oxygen transfer efficiency was determined using the non-steady state test procedure as outlined in the ASCE Standard, Measurement of Oxygen Transfer in Clean

Water, 2006. This Standard uses the nonlinear regression method to determine the mass transfer coefficient from the graph of dissolved oxygen (DO) concentration versus time. One positive displacement blower (Aerzen Machine Factory GM 25S Delta) powered by a 75 HP electric motor provided the air supply. Concentric orifice plates were used to measure airflow. The concentric orifice plates were installed per ASCE power test code as prescribed by ASCE. Differential pressure was measured with a water manometer (Endress+Hauser) and the line pressure was measured with a mercury manometer (Endress+Hauser). Pressure transducers were used in conjunction with the manometers to monitor the differential and line pressure throughout the test. Thermocouples were used to obtain line temperature and ambient temperature measurements. Relative humidity and atmospheric pressure readings were obtained from the local Weather Service immediately before performing the tests. All values were corrected to standard conditions per ASCE guidelines.

The city public water supply (clean water) was used as the source of water in the tests, with the following quality parameters (historical data):

Table 1

Test water parameters

Parameter	M.U.	Value
pH		7,7
Total Dissolved Solids	mg/l	750
Conductivity	uS/cm	1.160
Alkalinity	mg/l	246
Hardness	mg/l CaCO3	424
Oxidability	mg O2/l	1,94
Salt content	mg/l	
- Fe		< 1
- M		< 1
- n		< 1
- Cu		< 4

Quick response DO meters (Model YSI 52) were used to measure the DO concentration. DO probes were anchored down to prevent movement during testing. DO concentration was recorded automatically using computerized data acquisition equipment (O2 Logger).

Anhydrous sodium sulfite (SC SAMCHIM SRL) was dissolved in solution in a separate mixing tank and then added to the aeration tank as per Section 6.7 of the ASCE Standard. Dosage ports were distributed uniformly along the aeration test tank.

2.1.Air flow calculation

The calculation is based on the following equation [4]:

$$q_{Vb} = N_{Vhp} * K * F_A * D_f^2 * Y * F_{Pb} * F_{Tb} * F_{Tf} * \sqrt{h_w * (P_f + 14.73)} \qquad (1)$$

where:

q_{Vb} = volumetric air flow rate at the selected base temperature and pressure

N_{Vhp} = N factor for the standard base volume of gas, 5,643067

K = flow coefficient

F_A = correction of the thermal expansion factor

D_f = diameter of the primary element orifice

Y = gas expansion factor
F_{Pb} = base pressure correction factor, 14,69595 / P_b
F_{Tb} = base temperature correction factor, T_b / 518.67
F_{Tf} = flow temperature correction factor, $[518.67 / (Tf + 459.67)]^{0.5}$
h_w = differential pressure on the primary element
P_f = absolute pressure under flow conditions

$$K = \frac{C}{(1-\beta^4)^{0.5}} \tag{2}$$

where:
C = discharge coefficient
β = ratio of primary element hole diameter to the pipe diameter

For D > 2.3, then:

$$C = 0.5959 + 0.0312 * \beta^{2.1} - 0.184 * \beta^8 + \frac{0.09 * \beta^4}{D * (1-\beta^4)} - \frac{0.0337 * \beta^3}{D} + \frac{91.71 * \beta^{2.5}}{R_N^{0.75}}$$
(3)

For D < 2.3, then:

$$C = 0.5959 + 0.0312 * \beta^{2.1} - 0.184 * \beta^8 + \frac{0.09 * \beta^4}{(1-\beta^4)} - \frac{0.0337 * \beta^3}{D} + \frac{91.71 * \beta^{2.5}}{R_N^{0.75}} \tag{4}$$

where:
RN = Reynolds number

$$R_N = \frac{163.5262 * q_{Vb}}{F_{Pb} * F_{Tb} * Z_b * \mu_{cp} * D * N_{Vhp}} \tag{5}$$

where:
Z_b = gas compressibility factor at base pressure and temperature, 0.9999
μ_{cp} = absolute viscosity in centipoise, 76865

$$F_A = 1 + \frac{2 * (\alpha_{PE} - \beta^4 * \alpha_P) * [(T_f + 459.76) - 68]}{(1-\beta^4)} \tag{6}$$

where:
α_{PE} = coefficient of thermal expansion for the pipe material, 0.0000099
α_P = coefficient of thermal expansion for the primary element material, 0.0000065
T_f = absolute temperature under flow conditions

$$Y = 1 - (0.41 + .35 * \beta^4) * x1 / k \tag{7}$$

where:
x_1 = pressure ratio based on upstream water pressure
k = isentropic exponent, 1.4

$$x1 = \frac{h_w}{27.73 * (P_f + 14.73)} \tag{8}$$

This volumetric flow rate is then corrected to actual conditions:

$$ACFM = \left(\frac{14.7}{B_p + P_f}\right)\left(\frac{460 + T_f}{528}\right) * q_{VB} \quad (9)$$

where:
$ACFM$ = ft^3 real per minute
B_p = barometric pressure
T_f= absolute temperature under flow conditions

The standard flow rate is calculated by adjusting relative humidity:

$$Q_s = 36.2 * \frac{\left(B_p + P_f\right) * \left(1 - \frac{R_h}{100} * \frac{P_{VA}}{B_P}\right)}{\left(460 + T_f\right)} * ACFM \quad (10)$$

where:
R_h = relative humidity
P_{VA} = vapor pressure of water at ambient temperature

The secondary flow element is the accutube. Flow is calculated from the following equation:

$$Qs = 128.789 * K * D^2 * \sqrt{\frac{\left(P_f + B_P\right) * h_w}{\left(T_f + 460\right)}} \quad (11)$$

where:
D = pipe diameter

2.2.Data analysis by Nonlinear Regression

Data was collected through the duration of the test in six second intervals. This data includes dissolved oxygen concentrations at five locations of the test tank (shown in Fig.1), differential pressure at the concentric orifice plate, and temperature upstream of the orifice plate. Line pressure is also measured upstream of the orifice plate at the start and end of each test. The temperature, differential pressure, and line pressure are used to accurately measure the average flow rate through the duration of the test. Accuracy is assured by a secondary flow measurement from an accutube.

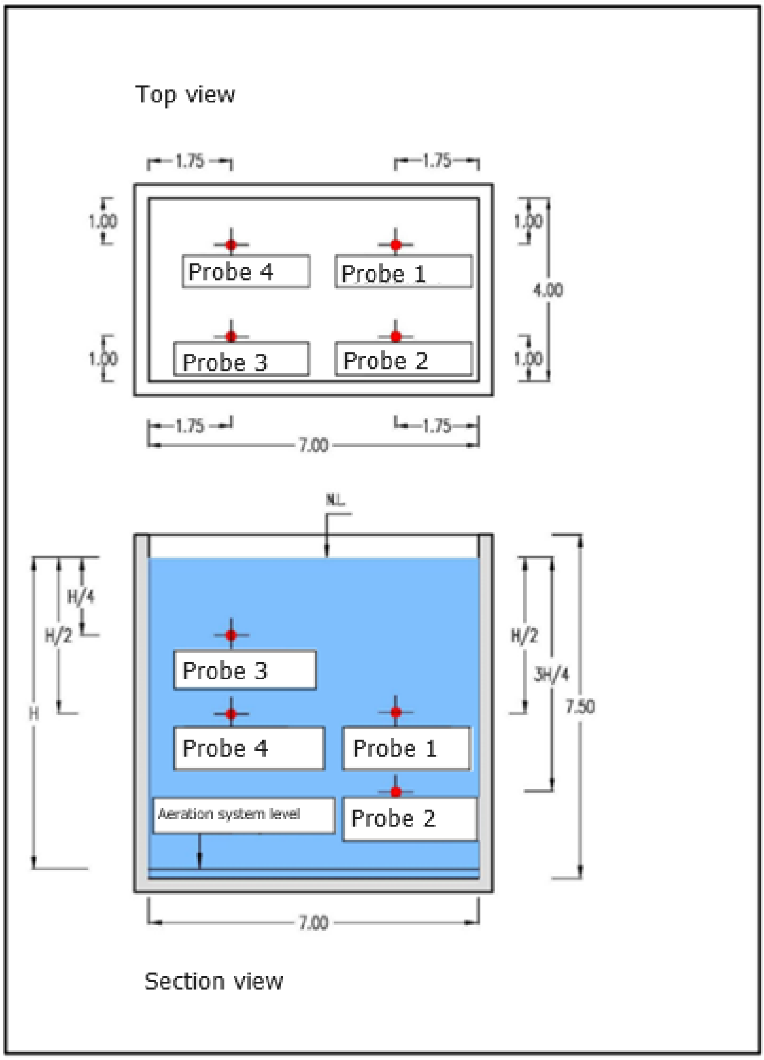

Fig. 1. Scheme of the installation and position of DO probes

Initial estimations of K_La (mass transfer coefficient, t^{-1}), C^*_∞ (saturation concentration, mg/L), and C_o (initial concentration, mg/L) were made based on standard assumptions. The initial concentration was the point on the curve which rises to 20% of saturation during reoxygenation. All data points prior to this were truncated. These parameters were used in an iterative calculation to determine the best fit value of dissolved oxygen yielding the lowest residual sum of squares.

Based on the best fit curve, actual values of K_La, C^*_∞ and C_o are calculated. C^*_∞ is determined from the convergence point of the model at $t = \infty$. The data is then plotted on a log deficit function of $Ln(C^*_\infty - C_t)$ vs. time. K_La is the resultant negative slope of the log deficit function. K_La and C^*_∞ values are normalized to the standard conditions of 1.00 atm and 20°C. These parameters are corrected to standard conditions by [5]:

$$K_L a_{20} = K_L a * \theta^{(20-T)} \quad (12)$$

The temperature correction value for theta, θ, is considered to be 1.024 for temperature ranges
between 15°C and 25°C, per the ASCE standard. Due to conditions beyond normal control, the water temperature may fall outside of this range. If operating outside of this temperature range, the value for theta changes accordingly (1.026 between 10°C and 15°C; 1.027 between 5°C and 10°C; 1.028 below 5°C).[6]

SOTE is also a function of total dissolved solids. To have a comparative representation
of results, SOTE is normalized further to a value of 2000 TDS by the following correction[7]:

$$K_L a_{20-2000} = K_L a_{20-TDS} * e^{0.0000963*(2000-TDS)} \quad (13)$$

where:

$K_L a_{20\text{-}2000}$ = mass transfer coefficient corrected to conditions of 1000 mg/L TDS

$K_L a_{20\text{-}TDS}$ = mass transfer coefficient under field conditions

TDS = total dissolved solids, mg/L

$$C^*_{\infty 20} = C^*_{\infty}\left(\frac{1}{\frac{C^*_{st}}{C^*_{S20}} * \Omega}\right) \quad (14)$$

where:

C^*_{st} = tabular value of DO at test temperature

C^*_{s20} = tabular value of DO at 20°C

Ω = pressure correction factor

After these parameters are calculated, SOTR can be calculated by the following formula[8]:

$$SOTR = K_L a_{20} * C^*_{\infty 20} * V \quad (15)$$

where:

SOTR = standard oxygen transfer rate, kg/h

V = volume of water in the test tank

SOTE can then be calculated by:

$$SOTE = SOTR/W_{O_2} \quad (16)$$

where:

SOTE = standard oxygen transfer efficiency, %

W_{O_2}= mass flow of oxygen in the air stream, kg/h

2.3.Test program scope

Tests were conducted in a tank 8.8m deep with a 18.6m^2 area. Test quantities and procedures
were as per Sections 6.2 and 8.5 of the ASCE Standard. A summary of the testing conditions is given in Table 2 and Table 3 presented below.

Table 2

Testing parameters

Test Site information	
Tank length (m)	6.1
Tank width (m)	3.3
Water depth (m)	6.6
Water volume (m^3)	121.8
Tank floor area (m^2)	18.6
Aeration device tested	
Manufacturer	EDI
Model	12” disc
Quantity of diffuser units	20.0
Membrane area per diffuser unit (m^2)	0.059
Total membrane area (m^2)	1.19
Diffuser density (%)	6.4%
Test summary	
Average water temperature (^{0}C)	9.9
Airflow per diffuser (Nm^3/h/diffuser)	7.35
Diffuser submergence (m)	6.2
SOTE (%/m)	6.16
SOTE (%)	38.5

Table 3

Airflow, water and chemical measurements

	Test parameters
Orifice plate (primary)	
Pipe I.D. (mm)	154.0513
β value	0.2532
θ value	1.027
Orifice diameter (mm)	39.0058
Ambient temperature (^{0}C)	5.8
Barometric pressure (kPa)	100.31
Relative humidity (%)	43.5
Line temperature (^{0}C)	92.8
Line pressure (kPa)	67.7
Differential pressure (kPa)	1.7
Calculated airflow (Nm^3/h)	147.0
Airflow per diffuser (Nm^3/h/diffuser)	7.35
Water temperature	
Average (^{0}C)	9.9
Sodium sulfite	
TDS start (mg/L)	605
TDS end (mg/L)	778
Actual sulfite added (kg)	21.1
Cobalt chloride	
Concentration (mg/L)	0.4
Cobalt added (g)	48.7

3. Results

All tests were completed according to the latest version of ASCE Standard "Oxygen Transfer
Testing in Clean Water".

According to the test results presented in Table 3 below, the achieved aeration efficiency is
38.49%. Therefore, this is the standard oxygen transfer efficiency that can be reached by using a diffused air aeration system with EDI FlexAir ISM 12" disc diffusers, EPDM membrane, 0.059m^2 active membrane surface per diffuser (Environmental Dynamics international). The SOTE was reached with a 6.20m water depth, the system providing 16.74 kgO_2/h, with a 7.35 Nm^3/h airflow/ diffuser and 6.4% diffuser density. These results can be extrapolated for real applications, assuming the water depth, diffuser density, airflow/ diffuser, etc. are kept the same.

Table 3

Calculation summary

	Average	Std Dev	Probe A	Probe B	Probe C	Probe D
SOTE (%)	**38.49**	0.44	37.95	38.97	38.36	38.67
SOTR (kgO_2/h)	**16.74**	0.19	16.50	16.95	16.68	16.82
Sum of squares	**0.79**	0.40	1.34	0.41	0.63	0.78
Est. Error RMS	**0.032**	0.008	0.043	0.024	0.030	0.033
LSE C_0	**2.56**	0.07	2.49	2.65	2.57	2.52
K_La prime (1/h)	**7.87**	0.04	7.84	7.92	7.90	7.83
TDS Adjusted K_La_{20} (1/h)	**10.53**	0.06	10.49	10.59	10.56	10.47
LSE C^*	**13.86**	0.14	13.72	13.95	13.78	14.01
C^*_{20} (mg/l)	**11.23**	0.11	11.12	11.30	11.16	11.35

4. Conclusion

The presented paper analyzes and proves the oxygen transfer efficiency of a fine-bubble diffuser aeration system in clean water. The tested aeration system managed to exceed the design SOTE set to approximately 38%.

The main challenge of the testing was matching the design parameters to factory testing conditions, calibrating the DO sensors and the blower to the design airflow. Also, the diffuser density had to be identical to the density in the design calculations. All the factors presented in Chapter 1 had to be matched and calibrated, as per the theoretical calculations. The diffusers used in this Factory test were in new condition. After a period of operation, the diffuser membrane degrades and fouls, thus the aeration efficiency decreases. To maintain the guaranteed and tested oxygen transfer efficiency, the Wastewater Treatment Plant operator shall implement maintenance works for diffuser cleaning using, as an example, formic acid cleaning.

The main purpose of this paper was to set a SOTE Factory testing method for fine-bubble diffuser aeration and prove that the influencing factors carry great importance for Oxygen Transfer Efficiency of a fine-bubble diffuser system. In future papers I will analyze and test the same aeration system using a different aeration depth, different airflow/ diffuser unit as to show the differences in OTE.

REFERENCES

[1]. *Robescu L.D., Stroe F., Presura A., Robescu D.N.*, Tehnici de Epurare a Apelor Uzate (Techniques for wastewater treatment), Ed. Tehnica, Bucuresti, 2011

[2]. *Drewnowski J., Remiszewska-Skwarek A., Duda S., Łagód G.*, Aeration Process in Bioreactors as the Main Energy Consumer in a Wastewater Treatment Plant. Review of Solutions and Methods of Process Optimization, MDPI, 2019

[3]. *Stopien J. K.*, Oxygen transfer efficiency and its influencing factors, Forum Eksploatatora, 2012

[4]. *American Society of Civil Engineers*, ASCE standard – measurement of oxygen transfer in clean water, American Society of Civil Engineers, New York, 1993 transfer efficiency and its influencing factors: Part 1. Forum Eksploatatora 2012, 4, 44–49.

[5] *Miller, Richard W.*, Flow Measurement Engineering Handbook, Second Edition, McGraw-Hill, Inc., 1989

[6]. *Stenstrom M.K., Gilbert R.G.*, Effects of α, β and θ factor upon the design, specification and operation of aeration systems, 1981

[7]. *Krampe J., Krauth K.*, Oxygen transfer into activated sludge with high MLSS concentrations, Water Sci. Technol., 2003

[8]. *Xiaofei Xu, Wenze Wei, Fengxia Liu, Wei Wei, Zhijun Liu,* Experimental study on aeration efficiency in a pilot-scale decelerated oxidation ditch equipped with fine bubble diffusers and impellers, China, 2020, 10.1002/cjce.23919, pg. 33.

[9]. *Marunțălu O., Manea E.E., Robescu Diana, Necșoiu M., Lăzăroiu G., Bondrea D.A.*, Research on the Aeration Systems' Efficiency of a Lab-Scale Wastewater Treatment Plant, World Academy of Science, Engineering and Technology International Journal of Environmental and Ecological Engineering Vol:9, No:9, 2015.