

Air–water ratio as a characteristic criterion for fine bubble diffused aeration systems

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Abstract

The performance of fine bubble diffused aeration systems are conventionally evaluated by such characteristic criteria as specific standard oxygen transfer efficiency (SSOTE), transfer number (N_T) and oxygen transfer coefficient ($K_L\alpha_{20}$), but these criteria cannot directly show the variation of air demand with wastewater volume. The ratio of air demand to the wastewater volume (named as air–water ratio) can directly relate the air demand to the wastewater volume, and it is more convenient for designing the aeration systems.

The standard oxygenation performances of fine bubble diffused aeration systems in clean water and wastewater, measured in 47 cylindrical tanks, are analyzed in this study. Two corresponding relationships between air–water ratio and dissolved oxygen (DO) concentration are established to estimate the effect of air–water ratio on DO concentration. Within the ranges of parameters studied, the DO concentration is an increasing function of air–water ratio which increases with such two factors: (1) the internal pressure difference between the initial air bubbles entering aeration tank and the terminal air bubbles breaking up from the water surface; (2) the diameters of the initial air bubbles. To verify the validity of air–water ratio, this paper compares the performance of three fine bubble diffused aeration systems evaluated by the ratio with those by SSOTE, N_T and $K_L\alpha_{20}$, and the process of the calculation of their design and operation based on air–water ratio with those based on the three criteria. The results show that their evaluations are consistent with each other and the process of the calculation based on air–water ratio is more convenient and direct than that based on the other three criteria.

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1. Introduction

Since the end of the 1980s, aeration tanks have been increasingly equipped with ethylene–propylene–diene monomer (EPDM) membrane diffusers. These fine bubble diffused aeration systems have several advantages, which contribute to their extensive development: high oxygenation performances, adaptability to varying oxygen requirements, and a reduction in the production of aerosols [1]. Much research has been done on choosing the appropriate performance evaluation parameters for the aeration systems. Zlokarnik [2], Kulkarni et al. [3], Dudley [4] and Hebrard [5] used the total oxygen transfer coefficient ($K_L\alpha$) as a characteristic criterion of the aeration system, Zlokarnik [2], Roustan [6] and Capela et al. [7] defined a trans-

fer number N_T and Capela [8] selected the specific standard oxygen transfer efficiency (SSOTE in %/m of submergence). Despite these criteria show the performance of fine bubble diffused aeration system, they cannot be directly applied to design and operation of the aeration systems, as they fail to exhibit the air demand varying with volume of wastewater in aeration tank. So the ratio of air demand to the volume (called as air–water ratio) can be chosen as a characteristic criterion.

The aim of this work is to establish the relationships between the concentration of dissolved oxygen (DO) in water and air–water ratio. In this study, these relationships are developed from the theoretical model development on the basis of the results from 47 oxygenation tests performed in clean water and wastewater on full-scale wastewater treatment plants. To verify the validity of air–water ratio, this paper performs the comparison of performance evaluation three fine bubble diffused aeration systems by the ratio, SSOTE, N_T and $K_L\alpha_{20}$, and studies the

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Nomenclature

C	dissolved oxygen concentration (ML^{-3})
C_n	the dissolved oxygen concentration when $\lambda = n\xi_{b \max}$ (ML^{-3})
C_{wi}	dissolved oxygen when λ_b arrives at $\lambda_{b \max}$ for i times (ML^{-3})
C_0	initial dissolved oxygen concentration (ML^{-3})
C_{11}	the increment of dissolved oxygen due to oxygen transferring in the sewage during the process when λ_b arrives at $\lambda_{b \max}$ firstly (ML^{-3})
C_{12}	the decrement of dissolved oxygen due to BOD decaying and ammonia nitrogen nitrification in the sewage during the process when λ_b arrives at $\lambda_{b \max}$ firstly (ML^{-3})
$C_{\infty t}^*$	oxygen concentration at saturation at $t^\circ\text{C}$ (ML^{-3})
d_b	average diameter of fine air bubble (L)
d_0	initial diameter of fine air bubble entering aeration tank (L)
D	tank diameter (L)
D_f	gas molecule diffusing coefficient (MT^{-1})
g	acceleration due to gravity (LT^{-2})
h	the diffuser submergence (L)
h_b	the vertical distance between the water surface and diffuser (L)
H	water depth (L)
k_C	first-order BOD decay rate constant (dimensionless)
k_i	constant (dimensionless)
k_N	first-order ammonia nitrogen nitrification decay rate constant (dimensionless)
k_0	spherical coefficient (dimensionless)
K_L	oxygen transfer coefficient (MT^{-1})
L	tank length (L)
L_C	biochemical oxygen demand concentration (ML^{-3})
L_{C0}	initial biochemical oxygen demand concentration (ML^{-3})
L_N	ammonia nitrogen (ML^{-3})
L_{N0}	initial ammonia nitrogen (ML^{-3})
m_i	exponent (dimensionless)
M_{O_2}	mass flow of oxygen in the air stream (ML^{-1})
n	the accumulative times ξ_b arrives at $\xi_{b \max}$ during aeration process (dimensionless)
N_T	transfer number (dimensionless)
p_i	the pressure of initial air bubbles entering aeration tank ($\text{ML}^{-1} \text{T}^{-2}$)
p_0	the pressure of terminal air bubble breaking up from the water surface ($\text{ML}^{-1} \text{T}^{-2}$)
P	Power input by the aeration system ($\text{ML}^2 \text{T}^{-3}$)
Q_g	air flow rate ($\text{L}^3 \text{T}^{-1}$)
S	surface area of the tank (L^2)
S_a	total surface area of the zones occupied by the diffusers (aerated area) (L^2)

S_C	Schmidt number (dimensionless)
S_P	total surface area of the perforated membrane (L^2)
SSOTE	specific standard oxygen transfer efficiency (L^{-1})
t_{ta}	total aeration time (T)
U_G	average air bubble velocity (LT^{-1})
U_{G0}	initial air bubble velocity (LT^{-1})
V	volume of aeration tank (L^3)
V_a	air volume (L^3)
V_w	aeration tank cubage (L^3)
We	Weber number (dimensionless)

Greek letters

α	interfacial specific area (M^{-1})
β	constant (dimensionless)
ε	torrential energy dissipation rate ($\text{L}^2 \text{T}^{-3}$)
γ	constant (dimensionless)
φ	constant (dimensionless)
λ	the total ratio of the air volume to water volume in an aeration process (dimensionless)
μ	dynamic viscosity of water ($\text{ML}^{-1} \text{T}^{-1}$)
ρ	dynamic viscosity of water (ML^{-3})
σ	water interfacial strain ($\text{ML}^{-1} \text{T}^{-2}$)
τ	shear stress of the interface between air and water (MLT^{-2})
v	average pulsant velocity (LT^{-1})
ξ_b	the air holdups within h_b (dimensionless)
$\xi_{b \max}$	the air holdups within h (dimensionless)

process of the calculation of their design and operation based on these different characteristic criteria.

2. Material and methods*2.1. Model development**2.1.1. Model for aeration in clean water*

In a given cylindrical aeration tank, during the period of aeration, the initial air bubbles enter into the water through fine bubble diffused aeration equipment, and supposedly rise vertically then break up from the water surface [9]. The air holdup in this process can be expressed as follows:

$$\xi_b = \frac{V_g}{V_w} = \frac{Q_g t}{V_w} = \frac{Q_g h_b}{V_w U_G} \quad (h_b \leq h) \quad (1)$$

$$\xi_{b \max} = \frac{V_{g \max}}{V_w} = \frac{Q_g h}{V_w U_G} \quad (2)$$

where V_g is air volume (L^3), V_w the volume of water (L^3), Q_g the air flow rate ($\text{L}^3 \text{T}^{-1}$), t the aeration time (T), h_b the vertical distance between the water surface and diffuser (L), U_G the average air bubble velocity (LT^{-1}), h the diffuser submergence (L), ξ_b the air holdups within h_b (dimensionless), $\xi_{b \max}$ the air holdups within h (dimensionless) and $V_{g \max}$ is total air volume (L^3). Kulkarni et al. [3] proposed that the shapes of the air bubbles were approximately spherical and the air–water

interfacial specific area of the whole tank could be expressed in the following form:

$$\alpha = \frac{k_0 \xi_b d_b^2}{d_0^3} \quad (3)$$

where α is interfacial specific area (L^{-1}), d_0 the initial diameter of fine air bubble entering aeration tank (L), d_b the average diameter of fine air bubble (L) and k_0 is spherical coefficient (dimensionless). During the period of ξ_b arriving at $\xi_{b \max}$, the differential equation about the oxygen transfer can be written as follows:

$$\frac{dC}{dt} = K_L \alpha (C_{\infty T}^* - C) \Rightarrow \frac{dC}{dt} = K_L \frac{k_0 \xi_b d_b^2}{d_0^3} (C_{\infty T}^* - C) \quad (4)$$

where C is dissolved oxygen concentration of aeration in clean water (ML^{-3}), K_L the oxygen transfer coefficient (MT^{-1}) and $C_{\infty T}^*$ is dissolved oxygen concentration at saturation at $T^\circ C$ (ML^{-3}). From Eq. (1), the following expression can be developed:

$$dt = \frac{V_W}{Q_g} d\xi_b \quad (5)$$

Therefore the analytical solution of Eq. (4) can be expressed as follows:

$$C = C_{\infty T}^* - (C_{\infty T}^* - C_{ini}) \exp\left(-\frac{k_0 K_L V_W d_b^2 \xi_b^2}{2 d_0^3 Q_g}\right) \quad (6)$$

where C_{ini} is the initial DO concentration of the aeration in clean water (ML^{-3}).

As shown in Fig. 1, the whole process of aeration is composed of n consecutive stages. The first stage is the process when ξ_b arrives at $\xi_{b \max}$ for the first time; the second stage is the process when ξ_b arrives at $\xi_{b \max}$ for the second time; similarly till the n th stage. These stages can be considered as n Continuous Stirred-Tank Reactors (CSTR) in series.

According to Eq. (6), a series of expression can be given as follows:

$$C_1 = C_{\infty T}^* - (C_{\infty T}^* - C_0) \exp\left(-\frac{k_0 K_L V_W d_b^2 \xi_{b \max}^2}{2 d_0^3 Q_g}\right) \quad (7.1)$$

$$C_2 = C_{\infty T}^* - (C_{\infty T}^* - C_1) \exp\left(-\frac{k_0 K_L V_W d_b^2 \xi_{b \max}^2}{2 d_0^3 Q_g}\right) \quad (7.2)$$

...

$$C_n = C_{\infty T}^* - (C_{\infty T}^* - C_{n-1}) \exp\left(-\frac{k_0 K_L V_W d_b^2 \xi_{b \max}^2}{2 d_0^3 Q_g}\right) \quad (7.n)$$

where C_i ($i = 1, 2, \dots, n$) is the terminal DO concentration of the i th stage of aeration in clean water (ML^{-3}). Integrating Eqs. (7.1)–(7.n), the following expression can be obtained:

$$C_n = C_{\infty T}^* - (C_{\infty T}^* - C_0) \exp\left(-\frac{nk_0 K_L V_W d_b^2 \xi_{b \max}^2}{2 d_0^3 Q_g}\right) \quad (8)$$

From Fig. 1, the relationship between air–water ratio and air holdup can be written as follows:

$$\lambda = n \xi_{b \max} \quad (9)$$

where λ is air–water ratio (the total ratio of the air volume to water volume in a process of aeration (dimensionless)), n is the times λ arrives at $\xi_{b \max}$ in the whole process of aeration.

According to a standardized procedure [10,11], C_0 is zero. Therefore Eq. (8) can be transformed into the following reduced form:

$$\begin{aligned} C_n &= C_{\infty T}^* \frac{nk_0 K_L V_W d_b^2 \xi_{b \max}^2}{2 d_0^3 Q_g} = \frac{k_0 C_{\infty T}^* K_L V_W d_b^2 \lambda^2}{2 n d_0^3 Q_g} \\ &= \frac{k_0 h C_{\infty T}^* K_L d_b^2 \lambda}{2 U_G d_0^3} \end{aligned} \quad (10)$$

Gillot et al. [12] developed the following relationships:

$$K_L \propto (D_f U_G)^{1/2} h^{-3/2}, \quad U_G \propto (g d_b)^{1/4} \left(\frac{\mu g}{\rho}\right)^{1/6} \quad (11)$$

where D_f is gas molecule diffusing coefficient (MT^{-1}), g the acceleration due to gravity (LT^{-2}), μ the dynamic viscosity of water ($ML^{-1}T^{-1}$), ρ the density of water (ML^{-3}). Kolmogoroff defined the Webber constant $We = \tau(\sigma/d_b)$ (dimensionless, τ is shear stress of the interface between air and water (MLT^{-2}), σ is gas–water interfacial strain ($ML^{-1}T^{-2}$)) as the ratio of the interfacial tension to the inertial force. Hinze reduced the rela-

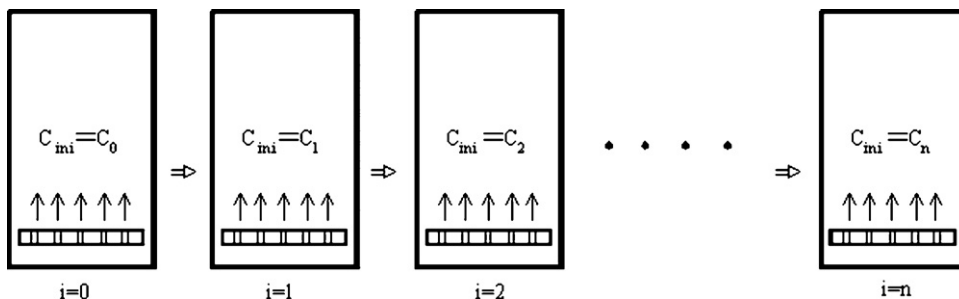


Fig. 1. Schematic diagram of the Reactors model of aeration in clean water.

relationship on τ ($\tau = \rho \bar{v}^2 / 2$). Therefore the correlative equation of homogeneous uniform flow can be written as follows:

$$\bar{v}^2 = 2(\varepsilon d_b)^{2/3} \tag{12}$$

where \bar{v} is average pulsant velocity ($L T^{-1}$), ε the torrential energy dissipation rate ($L^2 T^{-3}$) and can be calculated by the following expression [13]:

$$\varepsilon = \frac{P}{\rho V_W} = \frac{(p_i - p_O) Q_g}{\rho V_W} \tag{13}$$

where P is power input of the aeration system ($ML^2 T^{-3}$), p_i the pressure of initial air bubbles entering aeration tank ($ML^{-1} T^{-2}$), p_O is the pressure of terminal air bubble breaking up from the water surface ($ML^{-1} T^{-2}$). Therefore, the average diameter of air bubbles in the aeration tank can be exhibited as follows:

$$\begin{aligned} d_b &= k_1 \left(\frac{\sigma^{3/5}}{\rho^{1/5}} \right) \left(\frac{(p_i - p_O) Q_g}{V_W} \right)^{-2/5} \\ &= k_1 \left(\frac{\sigma^{3/5}}{\rho^{1/5}} \right) \left(\frac{(p_i - p_O) \lambda}{t} \right)^{-2/5} \end{aligned} \tag{14}$$

where k_1 is constant (dimensionless). Integrating Eqs. (10)–(14) and the Schmidt number $S_C = \mu / \rho D_f$ (dimensionless, constant), the following expression can be yielded:

$$\begin{aligned} C_n &= k_2 \mu^{5/12} S_C^{-1/2} \sigma^{9/8} \rho^{-19/24} g^{-5/24} C_{\infty t}^* h^{-1/2} \\ &\quad \times (p_i - p_O)^{-3/4} d_0^{-3} t^{3/4} \lambda^{5/4} \end{aligned} \tag{15}$$

where k_2 is constant (dimensionless). Due to S_C , μ , ρ , g , σ and $C_{\infty T}^*$ are all constants in a given temperature, they can be integrated into constant k_2 . Considering the effect on DO by the geometry of the tank/aeration system and layout of the aeration system [12], Eq. (15) can be transformed to the following equation:

$$\begin{aligned} C_n &= k_3 h^{-1/2} (p_i - p_O)^{-3/4} d_0^{-3} t^{3/4} \lambda^{5/4} \left(\frac{S_P}{S} \right)^{m_1} \left(\frac{S_P}{S_a} \right)^{m_2} \\ &\quad \times \left(\frac{D}{h} \right)^{m_3} \end{aligned} \tag{16}$$

where k_3 is constant (dimensionless), m_i ($i = 1, 2, 3$) are numerical exponents (dimensionless).

2.1.2. Model for aeration in sewage

In the process of aeration for sewage, the following effects should be taken into account: (1) effects of impurities in sewage on oxygen transfer rates; (2) oxygen consumption caused by decay of biochemical oxygen demand (BOD) and nitrification of ammonia nitrogen [14]. Synthesizing these factors, the corresponding expression in sewage can be written as follows:

$$\begin{aligned} \frac{dC_w}{dt} &= \varphi K_L \frac{k_0 \xi_b d_b^2}{d_0^3} (\beta C_{\infty t}^* - C_w) - k_C L_{C0} \exp(-k_C t) \\ &\quad - k_N L_{N0} \exp(-k_N t) \end{aligned} \tag{17}$$

where C_w is dissolved oxygen concentration of aeration in sewage water (ML^{-3}), φ the constant (dimensionless), β the constant (dimensionless), k_C the first-order BOD decay rate constant (T^{-1}), k_N is first-order ammonia nitrogen nitrification rate constant (T^{-1}), L_{C0} the initial BOD concentration (ML^{-3}) and L_{N0} is initial ammonia nitrogen (ML^{-3}).

The analytical solution of Eq. (17) can be obtained as follows:

$$\begin{aligned} C_w &= \beta C_{\infty T}^* - (\beta C_{\infty T}^* - C_{w0}) \exp \left(-\frac{\varphi k_0 K_L V_W d_b^2 \lambda_b^2 \max}{2 d_0^3 Q_g} \right) \\ &\quad + C_{w0} + \gamma_C L_{C0} \left(\exp \left(-\frac{k_C V_W \xi_b \max}{Q_g} \right) - 1 \right) \\ &\quad + \gamma_N L_{N0} \left(\exp \left(-\frac{k_N V_W \xi_b \max}{Q_g} \right) - 1 \right) \end{aligned} \tag{18}$$

where C_{w0} is initial DO concentration of aeration in sewage (ML^{-3}), both $\gamma_C = k_C / (k_C - k_L)$ and $\gamma_N = k_N / (k_N - K_L)$ are constants (dimensionless).

Being similar to Eq. (10), the following expression can be gained:

$$\begin{aligned} C_{wn} &= C_{\infty T}^* \left[-\beta \left(\frac{\varphi k_0 h^2 K_L d_b^2}{2 t U_G^2 d_0^3} \right)^2 \lambda^2 \right. \\ &\quad + \left(\frac{\gamma_C L_{C0} k_C V_W}{Q_g C_s} + \frac{\gamma_N L_{N0} k_N V_W}{Q_g C_s} \right) \frac{\varphi k_0 h^3 K_L d_b^2 \lambda^2}{2 t^2 U_G^3 d_0^3} \\ &\quad \left. + \frac{3 \varphi \beta h^2 k_0 K_L d_b^2 \lambda}{2 t U_G^2 d_0^3} - \left(\frac{3 \gamma_C h L_{C0} k_C}{U_G C_s} + \frac{3 \gamma_N h L_{N0} k_N}{U_G C_s} \right) \right] \end{aligned} \tag{19}$$

where C_{wn} is the terminal DO concentration of the n th stage of aeration in sewage (ML^{-3}).

Similar to Eq. (16), Eq. (19) can be transformed to the following:

$$\begin{aligned} C_{wn} &= C_{\infty t}^* [k_6 h^4 d_0^{-6} (p_i - p_O)^{-6/5} t^{-4/5} \lambda^{4/5} \\ &\quad + k_7 (k_8 L_{C0} + k_9 L_{N0}) h^3 d_0^{-3} (p_i - p_O)^{-1/2} t^{-1/2} \lambda^{1/2} \\ &\quad + k_{10} h^2 d_0^{-3} (p_i - p_O)^{-3/5} \lambda^{2/5} t^{-2/5} \\ &\quad + k_{11} (k_8 L_{C0} + k_9 L_{N0}) h (p_i - p_O)^{1/10} \lambda^{1/10} t^{-1/10}] \\ &\quad \times \left(\frac{S_P}{S} \right)^{m_4} \left(\frac{S_P}{S_a} \right)^{m_5} \left(\frac{D}{h} \right)^{m_6} \end{aligned} \tag{20}$$

where k_i ($i = 6, 7, 8, 9, 10, 11$) are constant (dimensionless) and m_i ($i = 1, 2, 3$) are numerical exponents (dimensionless).

2.2. Experimental equipment and database

The experimental equipment for aeration in clean water and sewage in cylindrical aeration tank is shown in Fig. 2. In the figure, the Laura MP₂ is an instrument measuring the bubble surface pressure difference. Measurements performed for clean water and sewage on 47 tests, respectively, and all equipped with EPDM membrane diffusers, are analyzed in this study. The

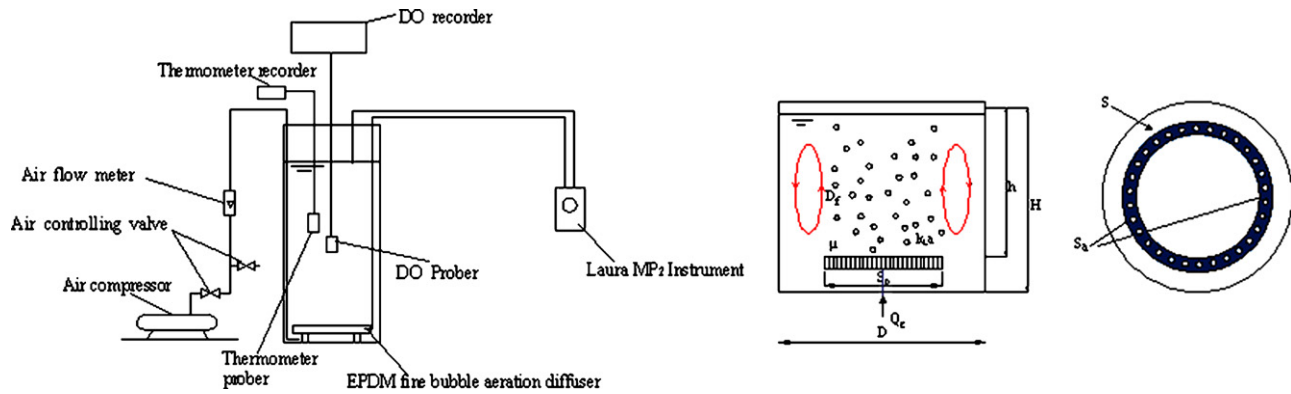


Fig. 2. Schematic diagram of experimental equipment and relevant design and operating parameters in cylindrical aeration tanks.

Table 1(a)

Summary of the range of the relevant parameters in aeration for clean water and sewage

Parameter	D (m)	H (m)	h (m ²)	V (m ³)	S (m ²)	S_a (m ²)	S_p (m ²)	D/h
Range	6.5–15.0	2.3–6.3	2.0–6.0	78–852	33–177	18.5–176.7	3.0–13.5	1.4–6.2
Parameter	$p_i - p_o$ ($\times 10^6$ Pa)	d_0 (mm)	Initial BOD (mg/L)	Initial NH ₃ - N (mg/L)	S_p/S	S_p/S_a	λ	
Range	0.23–0.47	0.02–1.0	22–100	15–70	0.05–0.15	0.07–0.35	0–9.6	

ranges of the parameters and dimensionless numbers obtained from these measurements are shown in Tables 1(a)–1(c). The aim of the measurements, performed according to a procedure in the NFEN 12255-15 standard (2004), is to determine the relationships between DO concentration and air–water ratio, analyzes the influence of air–water ratio on DO concentration and verifies the validity of air–water ratio as a characteristic criterion of aeration systems.

To compare the systems, the results of the oxygenation measurements are expressed at standard conditions:

- (1) initial DO concentration = 0 mg/L,
- (2) water temperature = 20 °C,
- (3) atmospheric pressure = 1013 hPa.

3. Results and discussion

3.1. Determining relationships between DO concentration of water and air–water ratio

The values of the constants and exponents m_i ($i=1, 2, 3, 4, 5, 6$) and k_j ($j=3, 6, 7, 8, 9, 10, 11$) in Eqs. (16) and (20) varying with such conditions: the tank geometry, layout and geometry of the aeration system, and operating conditions are determined by trial calculation using the Matlab software (v.6.0, The MathWorks Inc., Natick, MA).

In the literature, there are several performance criteria for simulation models that can be used also as objective function. Commonly they are based on the comparison between the simulated and measured values. In this work the root mean square error (RMSE) is used as the objective function for the optimization of the model. On the other hand, RMSE, R^2 (the Nash and Sutcliffe model efficiency coefficient) and absolute value of

balance error (ABE) are used for evaluation criteria during the calibration and validation periods, according to the following expressions:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (o_i - p_i)^2}{N}} \quad (21)$$

$$R^2 = 1 - \frac{\sum_{i=1}^N (o_i - p_i)^2}{\sum_{i=1}^N (o_i - \bar{o})^2} \quad (22)$$

$$\text{ABE} = \left| \frac{p_i - o_i}{o_i} \times 100\% \right| \quad (23)$$

where o_i is the i th observed DO, p_i the i th simulated DO of the models, N the number of the measurement in the calibration data set and \bar{o} is the mean value of the observed DO. Uniform random sets of the parameters m_i ($i=1, 2, 3, 4, 5, 6$) and k_j ($j=3, 6, 7, 8, 9, 10, 11$) were sampled for the calibration, and an optimum set was found based on RMSE, R^2 and ABE. RMSE of the optimum set is minimum in all the sets, and its corresponding ABE (less than 10%) is the relative low one and R^2 (greater than 0.9) is the relative high one in all the sets.

The data set of measurement is split up into two parts. One is called calibration set used for the derivation of the constants and exponents in Eqs. (16) and (20), and the other is called verification set used for verifying the goodness of fit between the calculated DO from the two calibrated equations and the measured DO. The corresponding ranges of the relevant parameters in these two sets are shown in Table 1(b) and Table 1(c), and Table 1(a) is the summary table of the other two.

Table 1(b)
The condition of the relevant parameters in aeration for calibration

No.	D (m)	H (m)	h (m)	V (m ³)	S (m ²)	S_a (m ²)	S_p (m ²)	D/h	Average $p_i - p_o$ ($\times 10^6$ Pa)	d_0 (mm)	Initial BOD (mg/L)	Initial NH ₃ –N (mg/L)	S_p/S	S_p/S_a	λ
1	6.7	5.7	4.5	201	35	30.6	5.0	1.5	0.24–0.36	0.91	42	35	0.14	0.16	4.5
2	6.8	2.5	2.2	91	36	30.9	3.6	3.1	0.25–0.35	0.10	30	20	0.10	0.12	4.7
3	7.8	6.1	5.4	291	48	31.9	7.4	1.4	0.23–0.34	0.40	26	57	0.15	0.23	3.1
4	8.3	3.3	3.0	179	54	46.0	4.9	2.5	0.26–0.35	0.20	55	35	0.09	0.11	5.0
5	8.6	4.6	3.4	267	58	47.8	7.7	2.5	0.23–0.41	0.07	48	17	0.13	0.16	7.7
6	8.8	5.7	4.8	347	61	52.0	7.3	1.8	0.29–0.47	0.28	92	44	0.12	0.14	9.1
7	9.0	4.5	3.6	286	64	60.5	8.9	2.5	0.27–0.35	0.23	32	28	0.14	0.15	3.0
8	9.2	4.1	3.4	272	66	56.3	7.8	2.7	0.26–0.32	0.19	28	24	0.12	0.14	0.2
9	9.3	5.4	4.7	367	68	65.1	6.8	2.0	0.28–0.38	0.26	80	64	0.10	0.10	9.4
10	9.4	5.4	5.0	375	69	67.8	8.3	1.9	0.27–0.35	0.60	41	22	0.12	0.12	7.6
11	10.2	4.7	4.3	384	82	69.4	6.5	2.2	0.30–0.38	0.50	70	45	0.08	0.09	7.1
12	10.4	5.0	3.9	425	85	80.1	6.5	2.7	0.26–0.35	0.48	49	65	0.08	0.08	1.6
13	10.6	2.9	2.5	256	88	85.0	13.3	4.2	0.26–0.38	0.31	90	34	0.15	0.16	6.4
14	12.0	2.5	1.5	283	113	98.9	8.7	8.0	0.29–0.35	0.98	56	41	0.08	0.09	5.2
15	12.3	5.3	5.0	629	119	101.0	8.3	2.3	0.36–0.43	0.60	45	55	0.07	0.08	6.9
16	12.9	6.0	5.3	784	131	122.4	11.2	2.4	0.26–0.36	0.47	45	29	0.09	0.09	3.4
17	13.0	5.1	4.2	677	133	128.5	8.5	3.1	0.23–0.28	0.23	59	67	0.06	0.07	0.2
18	13.0	5.4	5.0	716	133	115.3	8.2	2.6	0.29–0.41	0.15	52	58	0.06	0.07	6.9
19	13.6	6.1	5.8	772	127	107.6	11.4	2.1	0.39–0.45	0.80	65	60	0.09	0.11	5.3
20	13.1	2.6	2.1	350	135	117.8	8.0	6.2	0.28–0.37	0.43	67	53	0.06	0.07	4.4
21	13.3	5.3	4.9	736	139	123.3	11.3	2.7	0.30–0.39	0.98	97	16	0.08	0.09	6.6
22	14.1	3.9	3.2	609	156	110.0	7.5	4.4	0.29–0.39	0.77	85	16	0.05	0.07	4.1
23	14.5	5.0	4.3	825	165	20.7	6.5	3.4	0.27–0.37	0.02	95	33	0.04	0.31	4.1
24	14.8	2.7	2.2	464	172	145.2	9.8	6.7	0.28–0.36	0.51	69	66	0.06	0.07	2.4

Table 1(c)
The condition of the relevant parameters in aeration for verification

No.	D (m)	H (m)	h (m)	V (m ³)	S (m ²)	S_a (m ²)	S_p (m ²)	D/h	Average $p_i - p_o$ ($\times 10^6$ Pa)	d_0 (mm)	Initial BOD (mg/L)	Initial NH ₃ - N (mg/L)	S_p/S	S_p/S_a	λ
1	6.5	2.3	2.1	76	33	30.1	5.1	3.1	0.27–0.36	0.06	81	65	0.15	0.17	3.9
2	7.3	3.6	3.3	151	42	41.4	5.5	2.2	0.27–0.35	0.08	100	61	0.13	0.13	1.4
3	7.6	5.8	5	263	45	24.1	6.6	1.5	0.33–0.46	0.03	93	37	0.15	0.27	8.1
4	8.3	3.3	3	178	54	46.0	3.6	2.8	0.32–0.44	0.09	33	50	0.07	0.08	7.9
5	8.7	2.3	2	137	59	53.5	6.3	4.4	0.25–0.35	0.08	55	61	0.11	0.12	1.9
6	8.7	4.2	3.2	250	59	53.4	4.4	2.7	0.27–0.39	0.08	32	40	0.07	0.08	5.7
7	9.3	4.7	3.6	319	68	60.7	5.4	2.6	0.37–0.46	0.09	65	39	0.08	0.09	8.9
8	9.4	4.7	4.3	326	69	64.4	6.2	2.2	0.28–0.36	0.04	27	70	0.09	0.10	3.7
9	9.5	2.3	2	163	71	69.4	7.7	4.8	0.26–0.37	0.1	44	40	0.11	0.11	2.6
10	10.4	6.2	5.3	526	85	69.2	5.0	2.0	0.23–0.33	0.06	46	57	0.06	0.07	1.8
11	10.5	3.8	2.6	329	87	86.3	10.0	4.0	0.24–0.31	0.05	26	42	0.12	0.12	1.5
12	10.9	5.7	5.3	532	93	83.0	12.2	2.1	0.30–0.39	0.04	54	25	0.13	0.15	4.1
13	11.7	5.5	5.2	591	107	90.7	12.1	2.3	0.29–0.38	0.05	23	54	0.11	0.13	4.6
14	11.8	3.1	2.8	339	109	146.3	10.2	4.2	0.28–0.37	0.05	74	67	0.09	0.07	5.1
15	11.9	3.4	2.4	378	111	101.2	8.5	5.0	0.27–0.41	0.08	53	32	0.08	0.08	5.9
16	12.1	6.3	6	724	115	28.7	5.8	2.0	0.28–0.40	0.02	40	57	0.05	0.20	4.5
17	12.4	4.8	4.2	579	121	97.9	6.8	3.0	0.23–0.30	0.06	57	15	0.06	0.07	1.1
18	12.4	4	3	483	121	109.3	9.0	4.1	0.24–0.31	0.03	79	68	0.07	0.08	2.8
19	14.3	3.4	2.3	546	161	45.0	7.5	6.2	0.39–0.47	0.04	34	52	0.05	0.17	9.6
20	14.6	4.9	4.6	820	167	33.2	8.2	3.2	0.31–0.40	0.07	39	18	0.05	0.25	6.3
21	14.7	5	4.5	842	170	164.0	13.5	3.3	0.29–0.39	0.07	24	38	0.08	0.08	5.0
22	15	4	3.4	707	177	108.4	9.9	4.4	0.28–0.38	0.06	89	60	0.06	0.09	6.1
23	15	4.2	4.8	742	177	46.7	8.5	3.1	0.23–0.25	0.02	58	24	0.05	0.18	0.1

Therefore the following expressions can be gained respectively from Eqs. (16) and (20):

$$C_n = 3.6 \times 10^{-11} \times h^{-1/2} (p_i - p_o)^{-3/4} d_0^{-3} t^{3/4} \lambda^{5/4} \times \left(\frac{S_p}{S}\right)^{0.22} \left(\frac{S_p}{S_a}\right)^{-0.11} \left(\frac{D}{h}\right)^{0.14} \quad (24)$$

$$C_{wn} = 4.62 \times 10^{-18} C_{\infty t}^* [5.31 \times 10^{-5} h^4 d_0^{-6} \times (p_i - p_o)^{-6/5} t^{-4/5} \lambda^{4/5} + 2.93 \times 10^4 \times (2.88 \times 10^2 L_{C0} + 1.32 \times 10^2 L_{N0}) \times h^3 d_0^{-3} (p_i - p_o)^{-1/2} t^{-1/2} \lambda^{1/2} + 0.22 h^2 d_0^{-3} (p_i - p_o)^{-3/5} t^{-2/5} \lambda^{2/5} - 0.04 \times (2.95 \times 10^2 L_{C0} + 1.33 \times 10^2 L_{N0}) \times h (p_i - p_o)^{1/10} t^{-1/10} \lambda^{1/10}] \times \left(\frac{S_p}{S}\right)^{0.12} \left(\frac{S_p}{S_a}\right)^{-0.06} \left(\frac{D}{h}\right)^{0.11} \quad (25)$$

Figs. 3 and 4 show the measured DO as a function of the values calculated from Eqs. (24) and (25), respectively. The regression coefficients (r^2) of all are 0.9865 in clean water and 0.9845 in sewage. The relative differences between the measured and calculated values are on 3.72–4.73% in clean water and 3.05–4.51% in sewage, with a maximum value of 5.93% and 6.24%, respectively. The match between the calculated values and the measured ones is therefore considered good. The differences obtained owe to the empirical nature of the relationship established (not all the affecting parameters are taken into account), to measurement errors (geometric magnitudes, air flow rate, etc.), and to the quality of the water used for the test (tap water, river water). Both Eqs. (24) and (25) are only

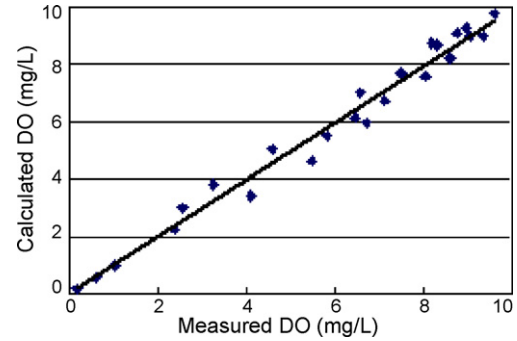


Fig. 3. Measured vs. calculated DO concentration in aeration for clean water.

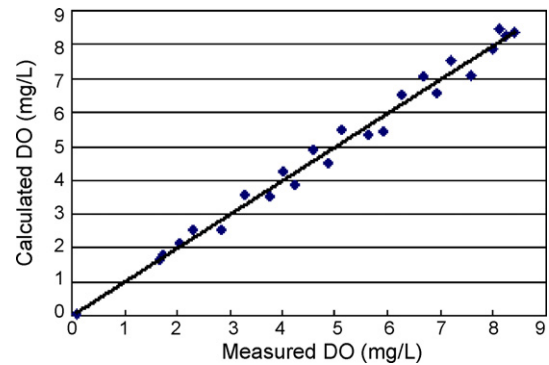


Fig. 4. Measured vs. calculated DO concentration in aeration for sewage.

applicable within the ranges of the geometric and layout parameters measured and the dimensionless numbers considered (cf. Tables 1(a)–1(c)).

When the geometry of the tank/aeration system and layout of the aeration system are given and the aeration time is invariable, in terms of DO concentration required, the value of air–water ratio can be calculated from Eqs. (24) and (25). Based on the

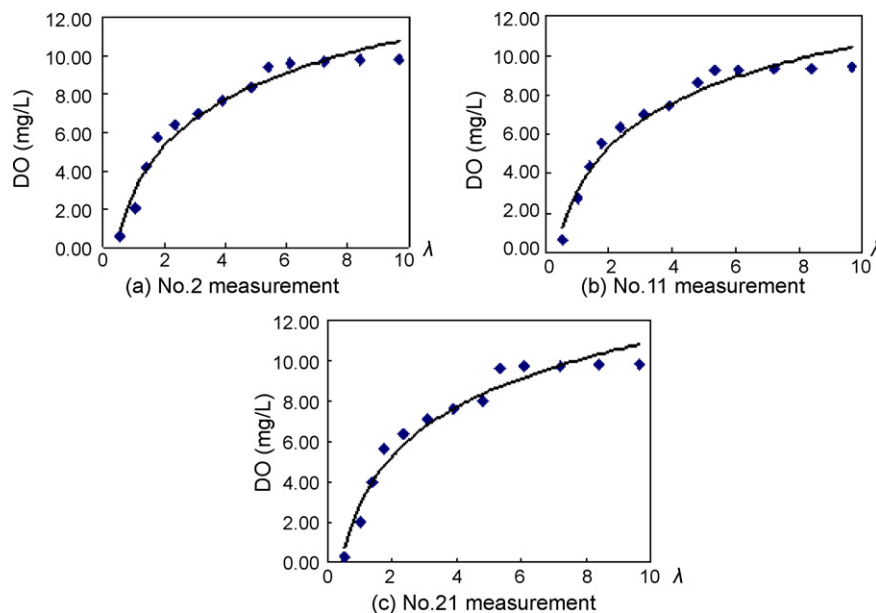


Fig. 5. Influence of air–water ratio (λ) on DO concentration in clean water in different measurements. (a) No. 2 measurement, (b) No. 11 measurement, (c) No. 21 measurement.

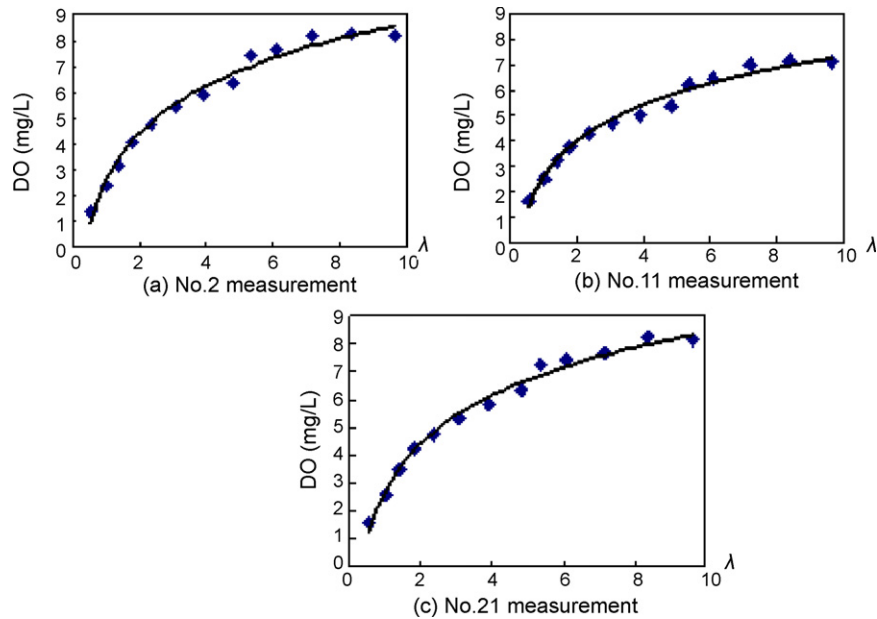


Fig. 6. Influence of air–water ratio (λ) on DO concentration in sewage in different me. (a) No. 2 measurement, (b) No. 11 measurement, (c) No. 21 measurement.

ratio and the volume of wastewater to be treated, the air demand can be determined directly.

3.2. Influence of air–water ratio on DO concentration

No. 2, No. 11 and No. 21 measurement in Table 1(c) are chose for this section. This choice depends on the value of D , H , h , S , S_a and S_p . And No. 2, No. 11 and No. 21 measurement are raised as examples of the relative low value, the relative middle value and the relative high value of all these parameters in Table 1(c), respectively. Although the values of D , H , h , S , S_a and S_p in these three measurements are different from the corresponding ones of each other, the values of S_p/S , S_p/S_a , D/h are approximate. In addition, all these three measurements are redone owing to the reset of λ for this section (its range is 0–10 and other parameters are invariable in these measurements).

According to Eqs. (24) and (25), DO concentration increases with increasing air–water ratio λ . This is confirmed by the measurement results shown in Figs. 5 and 6. Furthermore, according to Eqs. (24) and (25), when λ is the same, the DO concentration relies on not the values of D , H , h , S , S_a and S_p but the values of S_p/S , S_p/S_a , D/h .

3.3. Impact of the pressure difference and initial diameter on air–water ratio

Eqs. (24) and (25) show when other parameters are invariable and DO concentration required is given, air–water ratio will be scale-up with the internal pressure difference between the initial air bubbles entering aeration tank and the terminal air bubbles breaking up from the water surface. Similarly the relation between air–water ratio and the diameters of initial air bubbles entering aeration tank can also be concluded. The analysis on database measured in Figs. 7–10 can validate it. In Figs. 7–10, air–water ratio expresses as an increasing function of internal

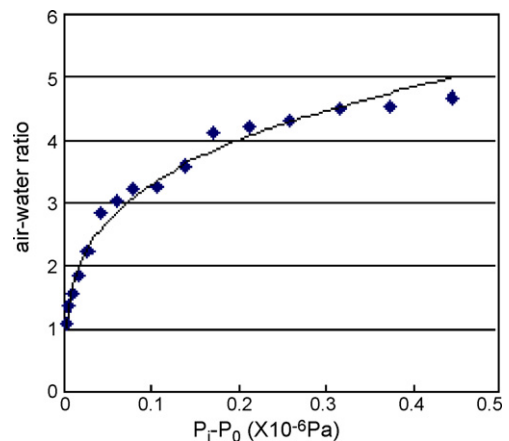


Fig. 7. Impact of internal pressure difference of air bubbles ($p_i - p_o (\times 10^6 \text{ Pa})$) on air–water ratio (λ) in clean water.

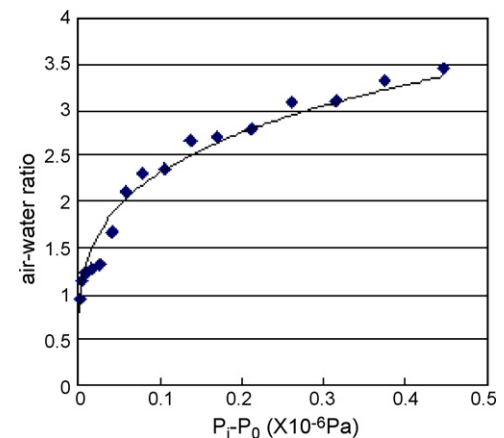


Fig. 8. Impact of internal pressure difference of air bubbles ($p_i - p_o (\times 10^6 \text{ Pa})$) on air–water ratio (λ) in sewage.

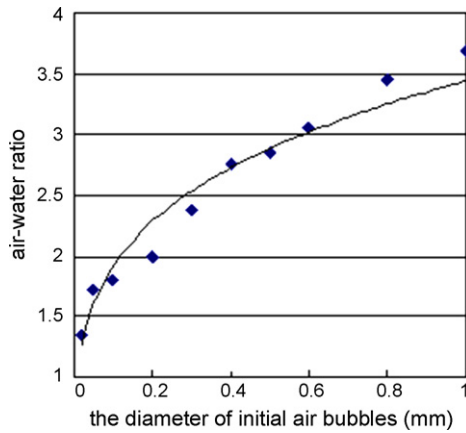


Fig. 9. Impact of the diameter of initial air bubbles on air–water ratio (λ) in clean water.

pressure difference and the initial diameter respectively for aeration in clean water and wastewater. In addition, because of the function of oxygen transfer, the values of $p_i - p_O$ are not equal to zero unless $\lambda = 0$, (namely the aeration is not performed). Similarly, it is natural that when $\lambda = 0$ (namely the aeration is not performed and none of air bubbles are produced), $d_0 = 0$.

3.4. Compared with other characteristic criteria

3.4.1. Comparison of the performance evaluation for fine bubble diffused aeration systems

The oxygenation performances are generally reported in terms of:

- (1) Total oxygen transfer coefficient at 20 °C ($K_L\alpha_{20}$)

The relationship between the oxygen transfer coefficient at 20 °C and the characteristic parameters of the tank/aeration system can be expressed as follows [12]:

$$K_L\alpha_{20} = K'' Q_g S^{-1-m_1+(m_2)/2} S_P^{m_1+m_2} S_a^{-m_2} h^{-m_3}$$

$$\text{where } K'' = \text{constant} = \frac{7.77 \times 10^{-5}}{(v^2/g)^{1/3}} \left(\frac{4}{\pi}\right)^{0.13/2}$$

$$\Rightarrow K_L\alpha_{20} = 1.57 Q_g S^{-1.275} S_P^{0.11} S_a^{0.11} h^{-0.14} \quad (26)$$

- (2) Specific standard oxygen transfer efficiency per meter (SSOTE in %/m of diffuser submergence), ratio of the quantity of oxygen transferred to the quantity of oxygen injected divided by the diffuser submergence:

$$\text{SSOTE} = \frac{K_L\alpha C_{s20} V}{10hM_{O_2}} \quad (27)$$

where $M_{O_2} = 0.3Q_g$.

The specific standard oxygen transfer efficiency can be determined using Eq. (27). The value of DO concentration at saturation at 20 °C is deduced from the measurements performed during the aeration tests (Winkler method). The oxygen concentration at saturation is written as follows:

$$C_{\infty 20}^* = 8.84h^{0.17} \quad (28)$$

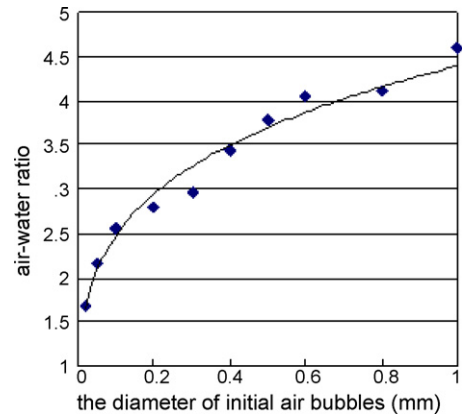


Fig. 10. Impact of the diameter of initial air bubbles on air–water ratio (λ) in sewage.

This relationship corresponds to an overpressure of 33% of the diffuser submergence [4]. The equation linking the specific standard oxygen transfer efficiency (SSOTE) to the characteristic parameters, is therefore expressed as follows:

$$\text{SSOTE} = 4.90 S^{-1.175} S_P^{0.14} S_a^{0.10} h^{-0.02} \quad (29)$$

- (3) Transfer number N_T

Developed from the experiential relationship for fine bubble diffused system developed by Roustan [6] and Gillot et al. [12], the transfer number N_T can be expressed as follows:

$$N_T = 7.77 \times 10^{-5} \left(\frac{S_P}{S}\right)^{0.24} \left(\frac{S_P}{S_a}\right)^{-0.15} \left(\frac{D}{h}\right)^{0.13} \quad (30)$$

The comparison of the four characteristic criteria (λ , $K_L\alpha_{20}$, SSOTE and N_T) for three different types of EPDM membrane fine bubble diffused aeration systems is shown in Fig. 11. These three different aeration systems were in the same geometry of the tank/aeration system, layout of the aeration system and the diffuser submergence were all 2.5 m, but the initial diameters of air bubbles in aeration system 1, 2 and 3 were 1, 0.5, and 0.05 mm, respectively. Fig. 11 shows the values of the above criteria when the DO reaches 5 mg/L (the units of λ , $K_L\alpha_{20}$, SSOTE and N_T are dimensionless, h^{-1} , m^{-1} and dimensionless ($\times 10^{-5}$), respectively, the y-axis in Fig. 11 is the value of these criteria).

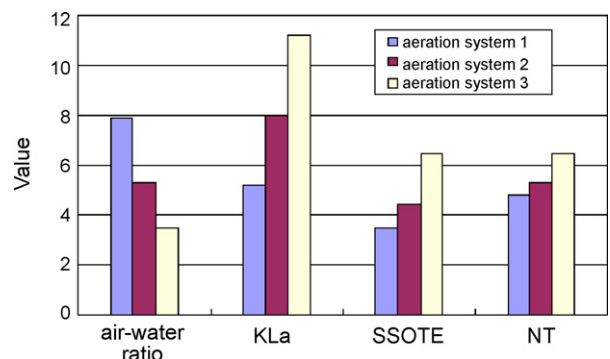


Fig. 11. Comparison of different characteristic criteria.

Commonly when the DO concentration of water in aeration arriving at a given value, the performance of aeration systems will be better with the decrement of $K_L\alpha_{20}$, SSOTE, N_T and the increment of air–water ratio. In Fig. 11, the performance evaluation of these aeration systems by air–water ratio are consistent with those by SSOTE, N_T and $K_L\alpha_{20}$. Therefore air–water ratio is a valid characteristic criterion of fine bubble diffused aeration systems.

3.4.2. Comparison of the design for fine bubble diffused aeration systems

In the case of design and operation of fine bubble diffused aeration systems, air flow rate Q_g is a key parameter. Based on the four criteria (λ , $K_L\alpha_{20}$, SSOTE and N_T), the following calculation of Q_g in fine bubble diffused aeration system for clean water (20 °C), are raised as an example for comparison:

(1) $K_L\alpha_{20}$

According to Eq. (4), the following expression can be gained:

$$C_1 = C_{\infty 20}^* - C_{\infty 20}^* \exp(-K_L\alpha_{20} \cdot t) \quad (31)$$

Therefore, The calculation of Q_g are determined as follows:

$$Q_g = \frac{K_L\alpha_{20} \times C_1 \times V_W}{0.3} \quad (32)$$

(2) SSOTE

According to Eq. (27), the following expression can be obtained:

$$Q_g = \frac{K_L\alpha \cdot C_{\infty 20}^* \cdot V_W}{3 \cdot h \cdot \text{SSOTE}} \quad (33)$$

Therefore the calculation of Q_g depend on not only SSOTE but also $K_L\alpha_{20}$.

(3) N_T

Based on N_T , Q_g can be calculated as follows (Roustan [6] and Gillot et al. [12]):

$$Q_g = \frac{K_L\alpha \cdot S}{N_T} \cdot \left(\frac{v^2}{g}\right)^{1/3} \quad (34)$$

Eq. (34) indicates that the value of Q_g is determined by both N_T and $K_L\alpha_{20}$.

(4) λ

The value of Q_g can be gained from λ directly:

$$Q_g = \lambda Q \quad (35)$$

Q is flow rate of clean water ($L^3 T^{-1}$).

It is apparent that the process of the calculation of Q_g based on λ is more convenient and direct than other traditional criteria.

4. Conclusions

Air–water ratio used as a characteristic criterion is feasible for showing the performance of fine bubble diffused aeration

systems and it can be more convenient for the design and operation of the systems than conventional characteristic criteria such as specific standard oxygen transfer efficiency (SSOTE), transfer number (N_T), and oxygen transfer coefficient ($K_L\alpha_{20}$). The research on air–water ratio had been done in this paper as follows:

- According to model development and measurements performed for clean water and sewage on 47 tests, respectively, two relationships between the ratio and DO concentration in aeration tanks for fine bubble diffused aeration systems in clean water and sewage, are established.
- Within the ranges of parameters studied, the DO concentration is an increasing function of air–water ratio, and the ratio increases with such two factors: (1) the internal pressure difference between the initial air bubble entering aeration tank and the terminal air bubble breaking up from the water surface, (2) the diameters of the initial air bubbles.
- The performance evaluation of different fine bubble diffused aeration systems by air–water ratio, are consistent with those by SSOTE, N_T and $K_L\alpha_{20}$. In addition, raised as an example for comparison, the calculation of air flow rate of fine bubble diffused aeration systems based on air–water ratio is more convenient and direct than those based on the other three characteristic criteria.

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