Chemical Engineering Journal 243 (2014) 51–59

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Oxygen transfer model development based on activated sludge and clean water in diffused aerated cylindrical tanks

Erika Pittoors [a,b], Yaping Guo [a,*], Stijn W.H. Van Hulle [b,c,d,*]

[a] College of Biological and Environmental Engineering, Zhejiang University of Technology, 18 Chaowang Road, Hangzhou Zhejiang, PR China
[b] ENBICHEM Research Group, University College West Flanders, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium
[c] BIOMATH, Department of Mathematical Modelling, Statistics and Bioinformatics, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[d] LIWET, Department of Industrial Biological Sciences, Ghent University, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium

HIGHLIGHTS

- The volumetric oxygen mass transfer k_La was measured under different operational conditions.
- Experiments in clean water and with activated sludge were done.
- The experimental results were used to develop a high fit empirical model.
- The airflow rate was the main factor affecting the k_La.

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form 20 September 2013
Accepted 22 December 2013
Available online 10 January 2014

Keywords:
Dissolved oxygen (DO)
Activated sludge process (ASP)
Diffused aeration
Dimensional analysis
Volumetric mass transfer coefficient (k_La)
Static method

ABSTRACT

The oxygen mass transfer k_La is generally studied under non-reactive conditions, leaving out the most fundamental operational condition in activated sludge processes (ASPs). Existing oxygen transfer models, used in wastewater treatment plant design and optimizations, have therefore a major shortcoming. More accurate k_La models lead to improved system analysis and knowledge. This work studied the volumetric oxygen mass transfer k_La in an ASP, under varying operational conditions. An empirical correlation for k_La versus nine studied variables (tank volume (V_t), height (H_t), diameter (D_t), surface area (A_t), airflow rate (Q_a), diffusers surface area (A_d) and depth (h_d), bubble size (d_b) and dynamic viscosity (μ)) for clean water (k_La_{CW}) and for activated sludge (k_La_{AS}) in a diffused aerated cylindrical batch reactor is created. The experimental results were used to develop a high fit empirical model for k_La_{AS} ($R^2 = 0.96$) and k_La_{CW} ($R^2 = 0.95$). The following equations were obtained (k_La in s^{-1}):

$$\frac{D_t^2 k_L a_{CW}}{D} = 0.030 Re^{1.718} Fr^{-0.709} \left(\frac{d_b}{h_d}\right)^{-0.291} \left(\frac{H_t}{D_t}\right)^{-0.554} \left(\frac{A_d}{A_t}\right)^{0.135} \left(\frac{D_t}{h_d}\right)^{0.321} \left(\frac{H_t}{h_d}\right)^{0.086} \left(\frac{V_t}{A_d^{1.5}}\right)^{-0.017}$$

$$\frac{D_t^2 k_L a_{AS}}{D} = 0.060 Re^{1.906} Fr^{-0.631} \left(\frac{d_b}{h_d}\right)^{-0.23} \left(\frac{H_t}{D_t}\right)^{-0.120} \left(\frac{A_d}{A_t}\right)^{0.326} \left(\frac{D_t}{h_d}\right)^{0.164} \left(\frac{H_t}{h_d}\right)^{0.173} \left(\frac{V_t}{A_d^{1.5}}\right)^{-0.01}.$$

The Reynolds $\left(Re = \frac{vL}{\nu} = \frac{Q_a \rho}{D\eta}\right)$ and the (adapted) Froude number $\left(Fr = \frac{v}{\sqrt{Lg}} = \frac{Q_a}{\sqrt{D_t^5 g}}\right)$ were used. The coefficients for clean water and activated sludge varied up to 66% for the same base model but show similar trends and effects for different hydrodynamic, physicochemical and geometrical parameters. The airflow rate was the main factor affecting both k_La_{AS} and k_La_{CW}. Next were diffusers depth and bubble size. Airflow rate and diffusers surface area had a significantly larger impact in the presence of biomass, since it promotes bubble distribution, mixing of the solution and an improved oxygen transfer, therefor demonstrating the need for an adapted model for ASPs.

1. Introduction

The oxygen mass transfer, k_La, in wastewater is often studied under nonreactive conditions, even though it is known that biomass significantly impacts the oxygen transfer in activated sludge systems (ASPs) [1–3]. Existing oxygen transfer models, used among

* Corresponding authors. Tel.: +86 13858043191 (Y. Guo). Address: ENBICHEM Research Group, University College West Flanders, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium. Tel.: +32 56241251; fax: +32 56241224 (S. Van Hulle).

E-mail addresses: erika.pittoors@howest.be (E. Pittoors), luckyyaping@zjut.edu.cn (Y. Guo), stijn.vanhulle@ugent.be (S.W.H. Van Hulle).

1385-8947/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cej.2013.12.069

Nomenclature

α	alpha factor (–)
μ	dynamic viscosity (kg/m/s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
θ	temperature correction factor (–)
A/A/O	anaerobic–anoxic–oxic
A_d	total coverage area of the diffusers (m^2)
A_t	total area of the tank (m^2)
AS(P)	activated sludge (process)
B_t	width of the tank (m)
C_{O2}	concentration of dissolved oxygen (mgO_2/l)
C^*_{O2}	oxygen saturation concentration (mgO_2/l)
D	diffusion coefficient (m^2/s)
d_b	bubble diameter (m)
d_{eq}	equivalent bubble diameter (m)
D_t	tank diameter (m)
DO	dissolved oxygen (mg/l)
Fr	Froude number (–)
g	acceleration due to gravity (=9.8 m/s^2)
H_t	height of tank (m)
h_d	diffuser submergence (m)
HRT	hydraulic retention time (h)
k_La	volumetric mass transfer coefficient (h^{-1}, unless otherwise specified)
k_La_{AS}	volumetric mass transfer coefficient in activated sludge tank (h^{-1}, unless otherwise specified)
k_La_{CW}	volumetric mass transfer coefficient in clean water tank (h^{-1}, unless otherwise specified)
L	length of the tank (m)
MLSS	mixed liquor suspended solids (mg/l)
OTR	oxygen transfer rate (mgO_2/l/d)
OUR	oxygen up-take rate by microorganisms (mgO_2/l/d)
Q	volumetric wastewater flow rate (m^3/s unless otherwise stated)
Q_a	airflow rate (m^3/s)
SRT	sludge retention time (d)
T	temperature (°C)
TIC	Theil's inequality coefficient (–)
V	working volume reactor (m^3)
y_{calc}	calculated values
y_{exp}	data points obtained through the experiments

Table 1
Empirical correlations for k_La prediction for diffused aeration systems.

Empirical correlation	Reference
$\frac{L^2 k_La}{D} = 0.033 Re^{1.46} Fr^{-0.49} \left(\frac{d_b}{h}\right)^{-0.73} \left(\frac{H}{L}\right)^{-1.77} \left(\frac{A_d}{A_t}\right)^{-0.24}$	[12]
$k_La = 6.86 d_B^{-1.3} \nu^{0.93} \left(\frac{W}{H}\right)^{-0.49} \left(\frac{H}{L}\right)^{1.63} \left(\frac{p_h^{0.074} - p_h^{-0.44}}{p_h - 1}\right)$	[34]
$k_La = 49 Re \left(\frac{\nu}{D}\right)^{0.5} \left(\frac{D}{D_t^2}\right) \left(\frac{A_t}{h_d^2}\right)^{0.72}$	[10]
$\frac{k_La}{\nu} \left(\frac{\nu^2}{g}\right)^{1/3} = 7.77 \times 10^{-5} \left(\frac{A_p}{A_t}\right)^{0.24} \left(\frac{A_p}{A_d}\right)^{-0.15} \left(\frac{D_t}{h}\right)^{0.13}$	[6]

Table 2
Ranges of the operational variables and derived (non-dimensional) variables.

Variable	Name	Unit	Range or value
Q_a	Airflow rate	l/min	0.24–0.60
h_d	Diffusers depth	m	0.01–0.24
V_t	Tank volume	l	2.7–9.3
H_t	Tank height	m	0.13–0.53
D_t	Tank diameter	m	0.10–0.30
A_t	Tank surface area	m^2	1.8×10^{-3} – 7.4×10^{-3}
d_b	Bubble diameter	m	0.005
A_d	Diffusers surface area	m^2	7×10^{-4}
MLSS	Mixed liquor Suspended Solids	mg/l	918–2543
μ_{CW}	Dynamic viscosity CW	kg/ms	1.1×10^{-3} – 9.8×10^{-4}
μ_{AS}	Dynamic viscosity AS	kg/ms	1.4×10^{-3} – 1.9×10^{-3}
ρ	Density	kg/m^3	998
D	Oxygen diffusion coefficient	m^2/s	1.86×10^{-9}
Re_{CW}	Reynolds CW		13–105
Re_{AS}	Reynolds AS		14–54
Fr	Froude		2.6×10^{-5} – 1.1×10^{-3}
d_b/h			0.021–0.76
H_t/D_t			0.44–3.8
A_d/A_t			0.01–0.096
D_t/h_d			0.57–46
H_t/h_d			2–20
$V_t/A_d^{1.5}$			145–494

others in wastewater treatment plant (WWTP) optimizations, have therefore a major shortcoming as they are not based on the most fundamental operational condition in ASPs. Often oxygen mass transfer is measured to check the performance of ASPs before start-up of the WWTP or during design of a new one. These tests are mainly done in clean water, following the ASCE [4] and NFEN [5] standard. This leads to significant inaccuracies in oxygenation performance prediction of the full-scale system, since many factors in the wastewater affect the oxygen transfer [6]. Physicochemical (solution composition, biomass, viscosity, pH, TSS, dissolved oxygen (DO), etc.), geometrical (aerator submergence, length and width of the tank, total tank area, bubble diameter, diffusers total coverage area, reactor's working volume, etc.) and dynamical parameters (airflow rate, water density, surface tension, kinematic viscosity, airflow velocity, etc.) and aerator type contribute to aeration and oxygen mass transfer all to a different extent depending on the wastewater type, treatment system and equipment used. Refining the oxygen mass transfer prediction will lead to an improved optimized system, meaning reduced costs and increased effectiveness of ASPs and even WWTPs. This remark counts particularly for medium-sized plants, as operational inspections are more difficult to accomplish systematically [6].

Diffused aeration (subsurface or submerged bubble aeration) is defined as the injection of air or oxygen enriched air under pressure below a liquid surface [7]. Air is blown into the water by means of diffusers or mechanical agitators. This contribution deals with submerged fine pore diffusers ($d_b < 5$ mm). These release air via porous media or nozzles at increased depths [8]. The fine-pore aerators are different from coarse bubble aerators, owing to their flow regime. The former has low interfacial gas velocities, hence induces low flow regimes at gas–liquid interfaces. Due to this flow regime (and the added decrease through scaling and fouling over time) the alpha factor (α, [9]) is substantially lower compared to the wide variety of aeration systems, leading to a lowered k_La. In contrast coarse-bubbles produce greater velocity gradients at the gas–liquid interface [8]. However the k_La of coarse bubble aerators is about six times smaller in contrast to the fine bubble K_La. Nonetheless when demanding an equal k_La, 3 times more diffusers are needed for fine bubble diffusers as these have the highest A_d, but demand a lower airflow rate, hence a higher power consumption (at 10 m tank depth +40%) [10]. Diffusers are still the most