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OXYGEN TRANSFER WITH CIRCULATION FLOW RATE IN UNBAFFLED SURFACE AERATOR

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Abstract. Circulation flow rate and vortex in unbaffled surface aeration systems are interrelated. These properties exert a profound effect on the performance of the surface aeration systems affecting the oxygen transfer process. This work develops the scale up criteria for oxygen transfer rate based on the circulation flow rate. A relationship between circulation flow rate and vortex depth in surface aerators has been also developed.

Keywords: circulation flow rate; oxygen transfer; surface aerator; vortex.

1. Introduction

Surface aerators are the most common reactors that are used almost universally for gas dispersion and reactions in biochemical, fermentation, and wastewater treatment industries [1-3]. The way a liquid moves in an agitated vessel depends on many things: the type of impeller; the characteristics of the liquid especially its viscosity; and the proportions of the tank and impeller. The liquid velocity at any point in the tank has three components, and the overall flow pattern in the tank depends on the variations in these three velocity components from point to point. The first velocity component is radial and acts in a direction perpendicular to the shaft of the impeller. The second component is longitudinal and acts in a direction parallel with the shaft. The third component is tangential or rotational and acts in a direction tangent to a circular path around the shaft. In the usual case of a vertical shaft, the radial and tangential components are in a horizontal plane, and the longitudinal component is vertical. The radial and longitudinal components are useful and provide the flow necessary for the mixing action. The tangential component of flow follows a circular path around the shaft and creates a vortex in the liquid. The presence of baffles in baffled aerator subsidies the creation of vortex. Although baffled configurations are encountered in most industrial stirred vessels, there are numerous applications where unbaffled tanks are used [4-5]. Vortex in unbaffled tank is effective in drawing down floating solid particles or in removing gas bubbles from the liquid, thus reducing foam formation. Unbaffled tanks are also advisable in crystallizers, where the presence of baffles may promote the particle attrition phenomenon [6]. Unbaffled tanks give rise to higher fluid-particle mass transfer rates for a given power consumption, which may be desirable in a number of processes [7]. Besides that the power requirements in processes occurring in agitated vessels, it is proved that unbaffled vessels consume less power than those with baffles [8].

In an unbaffled vessel, circulation flow is induced by all types of impellers, whether axial flow or radial flow. If the swirling is strong the flow pattern in the tank is virtually the same regardless of the design of the impeller. Thus in this work, the focus is to quantify the circulation flow rate with vortex and also to try to correlate the mass transfer process with circulation flow rate in unbaffled surface aeration systems.

2. Theory

Circulation flow rate ζ is defined as:

$$V = \frac{V}{t_c} \tag{1}$$

where V is liquid volume of the tank and t_c is the circulation time. t_c is known as the time for a fluid element to cover the entire liquid volume of the tank. t_c is generally measured using the time period between two subsequent concentration peaks of tracer [9].

The determination of the circulation flow rate needs time-dependent information. The circulation flow rate is also defined for an impeller as the sum of the impeller flow rate and the flow rate generated by momentum transfer [10]. A vortex is produced owing to centrifugal force acting on the rotating liquid. When the impeller is rotating a vortex will develop on the surface of the liquid. Many investigators [4, 7, 11] have found that there are two types of motion in the flow of a liquid agitated by any types of mixer. A zone with a constant angular velocity (vortex zone) is formed in the central part of the vessel and a zone where the peripheral velocity of the liquid decreases according to the hyperbolic law (irrotational zone) is formed in the remaining part. The so-called vortex zone is supposed to exist inside a hypothetical cylinder of critical radius r_o ($0 \leq r \leq r_o$), in the centre of vessel, which is assumed to rotate as a solid body with an angular velocity to that of rotor [11]. The aforementioned type of vortex is called as Rankine vortex [11]. The distribution of tangential velocities is essentially independent of axial position and approximates to a Rankine vortex as follows:

$$V_d = \begin{cases} wr & (r \leq r_o) \\ w \; r_o^2 / r & (r > r_o) \end{cases} \tag{2}$$

where w is the angular velocity of the liquid and r is the radius of the tank.

This is also called as Nagata Model of Rankine vortex. The whole system can be analyzed in terms of energy balance. Referring to Figure 1, between the top edge of the vortex and the center of the vortex there is a difference in potential energy. To maintain this potential energy difference between the two points, there should be a continuous conversion of kinetic energy (impart by the impeller rotation) into potential energy. The most convenient term to choose to represent this kinetic energy is the one related to the speed at the tip of the rotating blades [12-13]. The energy balance is shown in Eq. (3):

$$V_d \, r g = k(p^2 d^2 N^2 r)/2 \tag{3}$$

where V_d is the vortex depth, r is density of liquid, d is the tank diameter and N is the rotational speed of the rotor.

3. Experimental

3.1. Measurements

Oxygen transfer rate has been determined by conducting experiments in two sizes of geometrically similar unbaffled surface aeration tanks. Numerical scheme has been adopted to calculate oxygen transfer rate and circulation flow rate and vortex depth, respectively, in unbaffled circular surface aerator.

The cross-sectional areas of the circular tanks tested are A = 1 m^2 and 0.5184 m^2. A schematic diagram of the aerator is shown in Fig. 1.

Conditions of geometric similarity, *i.e.* $\sqrt{A}/d = 2.88$, $H/d = 1.0$, l/d=0.3, $b/d = 0.24$ and $h/H = 0.94$: as suggested by Rao and Kumar [14] were maintained in all the surface aerators. The Rushton turbine has been used in the experiments, because it exhibits a significant decrease in power draw upon aeration [15]. Two-film theory [16] has been used to calculate oxygen transfer rate. According to the two-film theory [16], the oxygen transfer coefficient K_La_T at T (K) may be expressed as follows:

$$K_La_T = [ln(C_s - C_0) - ln(C_s - C_t)]/t \tag{4}$$

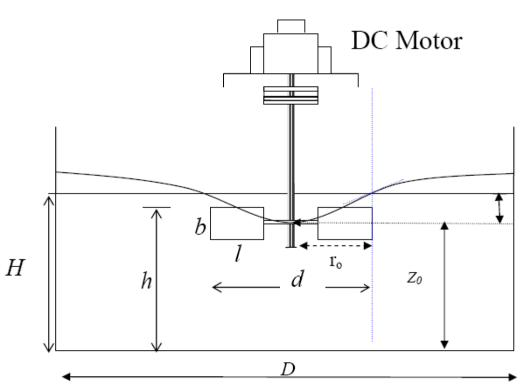

Fig. 1. Schematic diagram of the unbaffled surface aerator with vortex geometry: A is the cross-sectional area of the tank; H is the depth of water in the tank; D is tank diameter; h is the distance between the top of the blades and the horizontal floor of the tank; b and l are the linear dimensions of the blade; Z_o is the distance between the horizontal bottom of the tank and centre of the vortex

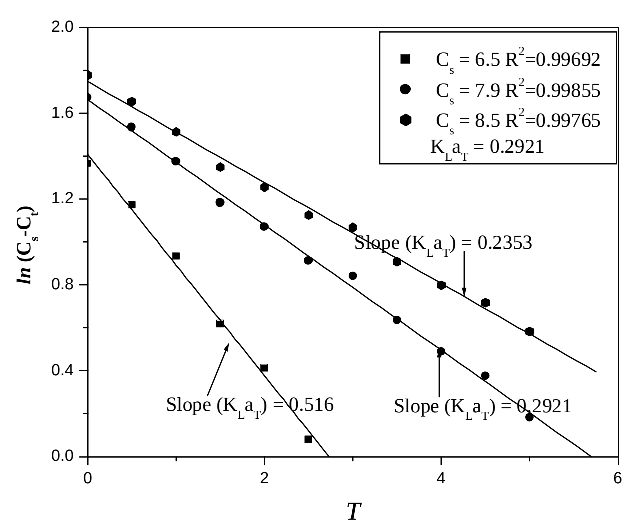

Fig. 2. Determination of K_La_T

where, *ln* represents natural logarithm and C_s, C_0 and C_t are dissolved oxygen (DO) concentrations in parts per million (ppm), C_s = the saturation DO at time tending to very large values, C_0 is at the beginning of time $t = 0$ and C_t is at time $t = t$.

The value of K_La_T can be obtained as slope of the linear plot between $\ln(C_s - C_t)$ and time t. The value of K_La_T can be corrected for a temperature other than the standard temperature of 293 K as K_La_{20}, using the Vant-Hoff Arrhenius equation:

$$K_La_T = K_La_{20}\ \theta^{(T-20)} \quad (5)$$

where θ is the temperature coefficient equal to 1.02 for pure water [17].

With the known values of DO measured in terms of C_t at regular intervals of time t (including the known values of C_o at $t = 0$), a line is fitted by linear regression analysis of Eq. (4), between the logarithm of $(C_s - C_t)$ and t. For this purpose, by assuming different but appropriate values of C_s the regression that gives the minimum "standard error of estimate" is taken and thus the values of K_La_T and C_s were obtained simultaneously. A typical plot of K_La_T determination has been shown in Fig. 2.

Thus, the values of K_La_{20} were determined for different rotor speeds N of the rotor in all of the geometrically similar tanks.

3.2. Calculation of Circulation Flow Rate and Vortex Depth

In this work, circulation flow rate and vortex depth of surface aeration systems has been calculated by using commercial software Visimix®. The Visimix® program can be helpful in analyzing the mixing parameters in stirred tanks [18-20]. Visimix® estimates the circulation flow rate based on the analysis of energy distribution in the tank volume. The total power used by the agitator depends on the difference in velocities of the tangential flow and the agitator blades. A part of this energy is estimated as:

$$P_{bl} = 0.5\, f_{bl}\, N_{bl}\, r \int \left(w r - v_{tg}\right)^3 H_{bl}\, Sin(a)\, r\, dr \quad (6)$$

where P_{bl} is the power consumed by blade, f_{bl} is the hydraulic resistance factors for blade; N_{bl} is the number of blades; ρ is the density of the liquid; v_{tg} is the tangential velocity; H_{bl} is the height of agitator blade and α is the pitch angle of blades.

The above calculated energy is spent on overcoming the flow resistance of the blades; it is transformed into kinetic energy of local eddies and dissipated in the vicinity of the agitator. The other part of the energy is spent in the main flow on overcoming the flow friction. When tangential velocity component is low, the major part of this energy is spent in circulation, mainly for the change of the flow direction and turbulent flow friction:

$$j\,P = 2p\,H\,r \int_0^{R_T} n_E \left(dv_{ax}/dr\right)^2 r\,dr + f_t\, r\, v_{ax}^2 / 2V \quad (7)$$

where j is the fraction of the energy dissipated outside the agitator zone; P is the power; v_{ax} is the axial velocity; R_T is the tank radius; ν_E is the eddy viscosity and f_t is the hydraulic resistance factors for tank. Vortex can be quantified by measuring the circulation about a closed path, which is perpendicular to the vortex axis.

4. Results and Discussion

The relationship between vortex depth and circulation flow rate is nonlinear as evident from Fig. 3. Interestingly Fig. 3 shows that in geometrically similar systems, relationship is size independent. Data pertaining to different tanks fall on a single curve. Regression curve showing the mentioned relationship is as follows:

$$V_d = 4899 V^{2.0977} \quad (8)$$

As discussed, understanding the circulation flow rate with oxygen transfer rate in a surface aerator has significant implications for design. Various correlations [8, 21] have been utilized to correlate the oxygen transfer coefficient (K_La_{20}) with the operation variables (N and P), the geometric parameters of the systems (V and d), and the physical properties of the fluids. This work develops the correlation for surface aeration systems which are geometrically similar. Fig. 4 shows the unique correlation of oxygen transfer rate with circulation flow rate for different sized surface aerators. The equation representing the correlation is:

$$K_La_{20} = a \exp\left(\frac{\left(-\left(V-b\right)^2\right)}{2c^2}\right) \quad (9)$$

Statistical details of the parameters used in Eq. (9) are given in the Table. Standard error of parameters used in regression analysis indicates confidence for many engineering applications. The standard error of a parameter is the expected value of the standard deviation of that parameter if the experiment has been repeated many times. It can be seen from the statistical details that parameters are well estimated at about 5 % noise level, which is good enough for engineering design purposes or scale up of the system.

The correlations proposed (Eqs. 8 and 9) in this work can be useful in scaling up the surface aeration systems. The scale up of mixing tanks from laboratory to plant size is a crucial issue in the design of industrial processes to find optimal configurations and operating conditions. Generally scale up has been done by keeping at least one of the mixing characteristics constant for both plant and lab scale size. However, scale up from labora-

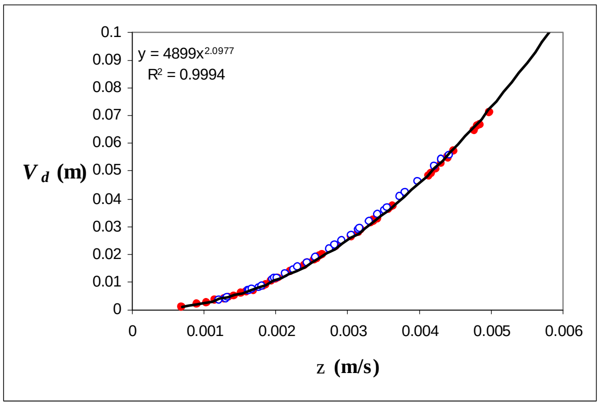

Fig. 3. Relationship between vortex depth and circulation flow rate: C/s area = 1 m^2 (●) and 0.5814 m^2 (○)

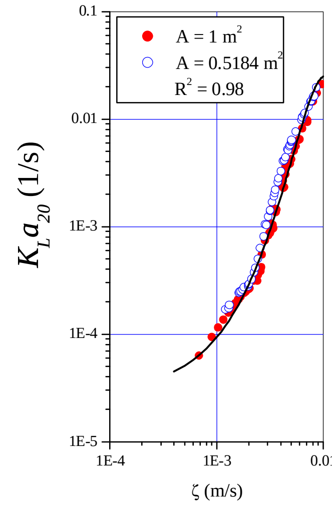

Fig. 4. Oxygen transfer coefficient as function of circulation flow rate

Table

Statistical properties of simulation

$R^2 = 0.97$		
Parameter Name	Estimate	Standard Error
a	2.5 E-2	4.7 E-4
b	10.6 E-3	1.8 E-4
c	2.8 E-3	8.8 E-5

tory scale to pilot and full-scale plant is not straightforward. Circulation results from the direct rotational movement of the impeller blade in the fluid. Here impeller size relative to the size of the tank is critical as well. It requires geometrical similarity that is the field installation should be built on a definite geometric ratio of the laboratory setup. Now by maintaining the present optimal geometrical similarity condition, one can predict oxygen transfer rate by knowing the circulation flow rate.

5. Conclusions

Experimental and numerical techniques have been employed to ascertain the effect of circulation flow rate on oxygen transfer process in unbaffled surface aeration systems. Simulation equation has been proposed to scale up the oxygen transfer process through circulation flow rate in geometrically similar surface aeration systems. Vortex exists in the systems because of the absence of baffles and it depends on the circulation flow rate. Empirical relationship between vortex depth and circulation flow rate has been also presented.

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List of symbols

A	the cross-sectional area of the tank (m^2)
b	the blade width (m)
D	tank diameter (m)
d	diameter of the rotor(m)
f_{bl}	the hydraulic resistance factors for blade
f_t	the hydraulic resistance factors for tank
H_{bl}	the height of agitator blade (m)
H	water depth (m)
h	distance between the horizontal bottom of the tank and the top of the blades (m)
K_La_{20}	the oxygen transfer coefficient at 20°C (1/s)
l	the blade length (m)
N	rotational Speed (1/minute)
N_{bl}	the number of blades
P_{bl}	power consumed by blade (Watt)
R_T	the tank radius (m)
r	radius of the rotor (m)
r_o	critical radius (m)
t_c	the circulation time (s)
V	liquid volume of the tank (m^3)
V_d	vortex depth (m)
v_{tg}	the tangential velocity (m/s)
v_{ax}	the axial velocity (m/s)
w	the angular velocity of the liquid. (1/minute)
Z_o	distance between the horizontal bottom of the tank and centre of the vortex (m)
j	the fraction of the energy dissipated outside the agitator zone
z	circulation flow rate (m/s)
a	the pitch angle of blades
n_E	the eddy viscosity

ПЕРЕНЕСЕННЯ КИСНЮ З ШВИДКІСТЮ ЦИРКУЛЯЦІЇ ПОТОКУ В НЕЕКРАНОВАНОМУ ПОВЕРХНЕВОМУ АЕРАТОРІ

Анотація. *Швидкість циркуляції потоку і завихрення у неекранованій системі поверхневої аерації взаємопов'язані. Досліджено вплив цих властивостей на продуктивність поверхневих аераційних систем, що впливають на процес перенесення кисню. В роботі розглянуто підвищені критерії до швидкості перенесення кисню на основі швидкості циркуляції. Досліджено взаємозв'язок між швидкістю циркуляції потоку і глибиною завихрення у поверхневих аераторах.*

Ключові слова: *швидкість циркуляції потоку, перенесення кисню, поверхневий аератор, завихрення.*