Retraction

Retracted: Oxygen Mass Transfer in an Aerated Stirred Tank with Double Impellers: A Generalized Correlation Including Spacing Impact

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At the request of the author, the article titled “Oxygen Mass Transfer in an Aerated Stirred Tank with Double Impellers: A Generalized Correlation Including Spacing Impact” [1] has been retracted. The data presented in the article were published without the permission of the University of Toulouse.

References

Research Article

Oxygen Mass Transfer in an Aerated Stirred Tank with Double Impellers: A Generalized Correlation Including Spacing Impact

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Stirred aerated tanks by double impellers are used in fermentation and various biological processes for water treatment, food industry, and pharmaceutical production. In this study, a generalized correlation model was developed for the dependent parameter \( \frac{k_L}{a/N} \). The oxygen mass transfer from air to liquid takes place by rotating the double impellers (IBRC and PBPU) in the aerated tank. This model considers Reynolds number, Froude number, power number, the liquid height, and the spacing between impellers as the most significant specifications that are related to aerated tank performance. The spacing between the impellers is considered to be a design factor of such industrial equipment due to its remarkable impact on the oxygen mass transfer.

1. Introduction

Stirred tanks that generate a turbulent fluid flow regime are commonly used for aeration in various industrial processes like aerobic fermentation and wastewater treatment to obtain a complete oxygen mass transfer [1]. The oxygen mass transfer in an aerated tank actually takes place in two zones: the liquid surface and liquid body. At the liquid surface, there are two types of oxygen transfer: firstly, the direct transfer of oxygen to the liquid surface due to large eddies created by impeller rotation and, secondly, the oxygen transfer by the contact of projected water droplets with air, while the oxygen mass transfer inside the liquid body occurs mainly by the entrained air bubbles from the surface [2]. As it is so difficult and complicated to determine the surface mass transfer coefficient individually because there are no exact limits between these two zones. The final oxygen mass transfer in the liquid body is considered to be the total liquid side oxygen mass transfer. Hence, the dissolved oxygen inside the liquid body would refer to the total dissolved oxygen that came from any mass transfer pattern, above, at, and below the liquid surface.

The occurring oxygen transfer mechanism in the entirely liquid (water) body is the two-film theory [3]. The oxygen transfer in the water body is related to many parameters, such as water level, tank and impeller geometry, rotation speed, the number of impellers, and many operational conditions [4–6].

The theory of oxygen transfer in the surface aerated tank is relevant to the mixing that occurs within the tank. Therefore, mixing is improved by adding extra impellers at the rotating shaft to enhance the contact area between liquid (water) and air phases [7]. As the effective resistance to the oxygen mass transfer that takes place mainly exists in the liquid side of the gas-liquid mass transfer film, other resistance is neglected. Oxygen mass transfer coefficient in the liquid, \( k_La \), is regarded as an indicator for mass transfer rate [8]. The gas-liquid contact interfacial area for oxygen mass transfer is highly crucial in the rational design of gas-liquid equipment [9]. The volumetric oxygen mass transfer in liquid phase \( k_La \) is determined by a dynamic method for batch systems. Many tries were made to find a generalized correlation for oxygen mass transfer in surface aerators. There were various trends to correlate the relevant parameters with the oxygen transfer coefficient. Fuchs et al. [10] have proposed a correlation of \( k_La \) with energy dissipation in the liquid body \( (P/V) \) for surface aerators tank volume \( (V \geq 200 \text{ L}) \). The influence of tank and impellers geometry has been related in many correlations with oxygen transfer models. Zlokarnik [11] has correlated the oxygen mass transfer for various surface aerator geometries.
He has developed a generalized oxygen mass transfer parameter, as a dimensionless parameter \( \gamma \) that called sorption number \( \gamma = k_a D^2 (\mu/\rho g)^{1/3} = (G/\Delta c \cdot D^2) \cdot (\nu g^2)^{1/3} \), where, in his model, he related the surface flow characteristics and turbulence intensity with the transferred oxygen. Zlokarnek [11] has additionally related the mass transfer performance with the operational parameters such as Froude number, Reynolds number, and other geometrical factors (numbers and forms of impellers blades). He has derived a dimensionless formulation that combines the surface aerator efficiency \( E \) with aeration number and Froude number with \( \gamma \), for the ratio liquid to turbine diameter ratio \( h/D \) of 1.0:

\[
E = \frac{G}{\Delta c D^2} \left( \frac{\nu}{g^2} \right)^{1/3} N_p^{-1} \cdot Fr^{-3/2} = \frac{GD^{0.5}}{P \Delta c} \rho \left( \nu g^5 \right)^{1/6},
\]

where \( \Delta c \) is concentration difference \((kg \cdot m^{-3})\), \( G \) is oxygen uptake \((kgO_2 \cdot h^{-1})\), and \( E \) is aerator efficiency \((kgO_2 \cdot kW^{-1} \cdot h^{-1})\).

Patil et al. [12] have tested different surface aerators for optimum \( k_a \) with emphasis on the geometrical configuration; the affecting parameters they considered were liquid height, liquid volume, tank diameter, and impeller clearance. They derived a general correlation of oxygen mass transfer in depending upon the previous works in the same field for aeration, operation condition, and power consumption. The range of volumetric power consumption dissipation was \( 90 < P/V < 400 \) \( W/m^3 \):

\[
\frac{k_a}{N} = 7 \times 10^{-6} N_p^{0.21} H^{0.48} Re^{0.82} \left( \frac{H}{D} \right)^{-0.54} \left( \frac{V}{D^3} \right)^{-1.08}.
\]

Thakre et al. [13] have developed an oxygen transfer model for curved rotor surface aerator in oxidation ditches after they studied the liquid level effect. The model is applied for turbulent flow condition and power consumption. The relation between the dissolved oxygen and theoretical values of the dissolved oxygen are determined by \([23,24]\):

\[
C_t = C_s - (C_s - C_o) e^{-t/\tau}.
\]

The \( \tau \), response time, was determined for the dissolved oxygen probe and was 8.8 sec.

The relationship between the dissolved oxygen with the time with taking in account the effect of probe response time can be represented in the following equation \([25–27]\):

\[
\frac{dC_t}{dt} = k_a \left( C_s - C_t \right).
\]

By rearranging,

\[
\ln \left( \frac{C_s - C_t}{C_s - C_0} \right) = k_a \cdot t.
\]

The effect of probe response time on the dissolved oxygen concentration measurement for aeration processes was determined by the following equation \([28]\):

\[
C_t = C_s + \frac{C_s - C_t}{C_s - C_0} \left( k_a \cdot t e^{-t/\tau} - e^{-k_a t} \right).
\]

The dissolved oxygen probe response time was implied in the applied mass transfer equation that represents the experimental runs to take into account the experimental errors. It is needed to correct the measured oxygen transfer coefficient in the liquid to the standard conditions, where the following (Van’t-Hoff, Arrhenius) equation was applied \([29]\):

\[
(k_a)_{20} \cdot C = 1.024^{(20-\theta)} (k_a)_{\theta}.
\]
The experimental runs were carried out in a cylindrical flat bottom vessel (made of transparent fiberglass) with inside diameter of 0.8 m. The schematic diagram of the system is shown in Figure 1. Three baffles of width, b(0.17), are used with our experimentation, to prevent or lessen the tangential circulatory flow. The baffles have the same height of the vessel.

The surface aeration is attained by the water droplets projection with the rotation of an impeller and by the water surface renewal due to eddies generation. In the experimentation, two impellers (IBRC + PBPU) were used for mixing and aeration purposes with the up-pumping operation, where the rotating cone (IBRC) was placed at the water surface. To achieve acceptable mixing that provides a good contact interfacial area between the contents, the lower four-bladed propeller (PBPU) redirects the liquid flow toward the upper rotating cone (IBRC) to ensure continuous feeding intake of the rotating cone. Moreover, the propeller (PBPU) participates in achievement of the homogenous distribution of dissolved oxygen in the entire vessel by ensuring the flow circulation through the whole vessel especially the deep good levels.

The geometrical ratio for the propeller \((d/T) = 0.15\), where it is lower than the general applied ratio \((d/T)\) for axial flow impellers \((0.2–0.7)\). In our study the aim of the mixing process is supporting the main surface aeration process, so the desired mixing performance was performed. The number of blades of the rotating cone is 12 (blades width 0.24 m), with diameter ratio \(D/T = 0.24\). Water height was kept constant at 0.38\(T\).

To figure the most affecting limits during the operation, various parameters are considered to be independent variables to relate to the oxygen mass transfer, where the important aim is to verify and improve, through the experimentation, the effect of spacing with the oxygen transferred.

In the experimental part, the relationship between \(k_ao\) with power consumption, rotation speed \((N = 1.67–5.0\) rps), and liquid level \((H/D = 1.37–1.45)\) was conducted for three spacing levels between the used impellers \((S/d = 0.5, 0.7, 1)\).

### 3. Oxygen Mass Transfer Correlation Model

In this study, an oxygen mass transfer model was developed depending on the experimental results made by [30] and the previously performed studies. Normally in surface aeration process there are geometric, dynamic, and materials parameters that govern the system performance. These parameters may involve the rotational speed, the water viscosity, the gravity of acceleration, the impeller diameter (these parameters may refer to the intensity of turbulence inside the tank and at the water surface), the water height in the tank, and many others. The number of these parameters is different according to each case, but generally they are the same essential parameters that work for all the surface aeration cases. The Froude number \(Fr\) reflects the gravitational acceleration force and the water wave action generated by the aerator. The Reynolds number \(Re\) refers to flow state of the liquid. The power number \(N_p\) indicates the power consumed by the aerator considering the aerated fluid property. Finally the mass transfer dimensionless parameter forms (it is not restricted to use of one normalized mass transfer parameter, but it depends on the system distinction implemented). In accordance with experimental results, it is found that the best realistic independent variables that can affect the oxygen transfer are as follows:

\[
\left(\frac{k_ao}{N}\right) = f \left( N_p, \rho, \mu, D, S, H, g \right) . 
\]

The geometric ratios are chosen upon the standard design ratios that are generally implied in the surface aeration process.

By applying Buckingham \(\pi\) theory, (9) converted to the following relation:

\[
\left(\frac{k_ao}{N}\right) = f \left( N_p^a \ Fr^b \ \left(\frac{H}{D}\right)^c \left(\frac{S}{D}\right)^d \right) . 
\]

Equation (11) is solved to determine the values of the constants by applying multiple nonlinear regressions. The following correlation is developed:

\[
\left(\frac{k_ao}{N}\right) = 0.0121 \left[ N_p^{0.35} Fr^{1.435} \left(\frac{H}{D}\right)^{-1.786} \left(\frac{S}{D}\right)^{-0.564} \right] . 
\]

Here, the standard error for the constants in (12) is as follows: for \((f)\) a standard error is \(3.79 \times 10^{-2}\), for \((a)\) the standard error is \(1.07 \times 10^{-2}\), for \((b)\) the standard error is \(7.39 \times 10^{-3}\), for \((c)\) the standard error is \(7.49 \times 10^{-2}\), and for \((d)\) the standard error is \(7.98 \times 10^{-2}\).
Table 1: The most commonly stated oxygen mass transfer coefficient correlations for stirred and aerated vessels with multiple impellers (liquid volume of 0.036–0.46 m$^3$).

<table>
<thead>
<tr>
<th>System description</th>
<th>Correlation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 0.8$ m, $D/T = 0.24$, $N = 1.67$–5.0 rps, $H/D = 1.37$–1.45, $S/d = 0.5$–1.0</td>
<td>$\left( \frac{k_l a}{N} \right) = 0.0121 \left( N_p^{0.65} F_r^{1.435} \left( \frac{H}{D} \right)^{-1.786} \left( \frac{S}{D} \right)^{-0.564} \right)$</td>
<td>This work</td>
</tr>
<tr>
<td>$T = 0.6$ m, $D/T = 0.33$, $N = 2.5$–10 rps</td>
<td>$k_l a = 3.69 \times 10^{-3} \left( P_{tot} \right)^{0.601} U_s^{0.375} \left( \frac{P}{P_0} \right)^{0.521} N_p^{0.968}$</td>
<td>Moucha et al. 2009 [19]</td>
</tr>
<tr>
<td>$T = 0.3$ m, $D/T = 0.4$, $N = 8$–13 rps</td>
<td>$k_l a = 2.435 \left( P_{tm} \right)^{0.623} U_s^{0.769}$</td>
<td>Zhang et al. 2015 [20]</td>
</tr>
<tr>
<td>$T = 0.2$ m, $D/T = 0.5$, $N = 1$–10 rps</td>
<td>$k_l a = 0.0346 \left( \frac{P}{V} \right)^{1.60} \left( \frac{H}{T} \right)^{-0.912}$</td>
<td>Luo et al. 2015 [21]</td>
</tr>
</tbody>
</table>

4. Conclusion

The comparison of the predicted values by applying correlation with experimental results values shows that the coefficient of determination is 0.988, which is accepted in the frame of the error estimation (see Figure 2). The correlation model is developed for gas-liquid oxygen mass transfer coefficient in stirred tank with double impellers (with spacing effect) showing acceptable results for specified operational and geometrical ranges.
Symbols

\( a \) term in \( k_{a}a \): Interfacial area per unit volume in water body \( (m^{2}/m^{3}) \)

\( C_{i} \): Dissolved oxygen concentration in liquid (mg/L)

\( C_{s} \): Concentration of dissolved oxygen at saturation (mg/L)

\( C_{0} \): Concentration of dissolved oxygen at time \( t \) (mg/L)

\( D \): Rotated cone turbine or impeller diameter (m)

\( d \): Pitch blade propeller diameter \((PBP, U)(m)\)

\( Fr \): Froude number \((N^{2}D/g)\)

\( g \): Acceleration of gravity \((9.80665) (m/g/s)\)

\( H \): Water level in the vessel (m)

\( k_{a} \): Volumetric oxygen mass transfer coefficient \((liquid \ body \ mass \ transfer \ zone) \ (1/s)\)

\( k_{a20} \): Volumetric oxygen mass transfer coefficient at \(20\) °C \((liquid \ body \ mass \ transfer \ zone) \ (1/s)\)

\( k_{a0} \): Volumetric oxygen mass transfer coefficient at \(0\) °C \((liquid \ body \ mass \ transfer \ zone) \ (1/s)\)

\( N \): Rotation speed \((1/s)\)

\( N_{p} \): Power number \((P/\rho N^{3/2}D^{5})\)

\( P \): Power consumed \( (watt)\)

\( P_{s} \): Average specific power dissipated by the agitator under gassed condition \([19]\) \((W)\)

\( P_{b} \): Average specific power dissipated by the agitator under un-gassed condition \([19]\) \((W)\)

\( P_{m} \): Mean total specific energy dissipation rate \([21]\) \((W/kg)\)

\( P_{tot} \): Average specific total power dissipated in \( n \)-impeller vessel \([19]\) \((W/m^{3})\)

\( Re \): Reynolds number \((\rho ND^{2}/\mu)\)

\( S \): Spacing between two impellers \((m)\)

\( t \): Time \((s)\)

\( T \): Vessel diameter \((m)\)

\( U_{s} \): Superficial gas velocity \((m/s)\)

\( V \): Water volume \((m^{3})\)

\( W \): Turbine blade width \((m)\).

Greek Symbols

\( \rho \): Water density \((kg/m^{3})\)

\( \tau \): Probe time constant \((s)\)

\( \mu \): Water dynamic viscosity \((kg/ms)\)

\( \nu \): Water kinematic viscosity \((m^{2}/s)\)

\( \theta \): Temperature \((^\circ C)\).

Impellers Types Abbreviations

IBRC: Inverted pitched rotated cone (developed particularly for surface aeration), up-pumping

PBP, U: Pitch blade propeller, up-pumping

PDT: Parabolic-blade disk turbine \([21]\)

CBYN: CBY narrow blade \([21]\)

LSB: Long-short blade \([21]\)

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

References


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