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The use of circular surface aerators in wastewater treatment tanks

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Abstract: Aeration experiments were conducted in different sized baffled and unbaffled circular surface aeration tanks to study their relative performance on oxygen transfer process while aerating the same volume of water. Experiments were carried out with the objective of ascertaining the effect of baffle on oxygen transfer coefficient k. Simulation equations govern the oxygen transfer coefficient with the theoretical power per unit volume, X and actual power per unit volume, P_V. It has been found that, for any given X, circular tanks with baffle produce higher values of k than unbaffled circular tanks, but in terms of actual power consumption unbaffled tanks consume less power when compared to baffled circular tanks to achieve the same value of k. It has been found that in terms of energy consumption, ε, baffled tanks consume more energy than unbaffled tanks at any value of X. This suggests that the unbaffled circular tank gives a better performance as far as energy consumption is concerned and hence better economy. An example illustrating the energy conservation to aerate the same volume of water in both types of aerators is given.

Keywords: surface aerators; circular surface aerator; oxygen transfer coefficient; power per unit volume parameter

NOTATION

A	Cross-sectional area of an aeration tank (L^2)
B	Width of the baffle (L)
b	Width of the blade (L)
C_0	Initial concentration of dissolved oxygen at time t 0 (ppm)
C_s	Saturation value of dissolved oxygen at test conditions (ppm)
C_t	Concentration of dissolved oxygen at any time t (ppm)
d	Diameter of the tank (L)
D	Diameter of the rotor (L)
F_r	N^2D/g, Froude number
g	9.81 m s^{-2}, acceleration due to gravity (L/T^2)
H	Depth of water in an aeration tank (L)
h	Distance between the top of the blades and the horizontal floor of the tank (L)
h_f	Head loss due to rotational movement of the water in an aeration tank (L)
I_1, I_2	Input current at no load and under loading conditions, respectively
k	K_La_{20} $(\nu/g^2)^{1/3}$, non-dimensional oxygen transfer coefficient
K_La_T	Overall oxygen transfer coefficient at room temperature T °C of water
K_La_{20}	Overall oxygen transfer coefficient at 20 °C
l	Length of the blade (L)
N	Rotational speed of the rotor with blades (1/T)
n	Number of rotor blades (6)
n_b	Number of baffles (5)
P	Power available to the rotor shaft (ML^2/T^2)
P/V	Power per unit volume (M/LT^2)
P_V	$P/(V\gamma(g\upsilon)^{1/3})$, non-dimensional power per unit volume
R_e	ND^2/ν, Reynolds number
V	Volume of water in an aeration tank (m^3)
R_a	Armature resistance of DC motor
V_1, V_2	Input voltage at no load and under loading conditions, respectively
X	$N^3D^2/(g^{4/3}\nu^{1/3}) = F^{4/3}R^{1/3}$, theoretical power per unit volume parameter
θ	1.024, constant for pure water used in Eqn (2)
ν	Kinematic viscosity of water (M^2/T)
γ	Unit weight of water
ρ_a	Mass density of air (M/L^3)
ρ_w	Mass density of water (M/L^3)
ε	Energy consumption per unit volume

INTRODUCTION

Aeration is an essential part of almost all wastewater treatment systems and is usually the major energy-consuming unit process. The aeration process is also used to remove volatile substances and gases present in water and wastewater and to improve the dissolved oxygen (DO) content in the water and wastewater. Various aeration methods are used in the treatment of wastewater, namely diffused-air aerators, surface aerators and Venturi aeration systems. Among these, surface aerators are practically synonymous with the aeration systems employed in wastewater treatment systems. A typical surface aerator used in this study is shown in Fig. 1.

The main component of these surface aerators is an impeller or rotor. The rotor is rotated to create

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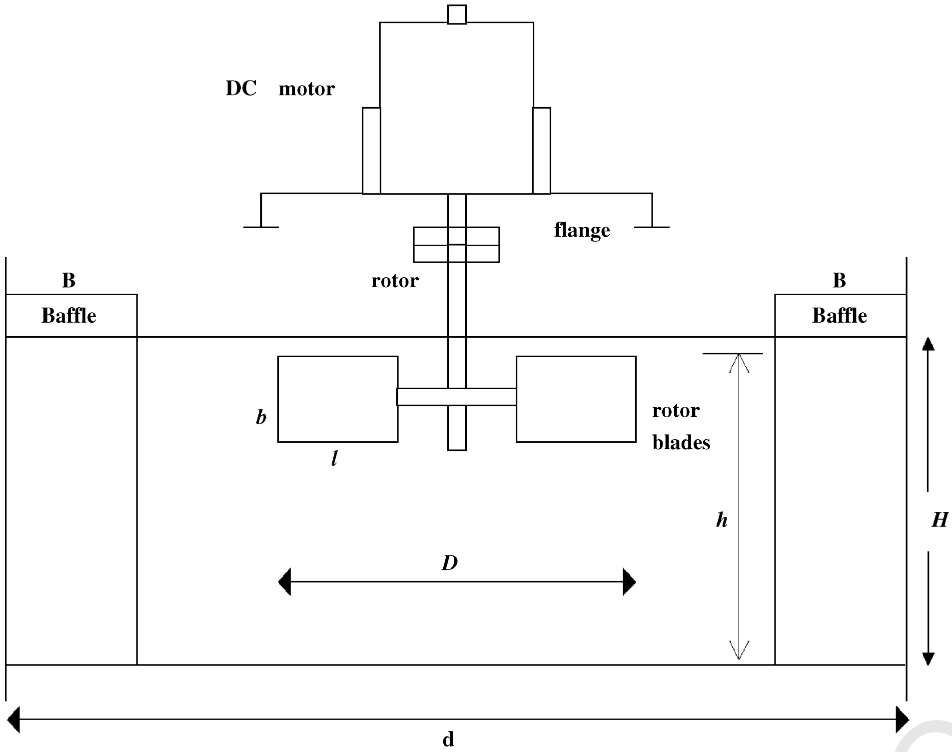

Figure 1. Schematic diagram of a surface aeration tank.

turbulence in the water body so that aeration takes place through the interface of atmospheric oxygen and the water surface. The rate of oxygen transfer depends on a number of factors such as intensity of turbulence, which in turn depends on the speed of rotation, size, shape and number of blades, diameter and immersion depth of the rotor, and size and shape of aeration tank, as well as on the physical, chemical and biological characteristics of water.[1] Many impellers, e.g. flat blade, pitched blade, vane disk, paddle and propeller, can cause surface aeration. Among these, the Rushton disk turbine is one of the most commonly used for surface aeration, with its lower critical impeller speed for onset of gas entrainment, higher volumetric mass transfer coefficient, lower power consumption and good gas–liquid mixing.[2,3] In the present study a six-flat-blade Rushton turbine has been used.

Whichever turbine is used, a significant amount of energy will be required to effect the transfer of oxygen. As reported by Hwang and Stenstrom,[4] the aeration process consumes as much as 60–80% of total power requirements in wastewater treatment plants. This shows how important the proper design of such systems is and implies that only energy-efficient designs should be used.

The performance of surface aeration systems is rated in terms of their oxygen transfer rate; hence the choice of a particular surface aeration system depends on its performance and efficiency of oxygen transfer rates. The spiraling costs of electricity and other energy forms are forcing economization regarding aeration systems, as the economics of an aeration system, particularly operating costs, are contributing much more heavily to system selection. Thus it can be said that sometimes mixing power requirements, not the oxygen transfer efficiency, controls the design of a wastewater treatment facility.[5,6] It is therefore essential that the design and operation of the aeration process are as near optimal as possible or practicable, particularly in terms of achieving energy efficiency.

Most wastewater treatment facilities use a baffled tank, as this provides a higher oxygen transfer rate in quick time, but power consumption of the rotor is increased by the baffles present in the tank.[7] Similarly, the unbaffled tank also has limitations, such as the vortex present in the unbaffled tank resulting in poor axial mixing. The present work compares and analyzes the suitability of using baffled or unbaffled surface aerators in wastewater treatment systems.

THEORY AND BACKGROUND INFORMATION

The oxygen transfer coefficient

According to the two-film theory,[8] mass transfer through the gas–liquid interface may be expressed by the following equation:

$$K_{\mathrm{L}}a_T = [\ln(C_{\mathrm{s}} - C_0) - \ln(C_{\mathrm{s}} - C_t)]/t \qquad (1)$$

where C_{s}, C_0 and C_t are concentrations usually expressed in parts per million (ppm). The value of $K_{\mathrm{L}}a_T$ can be obtained as the slope of the linear plot between $\ln(C_{\mathrm{s}} - C_t)$ and the corresponding time t. The value of $K_{\mathrm{L}}a_T$ thus obtained can be corrected for a temperature other than the standard temperature of 20 °C as $K_{\mathrm{L}}a_{20}$, using the van't Hoff Arrhenius equation:[9]

$$K_{\mathrm{L}}a_T = K_{\mathrm{L}}a_{20}\theta^{(T-20)} \qquad (2)$$

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where θ is the temperature coefficient 1.024 for pure water.

Process dynamics

The variables which can influence the oxygen transfer coefficient at 20 °C (i.e., K_La_{20}) for a given shape of aeration tank are given by[1,10]

$$K_La_{20} = f(A, H, D, l, b, h, n, n_b, N, g, \rho_a, \rho_w, \nu) \quad (3)$$

Equation (3) may be expressed in terms of non-dimensional parameters as follows:

$$k = f(\sqrt{A}/D, H/D, l/D, b/D, h/D, n, n_b, \rho_a/\rho_w, R_e, F_r) \quad (4)$$

where, $k = K_La_{20}\ (\nu/g^2)^{1/3}$ is the non-dimensional oxygen transfer coefficient, $R_e = ND^2/\nu$ is called Reynolds number and $F_r = N^2D/g$ is the Froude number. It can be expressed also as[1]

$$k = f(\sqrt{A}/D, H/D, l/D, b/D, h/D, n, n_b, \rho_a/\rho_w, X) \quad (5)$$

where $X = \Phi\bullet\ (F_r, R_e) = F_r^{4/3}R_e^{1/3}$ is the parameter governing the theoretical power per unit volume.

The intensity of turbulence and wave action on the water are the major sources normally associated with surface aeration. Turbulence and viscous effects are generally described by the Reynolds number (R_e), and the surface wave action is described by the Froude number (F_r). Hence both R_e and F_r are important as far as the surface aeration is concerned. It may be noted here that both F_r and R_e are implicitly expressed in X as $X = F_r^{4/3}R_e^{1/3}$. The number of blades n in the present experiments is constant and the number of baffles in a baffled circular tank n_b (= 5) is constant. Also, the parameter ρ_a/ρ_w is considered invariant. Thus, these parameters are omitted in the analysis. Therefore, the functional relationship of Eqn (5) can now be expressed as

$$k = f(\sqrt{A}/D, H/D, l/D, b/D, h/D, X) \quad (6)$$

Geometric similarity

Equation (6) suggests that, for any given shape of aeration tank, if geometric similarity of the first five variables on the right-hand side is maintained, then k depends only on X.

Conditions of geometric similarity for unbaffled circular tanks have been maintained as given by[11]

$$\sqrt{A}/D = 2.88;\ H/D = 1.0;\ l/D = 0.3;$$
$$b/D = 0.24;\ h/H = 0.94;\ n = 6 \quad (7)$$

whereas for baffled circular tanks the same geometric similarity is maintained along with $n_b = 5$ in which baffles are placed uniformly along the perimeter of the circular tank and its dimensions are $B/D = 0.5$. It has been found that the geometrical similarity condition mentioned in Eqn (7) is optimal in producing the aeration rate.[11,12]

Dynamic similarity

When the geometric similarity conditions are maintained, the functional relationship represented by Eqn (6) is reduced to a function of dynamic similarity[1] for any shape of aeration tank. However the functional relationship may be different for different shapes.

$$k = f(X) \quad (8)$$

where the parameter X governs the theoretical power per unit volume and can be defined from hydraulics principles[1] based on the concept that the power is related to the product of flow discharge and head loss. Therefore one may expect a correlation between the effective (actual or measured) power per unit volume (P/V) and X. Furthermore, the oxygen transfer coefficient (k) is a function of P/V because $k = f(X)$ and P/V and X are directly related. In this functional relationship P/V can be expressed in a non-dimensional form as P_V. Hence the relationship between k and P/V can be expressed as

$$k = f(P_V) \quad (9)$$

where P_V is the non-dimensional form of $P/V = P/(V\gamma(g\upsilon)^{1/3})$.

EXPERIMENTS

Experiments were carried out to ascertain the effect of baffles on oxygen transfer coefficient k under a wide range of dynamic conditions (X and P_V).

Experimental set-up

Baffled and unbaffled circular tanks (Fig. 1) of two cross-sectional areas 1 m^2 and 0.5184 m^2 were each tested under laboratory conditions. The significance of these dimensions is that each linear dimension, such as rotor diameter D, blade sizes b and l, water depth H, and the distance between the top of the blade to the bottom of the tank h, is kept the same as per the geometric similarity given in Eqn (7).

Determination of K_La_{20}

First the water in the tank was deoxygenated by adding the required amounts of cobaltous chloride ($CoCl_2$) and sodium sulfite (Na_2SO_3), which were thoroughly mixed in water. The deoxygenated water was aerated by rotating the rotor at the desired speed. When the DO concentration began to rise, readings were taken at regular intervals until DO increased up to about 80% saturation.[13]

Using the known values of DO measurements in terms of C_t at regular intervals of time t (including the known value of C_0 at $t = 0$) a line was fitted, by linear regression analysis of Eqn (1), between the logarithm of ($C_s - C_t$) and t, by assuming different but appropriate values of C_s (which gives the minimum 'standard error of estimate') and thus the values of $K_L a_T$ and C_s are obtained simultaneously. The values of $K_L a_{20}$ were computed by using Eqn (2) with $\theta = 1.024$ as per the standards for pure water.[9]

Determination of actual power available at the shaft

The power available at the shaft is calculated as follows.[14] Let P_1 and P_2 be the power requirements under no load and loading conditions at the same speed of rotation. Then the effective power available to the shaft, $P = P_2 - P_1 - \text{Losses}$, is expressed as

$$P = I_2 V_2 - I_1 V_1 - R_a (I_2{}^2 - I_1{}^2) \qquad (10)$$

where I_1 and I_2 are currents measured in amperes under no load and loading conditions, respectively; similarly, the respective voltages in volts are V_1 and V_2. Armature resistance R_a is measured in ohms.

SIMULATION OF OXYGEN TRANSFER COEFFICIENT *K* WITH THEORETICAL POWER PER UNIT VOLUME *X*

Oxygen transfer coefficient was investigated as a function of dynamic variable X to verify Eqn (8). The experimental data expressed in terms of $X = N^3 D^2 / g^{4/3} \nu^{1/3}$ and $k = K_L a_{20} \, (\nu/g^2)^{1/3}$ are plotted in Fig. 2.

It is interesting to note that the each set of data points pertaining to the given shape of the tank fall very closely on a unique curve suggesting the validity of Eqn (8); however, the functional relationships are different for baffled and unbaffled tanks. A simulation equation for unbaffled circular tanks between k and X has been established[10] and the same is plotted in Fig. 2 along with the data from the present experiments to verify the validity of such a simulation equation. In Fig. 2 the following equations fit quite well for all data points belonging to circular tanks; for unbaffled circular tanks:[10]

$$k = \{10.45 \exp[-4.5/X] + 2.45 - 0.7 \exp[-5(X - 0.35)^2]\} 10^{-6} \sqrt{X} \qquad (11)$$

and for baffled circular tanks:

$$k = \{3.26 \exp[-0.561/X] + 0.211 - 0.426 \exp[-0.472(X - 0.878)^2]\} 10^{-6} \sqrt{X} \qquad (12)$$

It is clear from Fig. 2 that at any given X the baffled tank is providing more oxygen transfer coefficient than the unbaffled tank. In the unbaffled tank, the liquid tends to move mainly along circular trajectories, resulting in small relative velocities between impeller and fluid and weak radial flows directed towards the tank walls. This results in a poor axial mixing and in the formation of a pronounced vortex on the free surface of the liquid, whose depth depends on the rotational speed of the rotor. Installation of the baffles effectively destroys the circular liquid patterns, inhibiting vortex formation so that the liquid surface becomes almost flat at moderate speeds. Moreover, axial flows become much stronger, leading to an improved mixing rate with the rotor speed. Such an outcome may also be attributed to the level of turbulence intensity in a given type of tank for a given speed of rotation. If it is accepted that turbulence intensity is responsible for aeration rate then it is greater in circular tanks with baffles and less in circular tanks without baffles, when both tanks contain the same volume of water and are run at the same speed of rotation. This could be a reason to install baffles in circular tanks to enhance the aeration rate. Experiments conducted in circular tanks

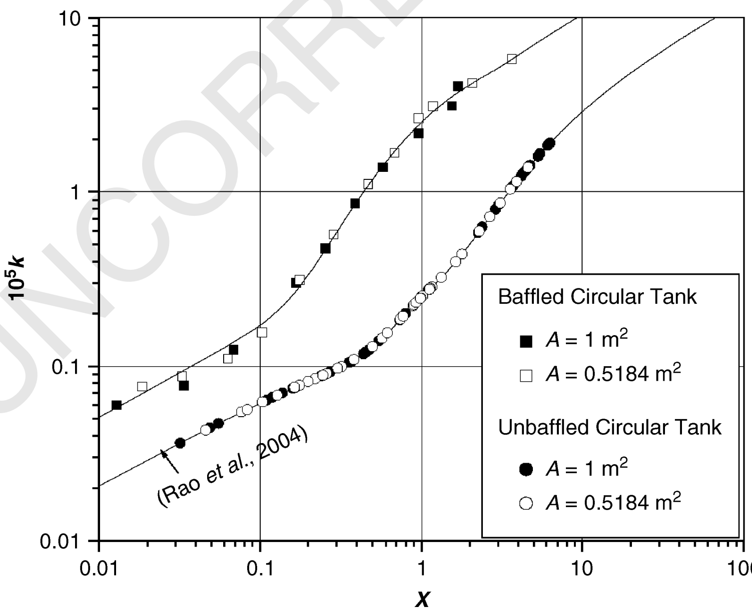

Figure 2. Simulation of oxygen transfer rate with theoretical power per unit volume (*X*).

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with baffles have supported this basic claim (Fig. 2), which produce relatively higher rates of aeration.

SIMULATION OF OXYGEN TRANSFER COEFFICIENT *K* WITH ACTUAL POWER PER UNIT VOLUME P_V

The rates of oxygen transfer can be correlated with effective power consumption per unit volume. Figure 3 shows the behavior of oxygen transfer coefficient with input power per unit volume of circular tanks. It is interesting to observe that data of an individual shape of aerator falls on a unique curve, suggesting that the oxygen transfer rates can be simulated with the actual power per unit volume; the associated relationships are presented in Eqns (12) and (13); for unbaffled circular tanks:

$$10^5 k = 7.38\, P_V \exp(-0.189/P_V) + 0.33(P_V)^{0.5} \tag{13}$$

and for baffled circular tanks:

$$10^5 k = 3.95\, P_V \exp(-0.85/P_V) + 0.15(P_V)^{0.5} \tag{14}$$

From Fig. 3 it is evident that for a given effective power per unit volume unbaffled circular tanks produce a higher oxygen transfer coefficient (k) than baffled circular tanks.

RELATIVE PERFORMANCE OF SURFACE AERATION TANKS

The relative performance of surface aerators on oxygen transfer rate is shown in Fig. 4. As shown in Fig. 4(A), the baffled tank produces more oxygen transfer coefficient than the unbaffled tank at any X. It reaches a maximum value at $X = 0.87$, such that the oxygen transfer coefficient of the baffled tank is about 10 times more than the unbaffled tank.

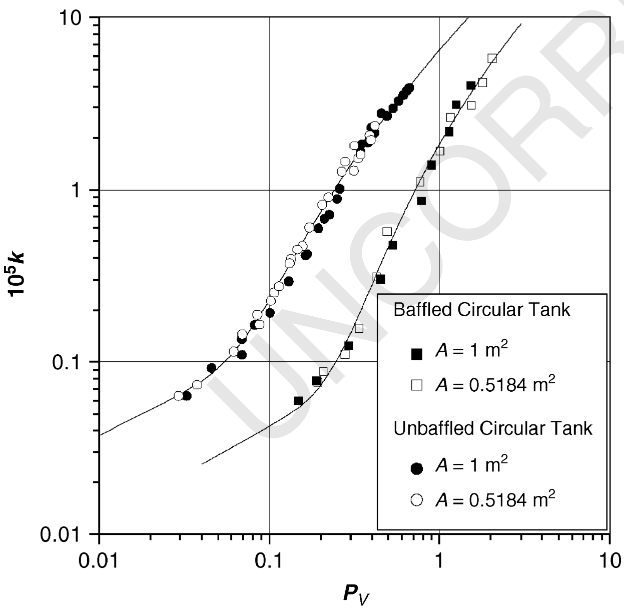

Figure 3. Simulation of oxygen transfer rate with actual power per unit volume (P_V).

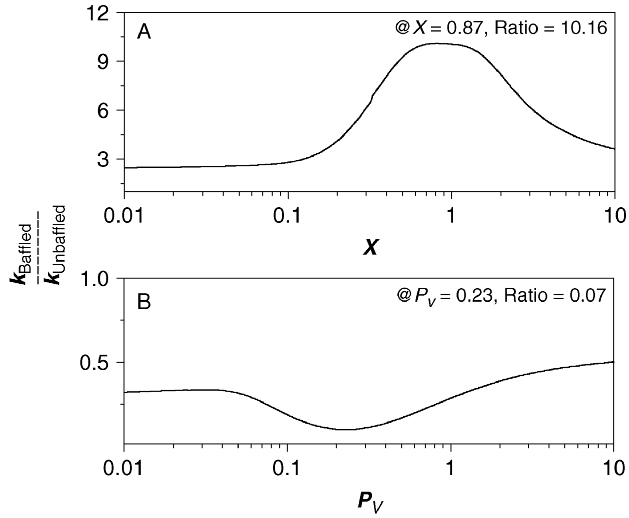

Figure 4. Relative performance of aeration tanks on oxygen transfer rates.

This trend is reversed in the case of actual and effective power per unit volume, as shown in Fig. 4(B), in which unbaffled tank is always producing more oxygen transfer coefficient than the baffled tank.

SUITABILITY OF USING UNBAFFLED CIRCULAR SURFACE AERATION TANKS

Energy requirements of surface aerators are of paramount importance when choosing and designing particular types of aerator to meet demand. The energy can be computed as the product of power and time required to achieve a desired level of DO concentration. As $K_L a_{20}$ has inverse time units, one may characteristically express the energy by a parameter $P/K_L a_{20}$. As k is a non-dimensional form of $K_L a_{20}$ and P_V is the non-dimensional form of P/V, the energy (parameter) per unit volume (ε) may be defined as $\varepsilon = P_V/k$. To obtain a comparative energy requirement for achieving the same oxygen transfer rates, with the help of simulation equations with theoretical power per unit volume (X) and simulation equations with effective (actual) power per unit volume (P_V), the ratio of the energy parameter ε with X has been plotted for all the surface aerators in Fig. 5.

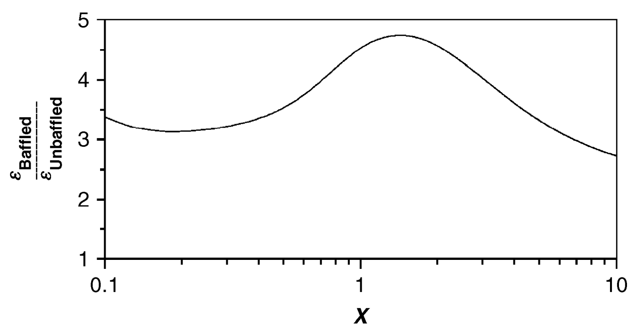

Figure 5. Comparison of energy characteristics of surface aeration tanks.

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Table 1. Geometrical parameters of different sized tanks (based on geometric similarity: $\sqrt{A}/D = 2.88$, $H/D = 1.0$, $l/D = 0.3$, $b/D = 0.24$ and $h/H = 0.94$)
For baffled tanks no. of baffles $n_b = 5$

Tank volume (m^3)	D = rotor diameter• (mm)	H = water height (mm)	h = rotor submergence depth (mm)	b = blade width (mm)	l = blade length (mm)
0.25	311	311	292	74.64	93.3
0.5	392	392	368	94.08	117.6
1	494	494	464	118.56	148.2

Table 2. Energy requirements to aerate 1 m^3 of water by employing different sized tanks at constant input power (P)

Volume of the tank (m^3)	Number of tanks	Total energy consumed at different effective input power (W h)			
		Baffled tanks		Unbaffled tanks	
		@ 50 (W)	@ 200 (W)	@ 50 (W)	@ 200 (W)
0.25	4	11.57	6.33	11.01	2.84
0.5	2	23.27	7.77	14.89	2.95
1	1	48.96	11.55	20.01	3.18

It is clear from Fig. 5 that at any given X the baffled tank is consuming more energy than the unbaffled circular surface aeration tank. The main component of total operation costs is constituted by the energy dissipated by the system of aeration.[15] Therefore, based on the fact depicted in Fig. 5, it can be said that unbaffled circular tanks are more economical as they consume less energy than baffled circular tanks.

DESIGN EXAMPLE

Problem: Analyze the energy requirements to aerate a volume of water, $V = 1\,m^3$, by a single tank and a number of smaller sized tanks of equal volume (V_s), when each tank is subjected to a constant installed input power (P) to the shaft in both types of circular (baffled and unbaffled) tank. Thus, the number of smaller tanks needed to aerate $1\,m^3$ of water is equal to V/V_s to aerate the $1\,m^3$ volume of water. The rotor is run until DO concentration, C_t, attains 80% of the saturation value. The initial DO concentration $C_0 = 0$ at $t = 0$ and water temperature are assumed constant and equal to 25 °C and hence $\nu = 0.88 \times 10^{-6}$.

Solution: Three different sized tanks of volume $V_s = 0.25\,m^3$, $0.5\,m^3$ and $1\,m^3$ are used to analyze their energy consumption in aerating $1\,m^3$ of water at constant input power P, such that the number of tanks of each size is respectively 4, 2 and 1.

Geometrical parameters can be obtained by the geometric similarity conditions ($\sqrt{A}/D = 2.88$, $H/D = 1.0$, $l/D = 0.3$, $b/D = 0.24$ and $h/H = 0.94$, and $n_b = 5$ for baffled tanks) adopted in the present work for a typical surface aerator shown in Fig. 1. Geometric dimensions of all the tanks are given in Table 1.

The problem is analyzed for two power values of $P = 50$ and 200 W. With the help of simulation Eqns (12) and (13), as the volume of water and power are known, actual values of $K_L a_T$ have been calculated and from there energy consumed by aerators has been calculated as power supplied multiplied by the total volume of water and time. Results are tabulated in Table 2.

It is clear from the calculation shown in Table 2 that baffled tanks are taking more energy than unbaffled tanks. Also from the calculation shown in Table 2, one interesting conjecture can be made that smaller tanks are consuming less energy; for example, one tank of $1\,m^3$ volume of water consumes an energy of 48.96 W h, whereas four tanks of $0.25\,m^3$ each, to aerate the same volume of water, consume a total energy equal to 11.57 W h; again one can think of time saving also by employing smaller tanks. Thus smaller tanks are more energy efficient in both types of circular tank.

CONCLUSIONS

This paper deals with the performance of baffled and unbaffled circular tanks with regard to aeration rates and their suitability for application in wastewater treatment plants.

Simulation equations governing the oxygen transfer coefficient, theoretical power per unit volume and actual power per unit volume have been developed for designing circular surface aeration systems.

The performance of the baffled tank is better at any value of X but, comparing actual power consumption, the unbaffled circular tank takes less power than the baffled circular tank. This means that for quick aeration it is advantageous to use a baffled tank.

Unbaffled circular tanks are more energy efficient than baffled circular tanks.

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