RECTANGULAR SURFACE AERATORS

By Achanta Ramakrishna Rao[1*], Bimlesh Kumar[2], and Ajey Kumar Patel[2]

Abstract:

Aeration experiments were conducted in two rectangular surface aeration tanks of L/B ratios 1.5 and 2 along with a square tank (L/B=1) to study their relative performance on oxygen transfer process while re-aerating the same volume of water such that the cross-sectional area of all the three tanks is the same. Experiment were carried out with an objective to find the shape effect on oxygen transfer coefficient k under a wide range of dynamic condition (variable X-the parameter governing power per unit volume) for rectangular tanks. An identical rotor with six flat blades was used in all the three tanks. The geometric dimensions, which were developed to produce maximum aeration in square tanks by a previous study, were used in the present study. Results have confirmed that at lower values of X (X<0.8) non dimensional oxygen transfer coefficient (*k*) is maximum in square tanks followed by rectangular tank of L/B=2 and it is the least in rectangular tank of L/B=1.5. However the rectangular tank of L/B=1.5 produces always lower k values for any given rotor speed when compared to square tank, whereas the performance of rectangular tank of L/B=2 is slightly better than square tanks when rotor speeds are higher.

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INTRODUCTION

Oxygen transfer, the process by which oxygen is transferred from the gaseous to liquid phase, is a vital part of the wastewater treatment process (Metcalf & Eddy Inc, 2004). Because of low solubility of oxygen and consequent low rate of oxygen transfer, sufficient oxygen to meet the requirements of aerobic waste does not enter through normal surface air-water interfaces. To transfer the large quantities of oxygen that are needed, additional interfaces are created by employing aeration process. The creation of additional interfaces enhance the rate of oxygen transfer so that the dissolved oxygen (DO) level gets raised to allow aerobic bacteria to reduce biochemical oxygen demand (BOD) of the effluent. To provide the required amount of oxygen, an aeration system is always needed. The two basic methods of aerating wastewater are: (1) to introduce air or pure oxygen into the wastewater body with diffusers generally called as bubble or diffused aerators and (2) to agitate the wastewater mechanically so as to promote the mass transfer of air from the atmosphere into the wastewater body, which is generally achieved by surface aerators. The Surface aerators are widely used because they offer better efficiency as well as convenience in operation and maintenance.

In the present study a surface aerator with six flat blades, is used as shown in Fig. 1. Surface aerators are driven by mechanical means to create turbulence in the wastewater body so that oxygen is entrained from the atmosphere to reduce the biochemical oxygen demand (BOD) of the effluent. The oxygen transfer process depends on various factors such as intensity of the turbulence, speed of the rotation, rotor dimension, physical, chemical and biological characteristics of the wastewater.

All the three tanks, which were studied, were having the same cross-sectional area, A=0.5184 m^2.The other geometrical dimensions such as water depth, impeller height etc. were maintained as per the earlier developed for square tanks (Udaya Simha et.al, 1991).The focus of this work is to analyze the relative performance of surface aerators having rectangular shape of L/B ratio1.5 and 2 with respect to square tank.

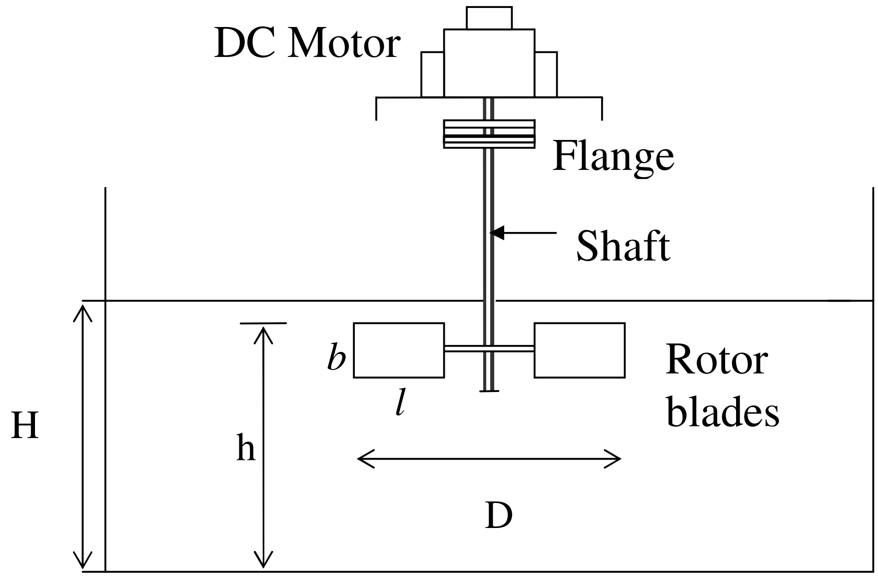

Figure 1 **Schematic diagram of a surface aerator**

THEORY AND BACKGROUND INFORMATION

The Oxygen Transfer Coefficient

According to the two-film theory (Metcalf & Eddy Inc, 2004), the mass transfer through gas-liquid interface may be expressed by an equation dm/dt = $k_l A_i(C_s - C_l)$, where k_l is coefficient of diffusion of oxygen in liquid; A_i is the interfacial area (area through which oxygen is diffusing); C_s is the saturation concentration of dissolved oxygen in the liquid and C_l is the concentration of oxygen in the liquid bulk phase. By noting $\partial m/\partial t = V\,\partial C/\partial t$, where V is volume of the liquid, the expression becomes $\partial C/\partial t = (k_l A_i/V)(C_s - C_l)$. The parameter $k_l A_i/V$ is generally designated by $K_L a_T$, the oxygen transfer coefficient at test temperature T (^{o}C). Integrating the above equation between the limits $C = C_0$ at time $t = 0$ and $C = C_t$ at $t = t$, one can obtain the following equation, as

$$K_L a_T = [\ln(C_s - C_0) - \ln(C_s - C_t)]/t \qquad (1)$$

Where ln represents natural logarithm of the given variables and the concentrations C_s, C_0 and C_t are concentrations usually expressed in parts per million (ppm). The value of $K_L a_T$ can be obtained as the slope of the linear plot between $\ln(C_s - C_t)$ and the corresponding time t. The value of K_La_T thus obtained can be corrected for a temperature other than the standard temperature of 20°C as K_La_{20}, using the Vant- Hoff Arrhenins equation (Manual 1988):

$$K_La_T = K_La_{20}\ \theta^{(T - 20)} \qquad (2)$$

where θ is the temperature coefficient 1.024 for pure water.

Dimensional Analysis

Many investigators like Schmidtke *et al* [1977], Udaya Simha et.al [1991], and Rao,ARK [1999] have successfully made use of the theory of dimensional analysis in their studies on the aeration process. The aeration process generally depends on three types of variables namely geometric, physical and dynamic variables and they are all explained as follows:

Geometric variables: -Shape of the aeration tank; cross-sectional area of the tank (A); depth of water in the tank (H); diameter of the rotor(D);length of the blades (l); width of the blades (b); the distance between the top of the blades and the horizontal floor of the tank (h); and the number of blades (n).

Physical variables: - density of air (ρ_a); density of water (ρ_w); and the kinematic viscosity of water (ν).

Dynamic variables: - rotational speed of the rotor with blades (N).

The variables, which can influence the oxygen, transfer coefficient at 20°C (i.e., K_La_{20}) for a given shape of an aeration tank are given by Rao, ARK [1999] and Rao et.al [2004]

$$K_La_{20} = f\,(A, H, D, l, b, h, n, N, g, \rho_{a,} \rho_{w,} \nu\ ) \qquad (3)$$

Eq. 3 may be expressed in terms of non-dimensional parameters as follows:

$$k = \mathrm{f}\,(\sqrt{A}/D,\ H/D,\ l/D,\ b/D,\ h/D,\ n,\ \rho_a/\rho_w,\ \mathrm{X}\,) \qquad (4)$$

Where $k = K_L a_{20}\,(\nu/g^2)^{1/3}$ is the non-dimensional oxygen transfer parameter and X= $N^3D^2/g^{4/3}\,\nu^{1/3}$ is the parameter governing the power per unit volume. The first six non-dimensional parameters represent the "geometric similarity" of the system and the last parameter represents the "dynamic similarity".

As many of the investigators Schmidtke *et al* [1977], Udaya Simha et.al [1991], and Rao,ARK [1999] etc. have adopted six blades in their experimental studies, the experiments in the present study have been conducted using six flat blades fitted to the rotor in symmetrical and evenly manner.

Therefore, the number of blades, n in the present experiments is constant. Also, the parameter ρ_a/ρ_w is considered as invariant. Thus, these two parameters are omitted in the analysis. Therefore, the functional relationship of Eq. 4 can now be expressed as,

$$k = \mathrm{f}\,(\sqrt{A}/D,\ H/D,\ l/D,\ b/D,\ h/D,\ \mathrm{X}\,) \qquad (5)$$

Geometric Similarity

Equation (5) suggests for any given shape of aeration tank, that if geometric similarity of the first five variables on right hand side is maintained, then k depends only on X.

An optimal solution to the geometrical similarity has been investigated by Udaya Simha et.al [1991] for square tank by conducting series of experiments in different sized tanks and by varying $\sqrt{A}/D$, H/D, l/D, b/D and h/D to a great extent. He has suggested the following values for maximum $K_L a_{20}$, for any rotational speed N of the rotor fitted with six flat blades:

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

Equation (6) is the optimal geometric similarity condition for the square tanks. In order to compare and contrast the performance of rectangular tanks with the square tanks, the same geometric dimensions except the shape has been maintained in all the tanks in present experiments.

Dynamic Similarity

When the geometric similarity conditions are maintained, the functional relationship represented by Eq. 6 is reduced to a function of dynamic similarity (Rao ARK, 1999) for any shape of aeration tank. However the functional relationship may be different for different shapes.

$$K = \mathrm{f}\ (\mathrm{X}) \qquad (7)$$

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), where the surface wave action is described by the Froude number (F). Hence, both R and F are important as far as the surface aeration is concerned. It may be noted here that both F and R are implicitly expressed in X in Eq. 7 as $\mathrm{X} = F^{4/3}R^{1/3}$ where $F = N^2D/g$, and $R = ND^2/\nu$ such that X can be considered as a governing parameter to simulate k (Rao, ARK, 1999). Hence k can be uniquely related to X and this concept has been well established by Rao, ARK [1999] for square tanks and Rao et.al [2004] for circular tanks, with different simulation equations for square and circular tanks.

EXPERIMENTS

Experiment were carried out with an objective to find the shape effect on oxygen transfer coefficient k under a wide range of dynamic condition (Variable X in Eq. 7) for rectangular tanks.

Experimental Setup

Three types of rectangular tanks of L:B ratio 1 (square tank), 1.5 and 2 of the same cross-sectional area 0.5184 m^2 were tested under laboratory conditions. The significance of these dimensions is such that in each linear dimensions, 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, are kept as the same as per the geometric similarity given in Eq. 6, and they are listed in Table 1. The geometric scaling of the tanks thus followed had suggested to be optimal

(Udaya Simha et.al 1991) in producing maximum K_La_{20} in square tanks. Same optimal geometric dimensions were also used in the experiments of rectangular tanks.

Table 1. Range of experimental variables

Sl. #	No of exps	Tank Shape	C/S Area	Length, L and width, B		Rotor diam--eter	Water depth	Imme-rsion height	Blade dimensions		Rotor Speed	
			A	L	B	D	H	h	l	b	Min.	Max.
			m^2	mm	mm	mm	mm	mm	mm	mm	rpm	rpm
1	9	Square	0.5184	720	720	250	250	235	75	60	30	156
2	15	Rectangular	0.5184	882	588	250	250	235	75	60	42.5	135.6
3	10	Rectangular	0.5184	1018	509	250	250	235	75	60	38.9	126.8
Number of blades, n = 6; Range of water temperature = 20-28 ^oC												

Determination of K_La_{20}

Standard oxygen transfer tests were conducted in tanks of clean tap water under laboratory conditions. At first the water in the tank was deoxygenated by adding required amount of cobalt as cobalt chloride ($CoCl_2$) and sodium sulphite (Na_2SO_3) (Metcalf & Eddy Inc. 2004) and they were thoroughly mixed in water. The deoxygenated water reaerated by rotating the rotor at desired speeds by maintaining the variables as per Table 1. When the DO concentration began to rise, readings were taken at regular intervals till DO increased up to about 80% saturation. Lutron Dissolved Oxygen meter was used to measure the DO concentration in water. The DO meter was calibrated with the modified Winkler's method [standard methods, 1985].

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 is fitted, by linear regression analysis of Eq. 1, between the logarithm of (C_s - C_t) and t, by assuming different but appropriate values of C_s such that 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. The values of K_La_{20} are computed using by Eq. 2 with θ = 1.024 as per the standards for pure water (Manual

1998). Thus the values of K_La_{20} are determined for different speeds of rotation N of the rotor in all of the geometrically similar tanks. The ranges of data of different variables and parameters covered in the present experiments are listed in Table 1.

DATA ANALYSIS AND DISCUSSION

Oxygen transfer coefficient in the rectangular surface aeration tanks is investigated as a function of dynamic variable X, to verify the Eq. 7. The experimental data expressed in terms of X= $N^3D^2/g^{4/3}\nu^{1/3}$ and k= $K_La_{20}\,(\nu/g^2)^{1/3}$ are plotted in Fig. 2.

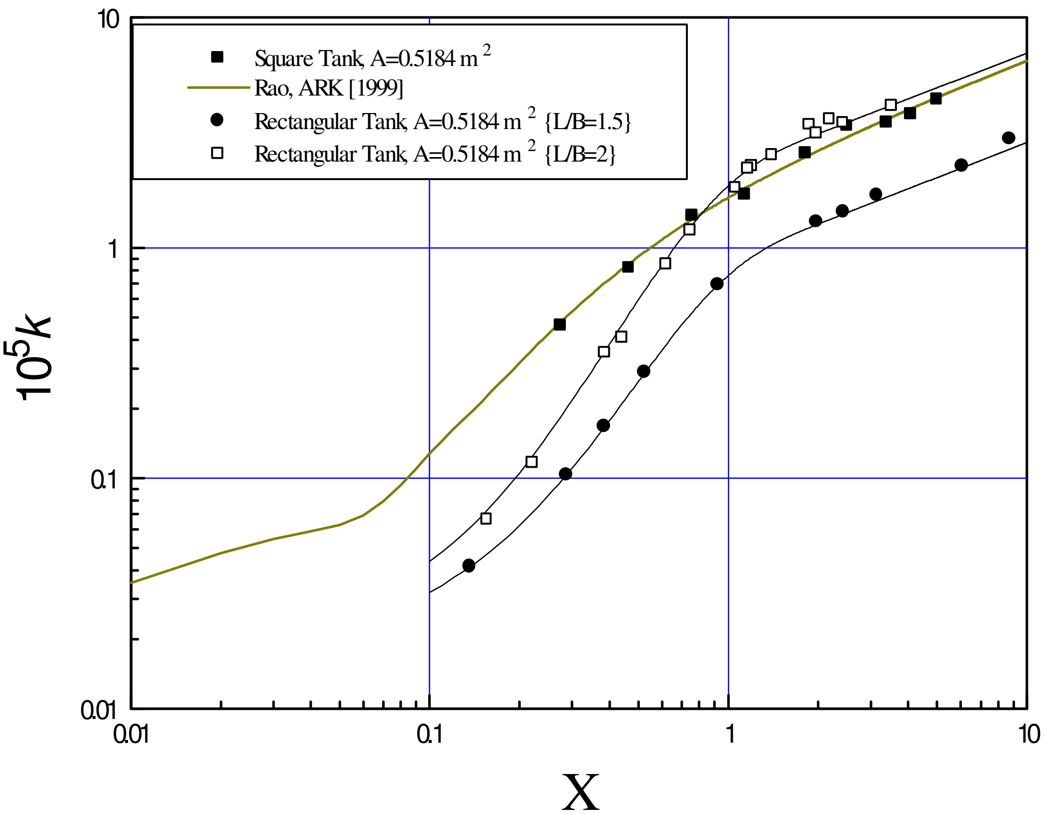

Figure 2 **Oxygen transfer in rectangular tank along with square tank**

It is quite 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 Eq. 7, however the functional relationship are different for different shapes as the data fall uniquely on different curves. A simulation equation for square tanks between k and X has been established by

(Rao, ARK 1999) and the same is plotted in Fig. 2 along with the data from present experiments to verify the validity of such a simulation equation.

It is also clear from the Figure 2 that at lower values of X (X<0.8), the square tanks give higher values of non dimensional oxygen transfer coefficient and is followed by the rectangular tanks in the order of L/B=2 and next by L/B=1.5. But at higher values of X (X>0.8) rectangular tank with L/B=2 gives marginally higher values of *k*, whereas the values of *k* are significantly the lowest in rectangular tank of L/B=1.5 at any given values of X.

The relative performance of the rectangular tanks of different L/B ratio is shown in Fig. 3 when compare to square tank of L/B =1. In Fig. 3 k_r and k_s are the non-dimensional oxygen transfer coefficients for rectangular and square tank.

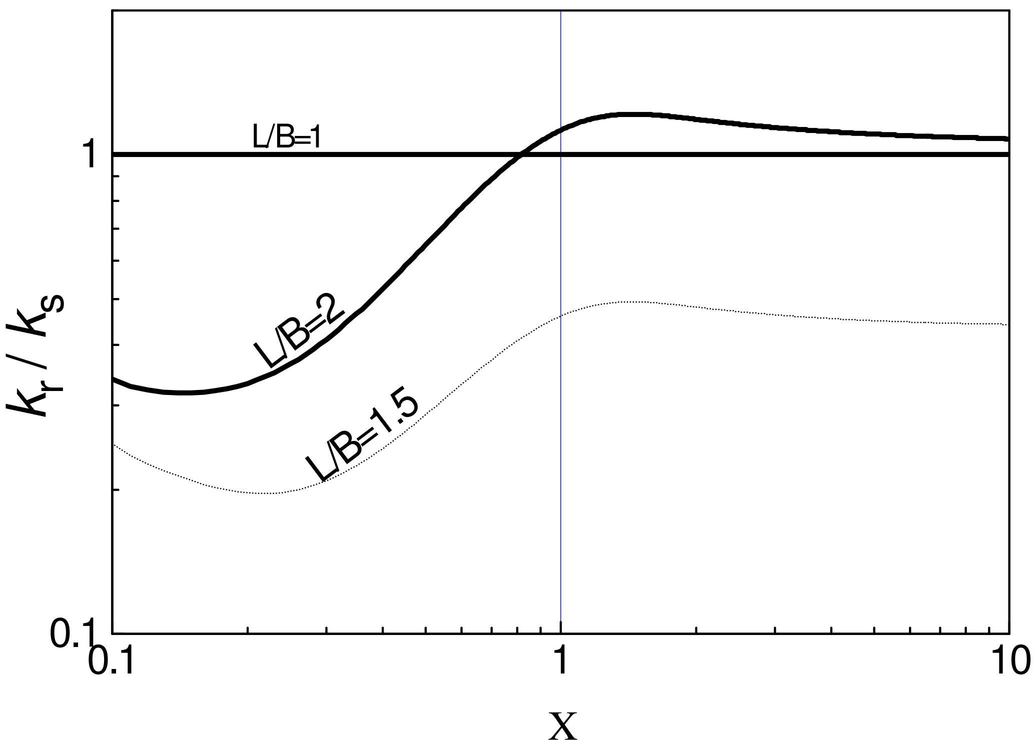

Figure 3 **Relative performances of rectangular tanks and square tank on oxygen transfer rates for any given X**

It is clear from Fig. 3 that for any given X, the ratio of k values of rectangular tank of L/B=2 and rectangular tank of L/B=1.5 i.e., $k_{r(2)} / k_{r(1.5)}$ is always greater than one. It means that the performance of rectangular tank of L/B=2 is better than the rectangular tank of

L/B=1.5. Interestingly, while comparing to rectangular tank of L/B=2 with square tank (L/B=1), it is evident from the Fig. 3 that at lower values of X (X<0.8), the performance of square tank is better than the rectangular tank of L/B=2. But at higher values of X (X>0.8) the performance of rectangular tank of L/B=2 is marginally better than the square tank.

Non uniform variation of oxygen transfer coefficient as shown in Fig. 2 may be attributed to various parameters such as turbulence intensity, actual power per unit volume, non uniform spacing around impeller etc. which needs further investigation. In the present investigation, it has been found that square tanks (L/B=1) is the best in terms of maximum *k* values and is followed by rectangular tank of L/B=2 and then rectangular tank of L/B=1.5. Thus it is very interesting to find that the order of performance is not in accordance with the L/B values. Therefore further studies are required on the intensity of turbulence and actual energy requirements. One may perhaps then relate turbulence intensity in terms of *k* and by making such measurements one may find an explanation for why the oxygen transfer coefficient *k* is not commensurate with L/B values

CONCLUSIONS

This paper deals with the performance of rectangular tanks on re-aeration rates and their suitability for application in wastewater treatment plants.

It has been found that the performance of rectangular tank of L/B=1.5 is least while comparing with rectangular tank of L/B=2 and square tank. The performance of rectangular tank L/B=2 is giving better re-aeration rate at higher values of X. But at lower values of X, square tank's performance is better than all other rectangular tank.

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NOTATION

The following symbols are used in this paper:

A = cross-sectional area of an aeration tank (L^2);

A_i = interfacial area (L^2);

B = width of the blade (L);

C = mass transfer per unit volume (M/L^3);

C_0 = initial concentration of dissolved oxygen at time $t = 0$ (ppm);

C_l = concentration of dissolved oxygen in the liquid bulk phase (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 rotor (L);

$F = N^2D/g$, 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);

$K = K_La_{20} / N$, non-dimensional oxygen transfer parameter;

$\boldsymbol{k} = K_La_{20}\,(\nu/g^2)^{1/3}$, non-dimensional oxygen transfer coefficient;

k_r = non-dimensional oxygen transfer coefficient for Rectangular tanks;

k_l = coefficient of diffusion of oxygen in liquid (L/T);

k_s = non-dimensional oxygen transfer coefficient for square tanks;

K_La_T = overall oxygen transfer coefficient at room temperature $T\,^{o}C$ of water;

K_La_{20} = overall oxygen transfer coefficient at 20 °C;

L = size of rectangular tank (L);

l = length of the blade (L);

m = mass of oxygen (M);

N = rotational speed of the rotor with blades (1/T);

n = number of rotor blades = 6;

$R = ND^2/\nu$, Reynolds number;

V_w = volume of water in an aeration tank (m^3);

$X = N^3D^2 / (g^{4/3}\nu^{1/3}) = F^{4/3}R^{1/3}$ = theoretical power per unit volume parameter;

θ = 1.024, constant for pure water used in Eq. 2;

ν = kinematic viscosity of water (M^2/T);

ρ_a = mass density of air (M/L^3);

ρ_w = mass density of water (M/L^3);