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Design considerations and economics of different shaped surface aeration tanks

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Abstract−This paper deals with the design considerations of surface aeration tanks on two basic issues of oxygen transfer coefficient and power requirements for the surface aeration system. Earlier developed simulation equations for simulating the oxygen transfer coefficient with theoretical power per unit volume have been verified by conducting experiments in geometrically similar but differently shaped and sized square tanks, rectangular tanks of length to width ratio (L/W) of 1.5 and 2 as well as circular tanks. Based on the experimental investigations, new simulation criteria to simulate actual power per unit volume have been proposed. Based on such design considerations, it has been demonstrated that it is economical (in terms of energy saving) to use smaller tanks rather than using a bigger tank to aerate the same volume of water for any shape of tanks. Among the various shapes studied, it has been found that circular tanks are more energy efficient than any other shape.

Key words: Aeration, Oxygen Transfer, Power Per Unit Volume Parameter, Surface Aerators, Water and Wastewater Treatment

INTRODUCTION

A surface aeration tank is a device for enhancing oxygen transfer to a liquid, in which an impeller placed near the liquid surface agitates the surrounding liquid and produces entrainment of liquid drops. The use of surface aerators as oxygen transfer devices in biological wastewater treatment systems has been a commonplace for at least several decades. Surface aeration is an important operation in chemical, bioengineering and other process industries. Surface aerators are also very effective in supporting the growth of cells in suspension and on micro-carriers [1]. Due to simplicity of design, surface aeration is a commonly used mechanism to supply oxygen to mammalian cells [2].

A typical surface aerator with six flat blades, used in this study, is shown in Fig. 1.

The main component of these surface aerators is an impeller or a rotor, to which the six flat blades are fitted. The rotor is rotated to create 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 like intensity of turbulence which in turn, depend 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 [3,4].

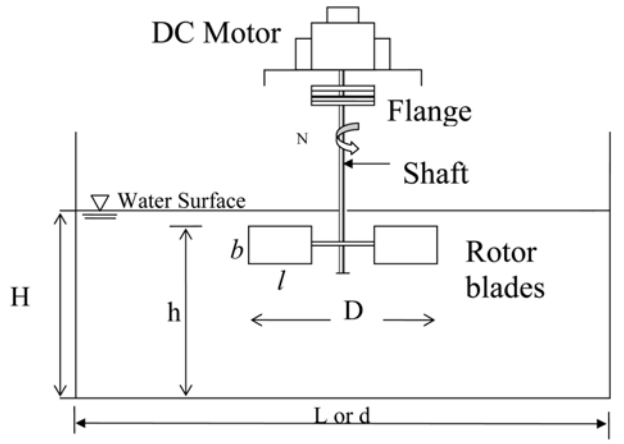

Fig. 1. Schematic diagram of a surface aeration tank.

Oxygen transfer and the corresponding power requirement are the two basic parameters necessary for design and simulation of surface aerators for which it is essential to have accurate laboratory simulations governing the hydrodynamic and mass transfer in the concerned area of application. There are several strategies frequently used to simulate the stirred tank phenomena, i.e., constant reactor geometry, constant volumetric oxygen transfer coefficient, constant maximum shear, constant power per unit volume, constant mixing time, constant Reynolds number etc. Among these strategies, constant reactor geometry is a kind of basic requirement for simulation and is called geometric similarity. After geometric similarity is maintained, the simulation of the operational variables such as oxygen transfer coefficient, power consumption, rotor speed etc. is required for optimal simulation of the process. Rao [3] has proposed that theoretical power per unit volume (X), which is a function of Reynolds ($R=ND^2/\nu$) and Froude number ($F=N^2D/g$) as $X=F^{4/3}R^{1/3}$, is a suitable parameter in simulating the oxygen transfer coefficient of surface aeration tanks, where N is the rotational speed of the rotor of diameter D and ν is kinematic viscosity of the water. This parameter, X, is also found to simulate the oxygen transfer coefficient in any shaped surface aeration tanks [5,6].

Power consumption is a basic integral quantity in an aerator, which determines the other processes involved in aeration phenomena such as 'mass transfer rates', 'gas hold up' etc. [7,8]. The power usage in mass transfer operations is very important in judging the aeration performance of the aerator. The costs associated with actual power draw contribute significantly to the overall costs of an aeration system. Therefore, it is desired to have simulation criteria for

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actual power consumption for differently shaped aeration tanks, which are used for aeration systems. The present paper mainly focuses on this aspect, i.e., simulating the actual power consumption in surface aeration tanks.

The present work tries to re-establish the simulation equation developed earlier for oxygen transfer coefficient and proposes a new simulation equation to simulate the actual power per unit volume and from these simulations equations, we tried to find the more energy efficient shape to be used as a surface aerator.

EXPERIMENTATION

Two sizes (A=0.5184 m^2 and 1 m^2) of rectangular tanks of L: W ratio 1.5 and 2, square and circular tank were tested under laboratory conditions. Different geometrical parameters of the tanks were maintained by using the geometrical similarity condition given by Udaya et al. [9] as:

$$\sqrt{A}/D=2.88;\ H/D=1.0;\ l/D=0.3;\ b/D=0.24;\ h/H=0.94 \qquad (1)$$

Where A is the cross-sectional area of the tank, H is the depth of water in the tank, D is the diameter of the rotor fitted with six blade of length (l) and width (b), and h is the distance between the top of the blades and the horizontal floor of the tank.

More advanced oxygen transfer models were developed in the recent past [10-13]; however, the two 'Film-theory' developed by Lewis and Whitman [14] seems to be quite satisfactory for clean water [15,16]; such a model is used in this study.

According to this theory, the oxygen transfer coefficient at T°C, K_La_T may be expressed as follows:

$$K_La_T=[\ln(C_s-C_0)-\ln(C_s-C_t)]/t \qquad (2)$$

Where ln represents natural logarithm and the concentrations C_s, C_0 and C_t are dissolved oxygen (DO) concentrations in parts per million (ppm), C_s=the saturation DO concentration at time tending to very large values, C_0 is at 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 20 °C as K_La_{20}, by using the van't-Hoff Arrhenius equation [17]:

$$K_La_T=K_La_{20}\theta^{(T-20)} \qquad (3)$$

where θ is the temperature coefficient 1.024 for tap water.

By maintaining the geometric similarity as per Eq. (1), tap water was deoxygenated by adding the required amount of cobaltous chloride ($CoCl_2$) and sodium sulphite (Na_2SO_3) [18] and mixed thoroughly. Deoxygenated water was re-aerated by rotating the rotor at the desired speed. When the dissolved oxygen (DO) concentration began to rise, readings were taken at regular intervals until DO increased up to about 80% of the DO saturation value. A Lutron Dissolved Oxygen meter was used to measure the DO concentration in water. The DO meter was calibrated with the modified Winkler's method [19,20].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. (2), 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 K_La_{20} are computed by using Eq. (3) with θ=1.024 as per the standards for pure water [11,17]. Thus, the values of K_La_{20} were determined for different rotational rotor speeds N in all of the geometrically similar tanks.

The power available at the shaft was calculated as follows [21, 22]: 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, $P=P_2-P_1$-Losses, is expressed as,

$$\text{The power available at the shaft, } P=I_2V_2-I_1V_1-R_a(I_2^2-I_1^2) \qquad (4)$$

Where I_1 and I_2 are current 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. Experimental data thus obtained has been listed in Table 1.

DESIGN EQUATIONS

The oxygen transfer coefficient, K_La_{20}, was non-dimensionalized as $k=K_La_{20}(\nu/g^2)^{1/3}$, where ν is the kinematic viscosity of the water and g is the gravitational acceleration. The simulation equations in terms of k and X given by earlier [3,5,6] were verified by the present experimental results. The following are the simulation equations and their verification by the present work is shown in Fig. 2.

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

Table 1. Experimental range

Sl.#	Tank shape	C/S area	Length, L or diameter d		Rotor diameter	Water depth	N		Effective power	
		A m^2	L (mm)	d (mm)	D (mm)	Min. (rpm)	Min. (rpm)	Max. (mm)	Min. (watt)	Max. (watt)
1a	Circular	1.0	-	1128	350	25	25	83	0.67	22.2
1b	Square	1.0	1000	-	350	15	15	83	0.53	19.2
1c	Rectangular L/W-1.5	1.0	1224.7		350	30	30	83	0.98	19.03
1d	Rectangular L/W-2	1.0	1414.2		350	30	30	83	0.94	14.52
2a	Circular	0.5184	-	812	250	55	55	60	0.24	17.3
2b	Square	0.5184	720	-	250	30	30	60	0.45	26.5
2c	Rectangular L/W-1.5	0.5184	882		250	42.5	42.5	60	1.12	15.8
2d	Rectangular L/W-2	0.5184	1018	-	250	38.9	38.9	60	0.85	16.7

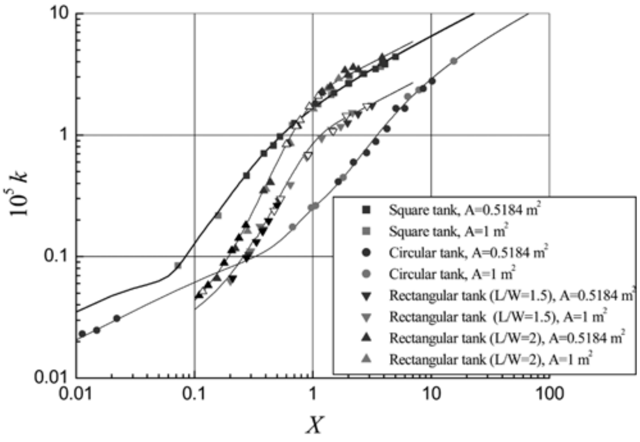

Fig. 2. Experimental verification of simulation equation for oxygen transfer rate with theoretical power per unit volume, (X).

$$k_s=\{17.32\exp[-0.3/X^{1.05}]+3.68 -0.925\exp[-750(X-0.057)^2]\}10^{-6}\sqrt{X} \tag{6}$$

$$k_{r1.5}=\{0.75\exp[0.19X^{0.25}]+8.035 -7.955\exp[-1.85(X-0.2)^2]\}\ 10^{-6}\sqrt{X} \tag{7}$$

$$k_{r2}=\{0.6275\exp[0.5X^{0.03}]+21.085 -20.955\exp[-1.85(X-0.2)^2]\}10^{-6}\sqrt{X} \tag{8}$$

Where $k=K_La_{20}\ (\nu/g^2)^{1/3}$ is the non-dimensional oxygen transfer coefficient, (k_c, k_s, $k_{r1.5}$ and k_{r2} are the non-dimensional oxygen transfer coefficient of circular, square, rectangular tank of L/W=1.5 and rectangular tank of L/W=2, respectively) and X ($=F^{4/3}R^{1/3}=N^3D^2/g^{4/3}\nu^{1/3}$) is the parameter governing the power per unit volume, (N is the rotor speed, D is the rotor diameter and ν is the kinematic viscosity of the water).

Based on the data collected (as given in Table 1), we tried to simulate the actual power consumption with theoretical power per unit volume parameter. Fig. 3 shows the behavior of actual power per unit volume of square, circular and rectangular tanks with X. It is quite interesting to observe that data of an individual shape of an aerator falls on a unique curve, suggesting that X can simulate the actual power per unit volume. From a statistical analysis of the data for an individual shape, the associated relationships are presented by Eqs. (9) to (12).

$$P_{VC}=0.001+0.0926\sqrt{X}+0.017e^{-x} \tag{9}$$

$$P_{VS}=0.213X+0.12\sqrt{X}+0.79Xe^{-x} \tag{10}$$

$$P_{VR1.5}=0.155+0.074X-0.142e^{-x} \tag{11}$$

$$P_{VR2}=0.3134+0.137X-0.2955e^{-x} \tag{12}$$

Where P_V ($=P/(V\gamma(g\upsilon)^{1/3})$) is the non-dimensional actual power input per unit volume of water (P_{VC}, P_{VS}, $P_{VR1.5}$ and P_{VR2} are the non-dimensional actual power input per unit volume parameter of circular, square, rectangular tank of L/W=1.5 and rectangular tank of L/W=2, respectively).

The relative performance of square and rectangular tanks of L/

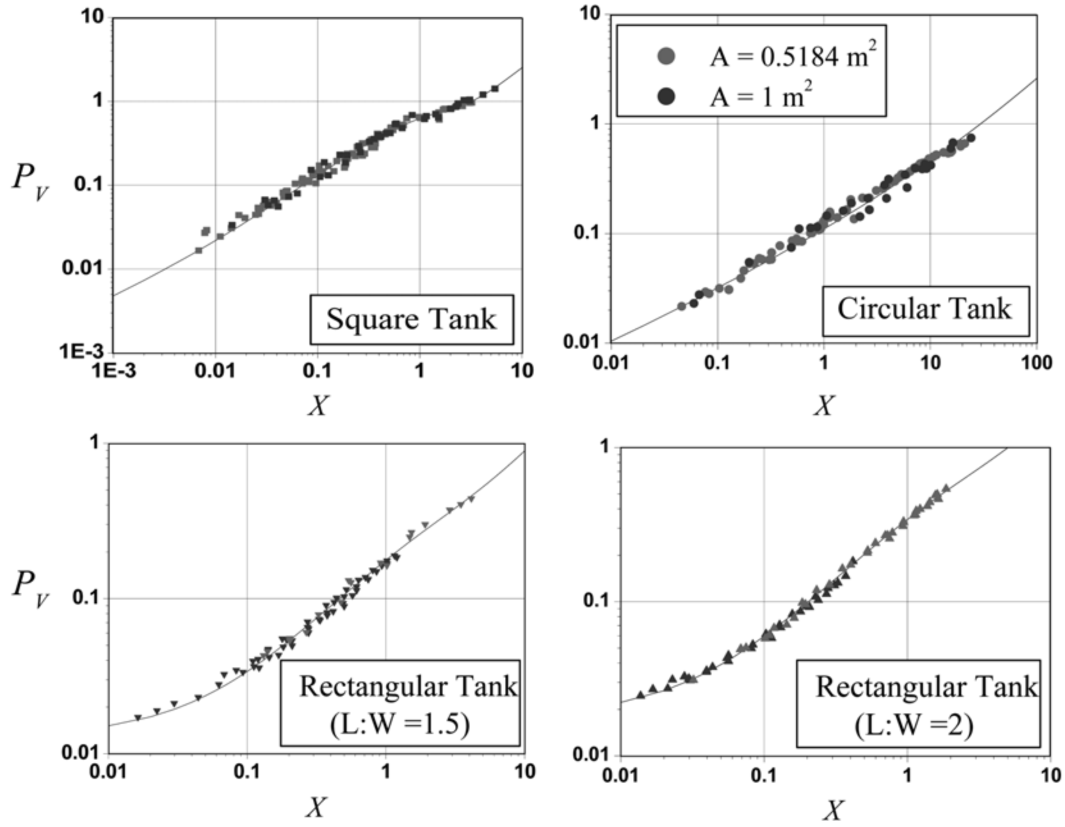

Fig. 3. Simulation of the actual power per unit volume, (P_V).

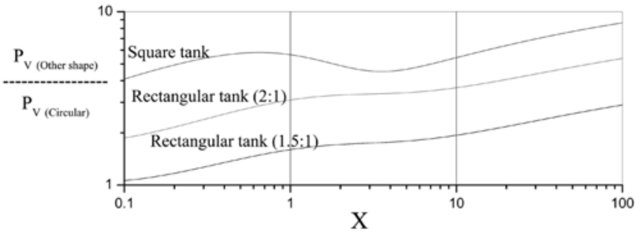

Fig. 4. Relative performance of aeration tanks on actual power per unit volume, for any given X compared to circular tank.

W=1.5 and 2 with respect to circular tanks in terms of dimensionless oxygen transfer parameter, P_V/P_{VC} for a given X is shown in Fig. 4.

It is clear from Fig. 4 that for any given X, the ratio of P_V/P_{VC} values of square, rectangular tank of L/W=2 and rectangular tank of L/W=1.5 are always greater than one with a square tank is the greatest.

ECONOMICS: CRITERIA FOR CHOOSING THE RIGHT SIZE AND SHAPE OF SURFACE AERATOR

The economics of an aeration system, particularly operating costs, contribute much more heavily to system selection [23,24]. As reported by Wesner et al. [25], the aeration process consumes as much as 60-80% of the total power requirement in biological treatment plants. Therefore, it is necessary to have a proper configuration for an aeration system. Based on curves (Figs. 2 and 3) or simulation equations, the economy in choosing the right shape and size is demonstrated as follows.

Energy requirements of surface aerators are of paramount importance while choosing and designing particular types of aerator to meet the demand. The energy can be computed as the product of power and time required to achieve a desired level of DO concentration. As K_La_{20} has the units of inverse of time, one may express characteristically the energy by a parameter P/K_La_{20} (where P represents the power and $1/K_La_{20}$ represents the time).

Four different size square tanks of volume V_s=0.1 m^3, 0.25 m^3, 0.5 m^3 and 1 m^3 were taken to analyze their energy consumption to aerate 1 m^3 of water at constant input power, P, such that the numbers of tanks of each size are, respectively, 10, 4, 2 and 1. The problem was analyzed for different assumed power values of P=50, 100, 150 and 200 watts. To aerate 1 m^3 of water, it is required to employ ten tanks of 0.1 m^3, four tanks of 0.25 m^3, two tanks of 0.5 m^3 and one tank of 1 m^3 capacity. So the total energy required to re-aerate 1 m^3 of water in multiple tanks is calculated as the product of the number of tanks multiplied by the power consumed in a single tank and time of each tank for aeration. The amount of energy that is required for a single tank as well as number of multiple tanks of smaller size of equitable volume while aerating the same volume of water (1 m^3) at constant input power is shown in Fig. 5 for a square tank, circular tank, rectangular tank (L/W=1.5) and rectangular tank (L/W=2), respectively.

The results from Fig. 5 can be summarized as follows:

I. Smaller tanks are consuming less energy than the bigger tanks.

II. The time consumed in smaller tanks is also less than in the bigger tanks.

III. As the input power increases, energy consumed in the process decreases.

Based on the analysis shown in Fig. 5, it can be said that for a

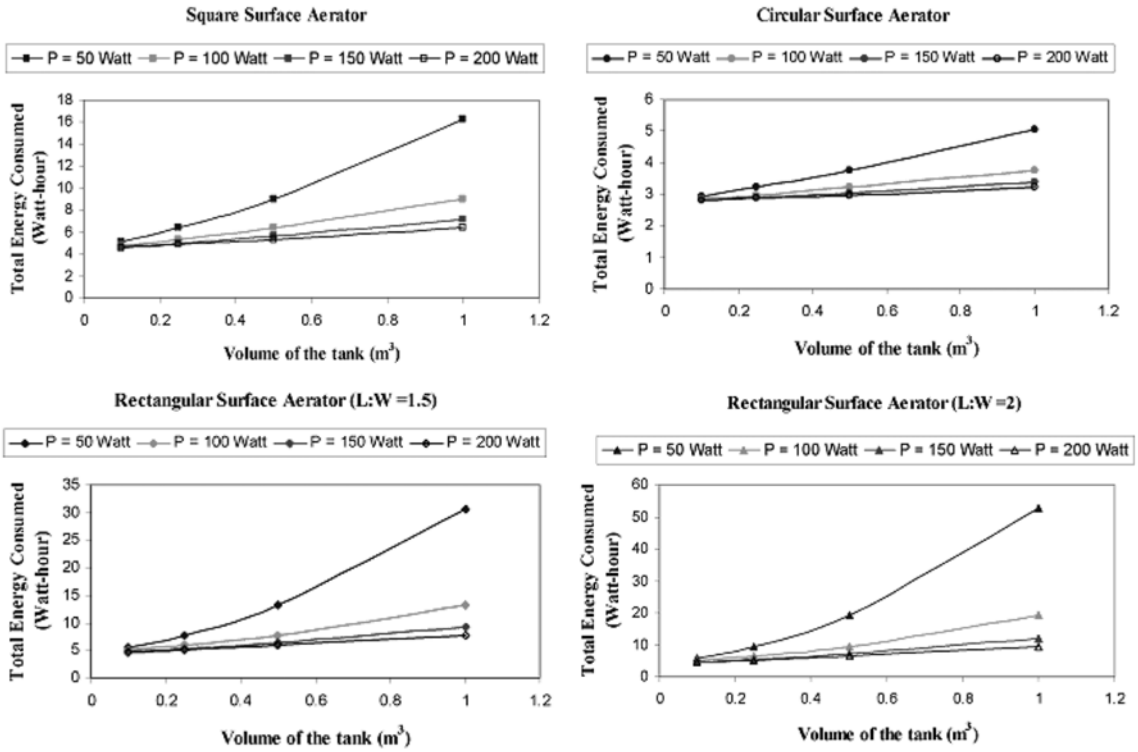

Fig. 5. Energy characteristics of different sized aerators, aerating the same volume of water.

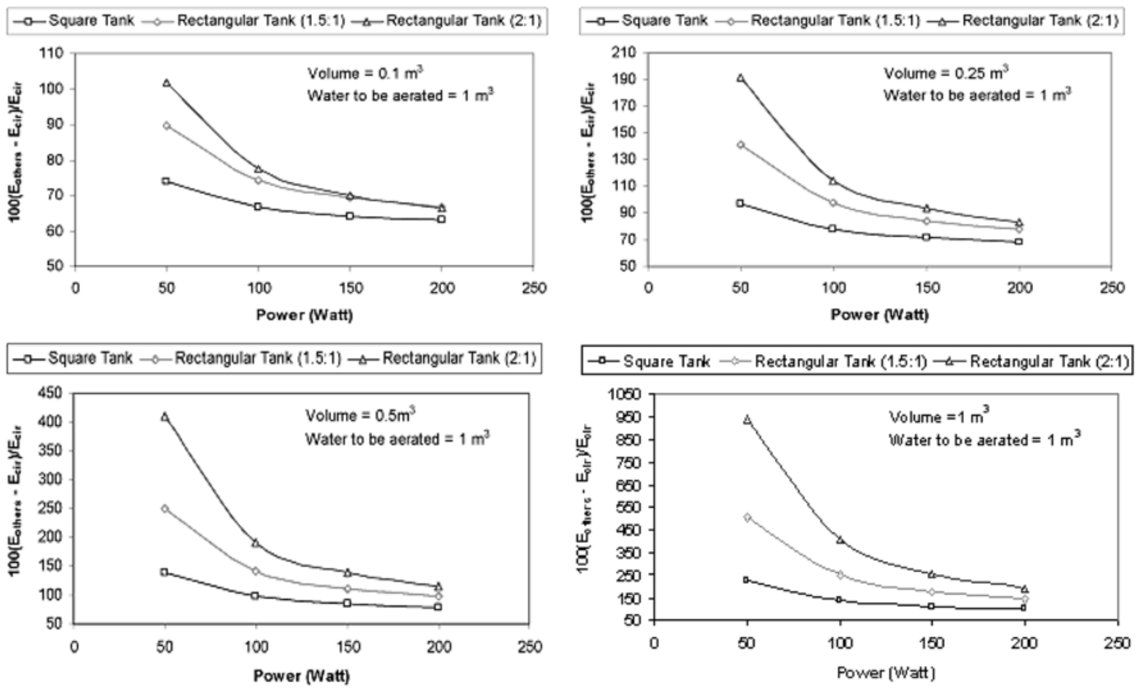

Fig. 6. Relative comparisons of different shaped surface aerators with circular tank.

particular shape, smaller tanks are more energy efficient than a bigger tank.

To choose the more energy-efficient shape, for each size, the percentage increase in energy has been calculated with respect to a circular tank and plotted in Fig. 6. It is found that the circular tanks are more energy efficient than any other shape analyzed in the present work.

As discussed, energy can be saved by employing smaller tanks than using a big tank, while aerating the same volume of water. Installing smaller tanks to aerate the same volume of water as a big tank is generally presumed to be an increase in construction and maintenance cost. Construction cost and maintenance cost generally depend upon the capacity of the aeration tank under construction. If the usual cost degression exponent of 0.7 [26] is assumed, the specific investment costs for a ten-time smaller tank are 20% higher than for a single big tank. By analyzing Fig. 5, we found that, for example, in the case of a square tank the energy saving by using smaller tanks varies between 30 to 68%, which is higher than the cost involved in construction and maintenance. Hence, it is more economical to use a number of smaller tanks than using a single bigger tank to aerate the same volume of water.

CONCLUSIONS

1. It has been re-established that k can also be simulated with the theoretical power per unit volume (X) for a given shape of the tank.

2. Based on the experimental investigations, new simulation equations to simulate actual power consumption in different shape surface aeration tanks have been proposed.

3. Based on the simulations equation, it can be concluded that smaller tanks are more energy efficient than a bigger tank, while aerating the same volume of water.

4. Smaller tanks are also time efficient.

5. Among all the shapes, the circular tanks are the most energy efficient.

NOMENCLATURE

A	: cross-sectional area of an aeration tank [L^2]
b	: width of the blade [L]
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
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]
I_1, I_2	: input current at no load and loading conditions, respectively
k	: $K_L a_{20} (\nu/g^2)^{1/3}$, non-dimensional oxygen transfer coefficient
k_r	: non-dimensional oxygen transfer coefficient for rectangular tanks
k_c	: non-dimensional oxygen transfer coefficient for circular tanks
k_s	: non-dimensional oxygen transfer coefficient for square tanks
$K_L a_T$	: overall oxygen transfer coefficient at room temperature T°C of water
$K_L a_{20}$	: overall oxygen transfer coefficient at 20 °C
L	: size of rectangular tank [L]
l	: length of the blade [L]
N	: rotational speed of the rotor with blades [1/T]
n	: number of rotor blades=6

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 : ND^2/ν, Reynolds number
V : volume of water in an aeration tank $[m^3]$
W : width or breadth of the surface aeration tanks [m]
R_a : armature resistance of DC motor [Ohms]
V_1, V_2: input voltage at no load and loading conditions respectively [Voltage]
X : $N^3D^2/(g^{4/3}\nu^{1/3})=F^{4/3}R^{1/3}$=theoretical power per unit volume parameter
ν : kinematic viscosity of water $[M^2/T]$
ρ_a : mass density of air $[M/L^3]$
ρ_w : mass density of water $[M/L^3]$

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