

Oxidation ditch process using curved blade rotor as aerator

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ABSTRACT: Oxidation ditch process is used to treat the municipal and domestic sewage. The untreated sewage generates fouling smell, harmful bacteria, etc. which is hazardous for public health and degrades the environment by liberating noxious gases. This paper examines the use of curved blade aerator for oxidation ditch process. The rotor, which controls the aeration, is the main component of the aeration process. Therefore, the objective of this study is to find out the variations in overall oxygen transfer coefficient and aeration efficiency for different configurations of aerators by varying the parameters like speed of aerator, depth of immersion and blade tip angles so as to yield higher values of overall oxygen transfer coefficient and aeration efficiency. Four aerators of different configuration were developed and fabricated in the laboratory and were tested for above mentioned parameters. A mathematical model is developed for predicting the values of k_a and aeration efficiency which has R^2 values of 0.97 and 0.99 for experimentally determined and calculated values. In laboratory studies, the optimum value of overall oxygen transfer coefficient and aeration efficiency were observed to be 10.33/h and 2.269 kg O₂/kWh for aerator speed of 48 rpm, 5.5 cm depth of immersion and 47° blade tip angle for curved blade aerator.

Key words: Dissolved oxygen, configurations, overall oxygen transfer coefficient, power, aeration efficiency

INTRODUCTION

Oxygen transfer, the process in which oxygen is transferred from the gaseous to liquid phase, is a vital part of the waste water treatment process (Metcalf and Eddy, 2004). Because of low solubility of oxygen and consequent low rate of oxygen transfer, sufficient oxygen to meet the requirement of aerobic waste does not enter through normal surface air water interface.

To transfer the large needed quantities of oxygen, additional interfaces are created by employing aeration process (Dudley, 1995; Gillot and Hedit, 2000). The creation of additional interfaces enhances the rate of oxygen transfer so that the dissolved oxygen level gets raised to allow aerobic bacteria to reduce biochemical oxygen demand of the effluent (Kumaran, 1992; Abusam *et al.*, 2002). To provide the required amount of oxygen, an aeration system is always needed. Aeration is usually the single largest cost in a wastewater treatment system comprising as much as 50-90 % of the total energy requirements of a secondary wastewater treatment plant (Wasner *et al.*, 1977). Dissolved oxygen (DO) concentration is one of the most important water quality parameters affecting the

quality of wastewater. Various types of aeration systems have been developed over the years to maintain the desired level of DO concentration in the wastewater as an effort to improve the energy efficiency of the oxygen mass transfer process. The three basic categories of aeration methods are :

1. Surface or mechanical aeration method which increase interfacial area by spraying water droplet into the air;
2. Diffused aeration methods which release air bubbles beneath the water surface;
3. Combined and turbine aeration methods which introduced large air bubble into water and reduced their sizes mechanically.

Out of these three, the mechanical surface aerators are widely used because they offer better efficiency, as well as convenience in operation and maintenance (Abusam *et al.*, 2001; Rao and Kumar, 2007). Further, oxygen transfer rate from gas to liquid phase is dependent on various factors for given method of aeration such as dynamic variables like speed, mixing intensity, turbulence and geometrical parameters like size and number of blades, depth of flow, etc. and physicochemical properties of the liquid (Nakasone and Ozaki, 1995). Even though the designer or operator can

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fix or control some of these parameters, successful design requires the knowledge of the effect of all such parameters on re-aeration rate. A wide variation in performance of aerators in terms of standard aeration efficiency was found, like, Taiwanese aerator (1.17 kg O₂/kWh), Japanese aerator (1.03 kg O₂/kWh) and Auburn university design (2.25 kg O₂/kWh) (Busch *et al.* 1974; Boyd and Watten 1989; Boyd, 1998; Colt, 2000a; 2000b). Ahmad and Boyd (1988) provided optimum designs of paddle wheels and Moulick *et al.* (2002) used similarity criteria in predicting the oxygen transfer performance of paddle wheel aerators. The centrifugal surface aerator along with the paddle wheel surface aerator had been traditionally used in wastewater treatment (Stukenberg *et al.*, 1977; ASCE, 1997). For proper aeration, i.e. proper mixing of DO throughout the water volume, Elliott (1969) suggested the aerator power-to-water volume ratio to be less than 0.1 kW/m³ while APHA (1980) mentioned that the above ratio should lie within 0.01-0.04 kW/m³. However, the water volume used in the aeration studies, conducted so far, has not been quantified properly. In the field of wastewater treatment, many investigators have successfully made use of the theory of dimensional analysis and obtained optimal geometric similarity of horizontal rotor aerators under different conditions (Schmidtke and Horvath 1977; Zlokarnik 1979; Ognean 1993). Rao (1999) presented the occurrence of scale effects due to the Reynolds and the Froude laws of the aeration performance under geometric similar conditions.

The criterion of power per unit volume was found to be very useful in geometrically similar systems for scale-up of horizontal rotor aerators (Horvath, 1984; Simha, 1991; Rao, 1999).

The present work focuses on development of unique configuration of aerator which should provide higher values of overall oxygen transfer coefficient and aeration efficiency with minimum power (P) consumption. The experimental apparatus of the oxidation ditch (OD) with different developed aerators were installed in the research laboratory of mechanical engineering department. The experimental work was completed on March 2008.

MATERIALS AND METHODS

The aeration experiments were conducted in oxidation ditch of dimension 2.5 m × 0.35 m × 0.2 m. The experimental setup mainly consists of an oxidation ditch, D.C. motor (0.25 H.P, 1 Amp) with variable speed controller, digital wattmeter (range 0-200 W), dissolve

oxygen meter, thermometer and digital tachometer. Curved blade aerator (CBR) was fabricated using impeller fans made up of fiber and used in centrifugal pump, available in market the size of 23 cm in diameter. 12 small fins the size of 5 cm × 3 cm are mounted on the fan disc in such a way that the effective diameter of the disc becomes 26 cm. A fiber pipe of 1.5 inch × 2 inch × 3 inch of appropriate length was cut into pieces such that 24 equal strips the length of 14 cm and width of 4 cm were yielded from each pipe. This was done to change the blade angles. A pair of fan disc was taken and thus the fabricated strips were screwed on projected fins of the fan discs. The strips were screwed in such a way that the projected length of the strip over the disc fins was 1.5 cm and thus the diameter of rotor was equal to 29 cm. This assembly of aerator was fastened tightly to the shaft and then fixed in the bearings provided on the collars or hubs. The depth of immersion (DOI) is varied from 4.8 cm to 7.2 cm and the speed is varied from 36 rpm to 60 rpm. The performance is evaluated for each kind of configuration of rotor aerator such as aerator's blade angle at different speeds and at different DOI with respect to power consumption.

Aeration test

The used deoxygenation-oxygenation procedure was the non steady state re-aeration test (APHA, 1980; Moulick *et al.*, 2005). The test water was deoxygenated with 10 mg/L of sodium sulphite, but cobalt chloride was not used during test, since it is considered hazardous to human health (Cancino, 2004). After maintaining DO between 0.0–0.1 mg/L for about 5 min both the aerator were put in operation at the same moment and at the same rotational speed and immersion depth.

Increase in DO concentration was measured by DO probe at the surface of water and at the half depth from the surface. The readings were taken at equal time intervals until DO increased from 0 % saturation to at least 90 % saturation. The dissolved oxygen saturation concentration (C_s) used for calculating the K₂a was estimated using the highest dissolved oxygen concentration from each test.

RESULTS AND DISCUSSION

Out of the various factors which may affect aeration or dissolve oxygen level such as time of aeration and depth of immersion, speed of aerator and blade tip angle mounted on the aerator are mainly considered. The temperature of the water was kept constant at 20 °C.

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For every set of observation, overall oxygen transfer coefficient $K_L a$, which is a measure of aeration, is computed and its behavior is studied with respect to other variables keeping the variables constant at that time. $K_L a$, the overall oxygen transfer coefficient, is the rate of oxygen transfer for a unit saturation deficit and is constant for a particular system of aeration.

Assessment of overall oxygen transfer coefficient of an aeration system is one of the most important factors. Underestimating the oxygen transfer rate results in an oversized system which may be energy intensive and expensive to operate. On the other hand, overestimating the oxygen transfer rate results in inadequate oxygen supply, which in turn, reduces efficiency.

Mathematical model for measurement of overall oxygen transfer co-efficient ($K_L a$) is defined as:

Aeration is transfer of air or oxygen in the water (Mueller *et al.*, 2002). The oxygen transfer through water is governed by Ficks' Law of diffusion and is a liquid film controlled process. In aeration, the rate of oxygen transfer was expressed earlier as:

$$dC/dt = K_L a (C_s - C) \quad (1)$$

Where, $K_L a$ is the rate of oxygen transfer for saturation deficit and it is constant for a particular

system of aeration. Therefore, this is referred as measurement of aeration and it forms a good basis of studying the behavior under various variables. This is employed in the studies in the unit of 1/min or 1/h.

The rate of oxygen transfer equation was converted into:

$$C_{(t-h)} = C_s e^{-K_L a t} + C_s (1 - e^{-K_L a t}) \quad (2)$$

This is comparable to the equation of straight line of the form:

$$Y = m.X + A \quad (3)$$

Thus, if a plot is drawn between $C_{(t-h)}$ and C_t , it would yield a straight line and slope of this line (m) represents the value of $e^{-K_L a t}$ from which $K_L a$ can be calculated. Similarly, the intercept on Y-axis (A) represents the term $C_s (1 - e^{-K_L a t})$ from which the value of C_s can be known. Thus, it clearly indicates that in order to determine the value of $K_L a$, it must be carried out at a uniform interval of time.

In the present study, the curves have been drawn between $C_{(t-h)}$ against C_t and h is taken as 15 min. The slope of this line is known and the value of $K_L a$ is calculated.

The plot between $C_{(t-h)}$ and C_t is obtained for different configurations of rotor aerator at different speeds, i.e. 36, 42, 48 and 60 rpm. The data generated from different

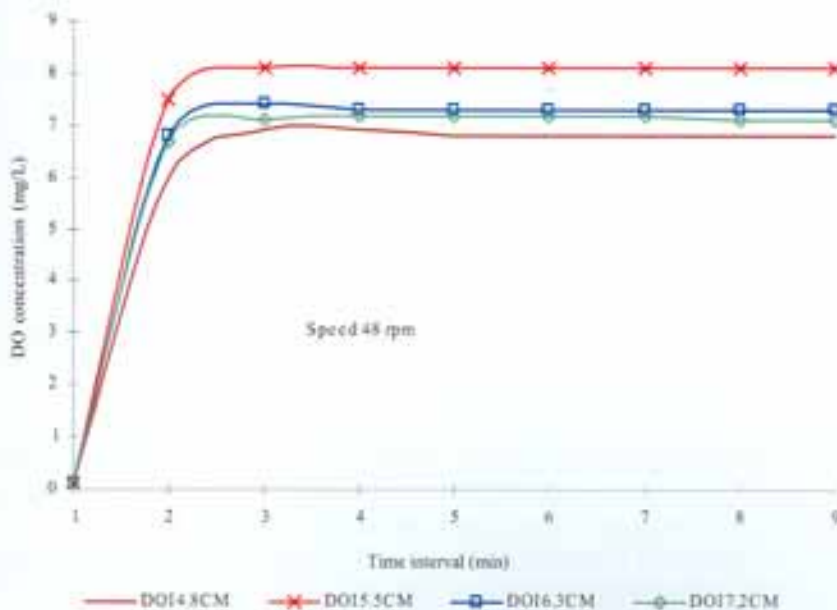


Fig. 1: Variation of DO with time for different depth of immersion and blade tip angle < 47°

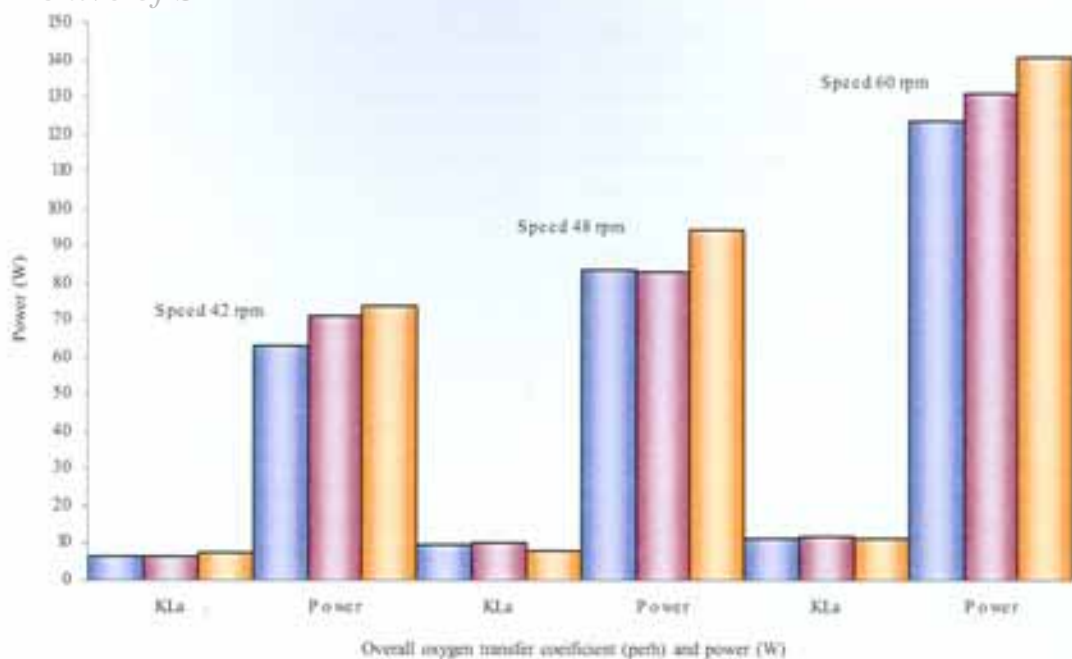


Fig. 2: Variation of $K_L a$ and power for CBR in various blade angles, Speeds and depth of immersion 5.5 cm

rotors followed different curves and indicated different values of $K_L a$ and aeration efficiency.

Variation of DO with time for various depths of immersion

Fig. 1 illustrates that the increase in DO concentration is very high in first 15 min, then it gradually attains a saturation value pertaining to the performance of the respective aerator. It is observed that the maximum increase in DO concentration, that is from 0.0 mg/L to 8.2 mg/L is attended by CBR aerator when the blade tip angle is 47° and the depth of immersion is 5.5 cm. All the curves were plotted at 48 rpm aerator speed. The literature cited by the author reveals that the optimum performance is generally obtained at blade angle of 45° . Therefore, the above blade angle is chosen.

Variation of $K_L a$ and power for various blade angles and speed

Fig. 2, which shows the variation of $K_L a$ and power for various blade angles and speed with respect to CBR aerator, considers the depth of immersion 5.5 cm as an optimum value. It is very clear from Fig.2 that as the power and speed increase, the corresponding values of $K_L a$ also increase. It is evident from the figure that at

a speed of 48 rpm, the power requirement is observed to be in the medium range that is 73.8 W, whereas there is a considerable increase in the value of $k_L a$ in the tune of 10.33/h. As the power consumption decreases below 73.8 W, the value of $K_L a$ also decreases correspondingly, which further decreases the aeration efficiency that is not acceptable as per the values quoted by the researchers.

When the power consumption increases beyond 73.8 W, there is a marginal increase in $K_L a$ value, but aeration efficiency drops sharply from 2.269 kg O_2 /kWh to 1.37 kg O_2 /kWh. Because of increase in speed of CBR aerator from 48 rpm to 60 rpm, it is observed that splashing of wastewater takes place outside the ditch, which deteriorates the surrounding atmosphere and thereby causing problems for working personals present at the plant. This may also create problems in driving mechanism as the motor is mounted below the ditch.

Variation in DO for various blade tip angle with time

The variation in DO for various blade tip angle with time is shown in Fig. 3.

This figure represents the curves plotted at 42 rpm and 5.5 cm depth of immersion. Three types of blade tip angles were tested which suggests that maximum

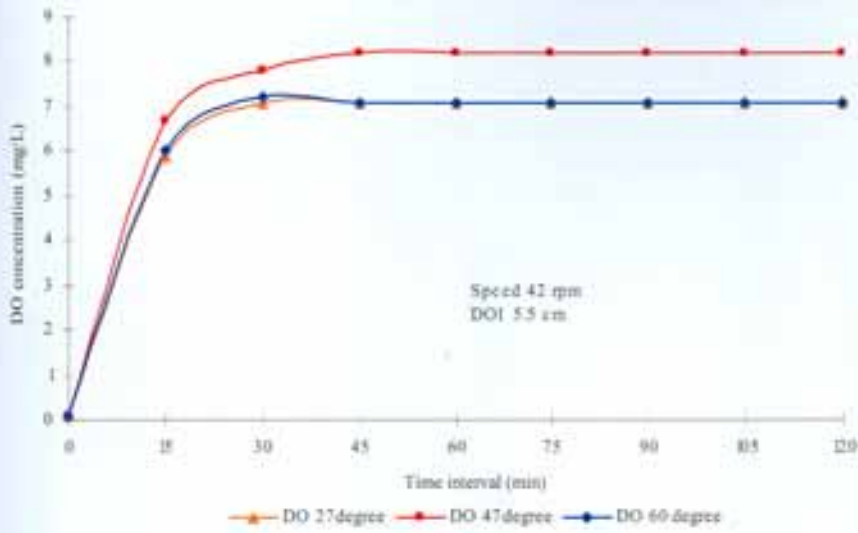


Fig. 3: Variation of DO Vs time for various angles of CBR, speed 42 rpm and DOI - 5.5 cm

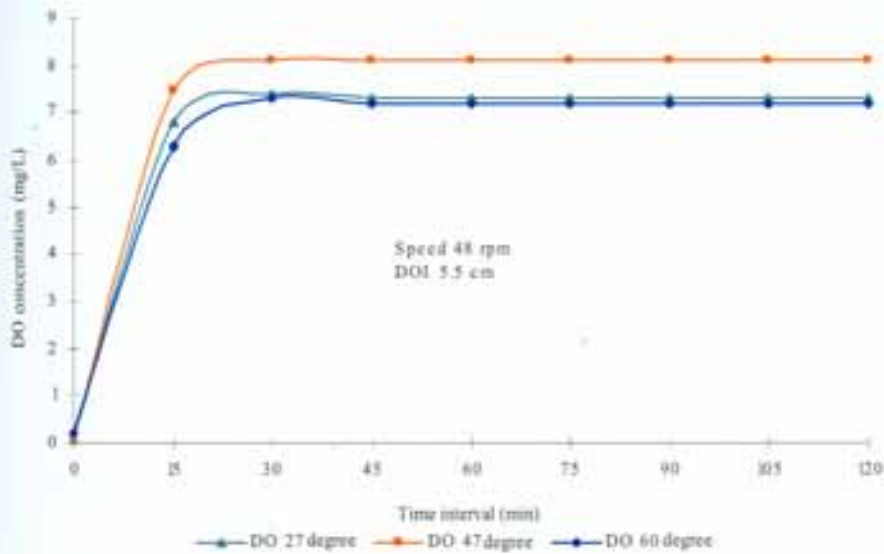


Fig. 4: Variation of DO vs. time in various angles of CBR, speed 48 rpm and DOI - 5.5 cm

DO concentration is achieved when the blade tip angle is at 47°. With this configuration, DO level of 8.2 mg/L is attended in 45 min and thereafter the DO concentration curve remains constant which indicates that the saturation deficit of oxygen is met.

Figs. 4 and 5, which represent the same plot as above, follow the similar trend as that of Fig. 3.

Combined analysis of all the three figures reveals that the optimum performance is recorded at blade tip angle of 47°.

Plot between $C(t+h)$ and Ct for determination of k_1a
As stated earlier, the plot between C_{t+h} and C_t will yield a straight line. The slope of the line is known and

the value of $K_L a$ is calculated. The time interval (h) is maintained as 15 min (Fig. 6). The data obtained for different depths of immersion produced different curves. It is quite evident from the figure that the curve obtained for 5.5 cm depth of immersion, 48 rpm speed and 47° blade tip angle yielded maximum value of $K_L a$.

The variation in $k_L a$ and required power is presented

in Table I. It also suggests that depth of immersion is directly proportional to the power consumption.

On the other hand, the increase in $K_L a$ is not so significant. As a golden mean, the value of $K_L a$ is finally taken as 10.33/h when the required power is 73.8 W and it is observed that the value of AE (aeration efficiency) is the highest for these values.

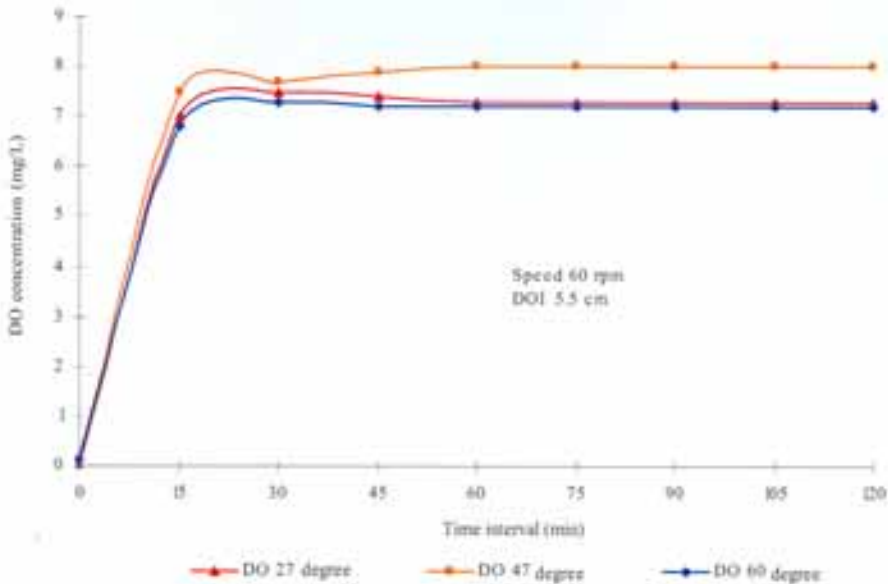


Fig. 5: Variation of DO vs. Time for various angles of CBR, speed 60 rpm and doi - 5.5 cm

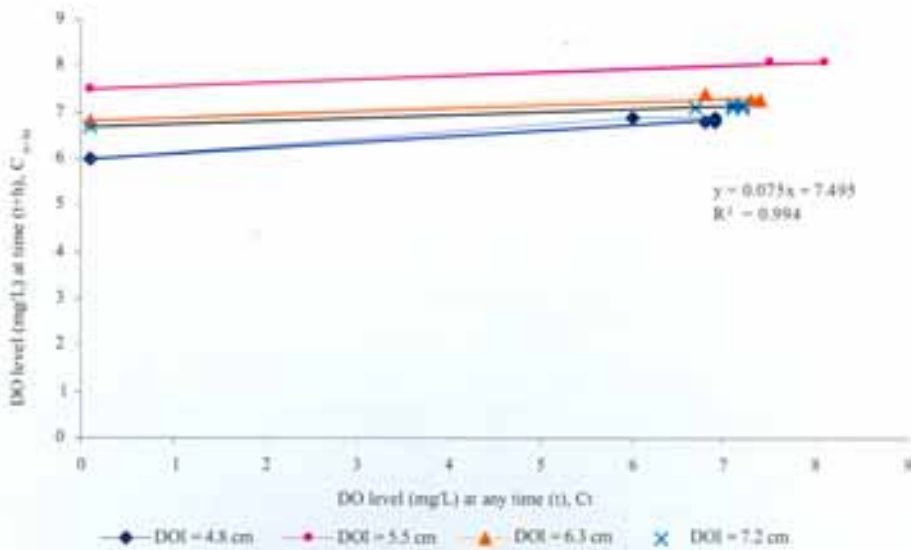


Fig. 6: DO level at time ($t+h$) vs. DO level at time (t) for determination of $K_L a$

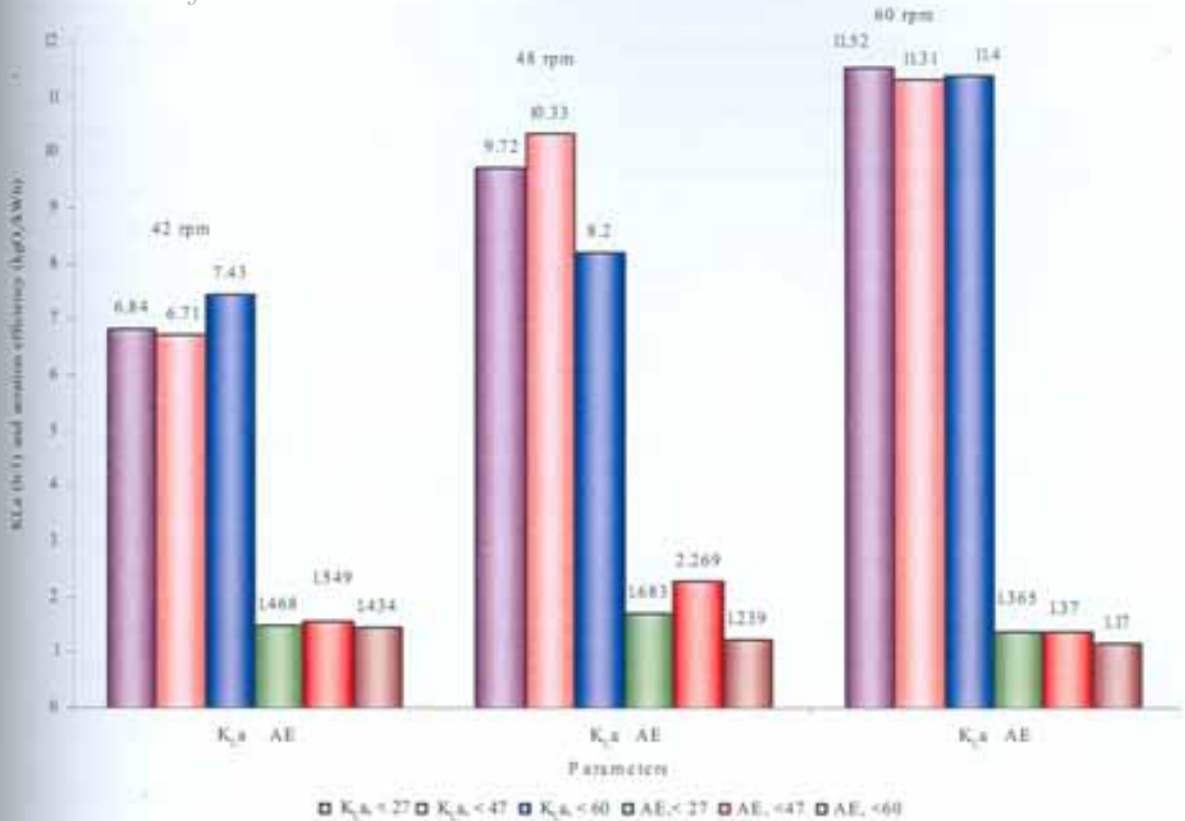


Fig. 7: Variation in $K_{L,a}$ and AE with different blade angles and speeds

Variation in aeration efficiency with respect to power and $K_{L,a}$

The performance of aerator is better judged by a parameter known as AE which is defined as the amount of oxygen transferred per unit power. Fig. 7 describes the variations of $K_{L,a}$ and AE for various blades tip angles and speeds. Out of three tested configurations, it can be seen that at 48 rpm and 47° blade tip angle, the optimum value of $K_{L,a}$ is observed to be 10.33/h and recorded the highest value of AE that is 2.269 kgO₂/kWh. This is because of the AE which is the function of power and as stated earlier the required power increases with increase in speed and depth of immersion. Even though the values of $K_{L,a}$ at 60 rpm and 27°, 47° and 60° blade tip angles are more than that of 48 rpm, the power required to attend the same is quite higher. Therefore, the AE values for above configuration and speed decreases drastically to 1.365, 1.37, 1.17 kg O₂/kWh as against 1.683, 2.269 and 1.239 kgO₂/kWh at speed of 48 rpm.

Developed model

In this paper, the attempts are made to correlate the data generated in laboratory and the data calculated using mathematical model. In this phenomenon, the author has used two models. From the study of the data generated in laboratory, the attempts are made to identify the dependent and independent variables and using Buckingham π theorem concept, these variables are interrelated by developing dimensionally homogeneous equations.

Equations may be used with confidence for predicting the $K_{L,a}$ and power and can be considered as design equations for CBR aerator.

$$K_{L,a} = 0.000746 \left[(N)^{1.768} \left(\frac{h}{D} \right)^{1.038} (\alpha)^{0.031} \right] \quad (4)$$

Where,

$K_{L,a}$: Overall oxygen transfer coefficient/ min

- N: Speed of aerator in rpm
- h/D: Ratio of depth of immersion to the diameter of aerator.
- α : Blade tip angle in degree.
- P: Required power in watts (W).

The calculated values using above models yielded good coefficient of determination (R^2) with the experimentally observed values which are in good agreement with standard error of estimation. A program

in computer programme C++ (CPP) is developed to inter the various influencing parameters mentioned above and are solved by multiple linear regression analysis methods. Figs. 8 and 9 is the plot between experimentally determined values and calculated values from the model formulated for $K_L a$ and power, respectively.

It has been estimated that the simulation of Eqs. 1 and 2 predict the values of $K_L a$ and power with an

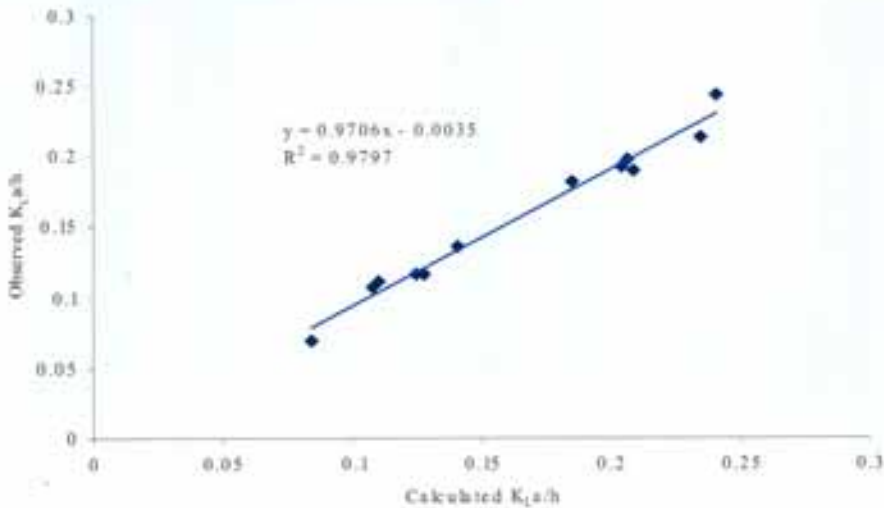


Fig. 8: Relationship between observed and calculated values of $K_L a$

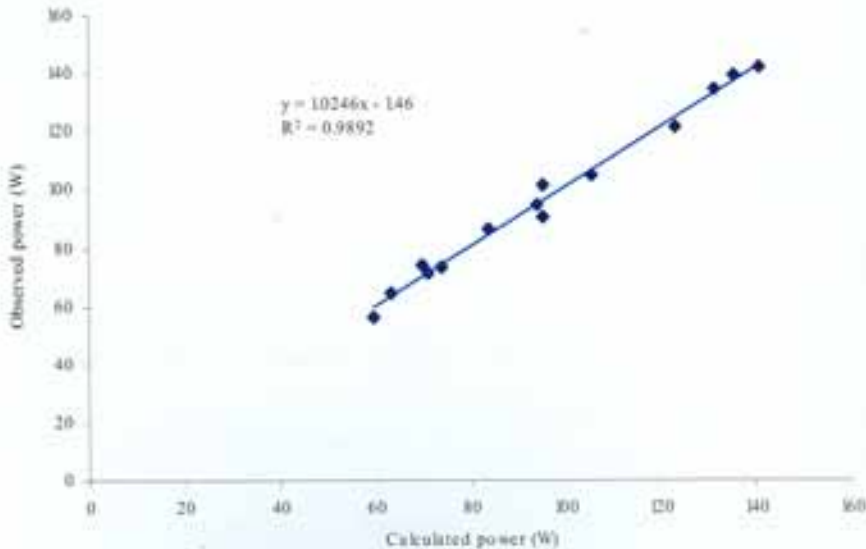


Fig. 9: Relationship between observed and calculated values of power (P)

$$P = 0.0694 \left[(N)^{2.062} \left(\frac{h}{D} \right)^{1.1412} (\alpha)^{0.1942} (K_{La})^{-0.1729} \right] \quad (5)$$

average standard error of estimation of 0.0164 and 7.66 and with R² values of 0.9797 and 0.9892, respectively, when compared with experimentally determined values.

Thus, Eqs. 4 and 5 are justifiable by taking into consideration all of the experimental errors.

Therefore, above equations may be used with confidence for predicting the k_La and power and can be considered as design equations for CBR aerator.

CONCLUSION

Considering the influence of various parameters simultaneously, it has been observed that to get the maximum value of overall oxygen transfer coefficient (K_La), following conclusion is justified:

1. The value of overall oxygen transfer coefficient (K_La) is proportional to the turbulence created by the aerator motion, i.e. the higher the aerator speed, the greater is the turbulence which results in enhanced value of K_La.
2. The value of overall oxygen transfer coefficient (K_La) and aeration efficiency depends upon the relative depth of immersion of the aerator in the liquid. At 5.5 cm depth of immersion, the maximum value has been obtained for AE..
3. The aeration time may be chosen between 30 to 60 min. The lower limits are chosen for the case of 5.5 cm depth of immersion, higher speed and for blades tip angle of 47° on the rotor, whereas the higher limit is for the case of lower depth of immersion, lower speeds and for blades angles more or less than 47°.
4. The aeration efficiency which compares the performance of aerators mainly depends on the power consumption of the aerator. In some cases, it is found that even though the value of K_La is higher, the aeration efficiency drops drastically. This is mainly because of the increase in power consumption for that particular set up. For example, at 60 rpm, 6.3 depth of immersion and blade tip angle of 27°, the value of K_La is found out to be 12.87/h, but the aeration efficiency drops

drastically to 1.385 kg O₂/kwh. This is mainly because the power consumption for this configuration, speed and depth of immersion is 135.3 W. As against, at 48 rpm, 5.5 depth of immersion and blade tip angle of 47° the value of K_La is found out to be 10.33/h., but the aeration efficiency increases sharply to 2.269 kgO₂/kwh, because for this configuration, the power consumption is 73.8 W.

5. A simplified simulation of Eqs. 1 and 2 are developed, which can be used to calculate the values of k_La and power for given diameter of aerator (D), depth of immersion (h) blade tip angle (α).

Finally, it can be concluded that aeration can be made more effective by optimizing various factors affecting it like speed of aerator, depth of immersion, blades angles, etc. Also, overall oxygen transfer coefficient (K_La) and aeration efficiency gives an excellent measure of oxygen transfer efficiency in conjunction with power required by eliminating combined effect of saturation dissolved oxygen level and initial lag in actual oxygen transfer.

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Table 1: Variation Of K_La and power with depth of immersion for speed 48 rpm

No.	Depth of immersion (cm)	K _L a /h	Power (W)
1	4.8	8.414	69.9
2	5.5	10.33	73.8
3	6.2	10.58	93.5
4	7.2	10.93	136

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