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Aeration Cost of Propeller-Aspirator Pump Aerator at Optimum Geometric and Dynamic Conditions

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***Abstract*—Aeration test was conducted in a brick masonry tank of dimension 5 m × 3 m × 1.5 m to evaluate the optimum geometric condition of Propeller –aspirator pump aerator, i.e., positional angle of propeller shaft (α) and dynamic condition, i.e., rotational speeds of propeller shaft (N) and submergence depth of propeller shaft (d). The results indicated a maximum SAE at $\alpha = 75°$. Keeping the geometric condition constant ($\alpha = 75°$), aeration experiments were further conducted at different rotational speeds of propeller shaft, N ranging from 1420 to 2840 rpm with an interval of 355 rpm and different values of submergence depth, d from 140 to 460 mm with an interval of 80 mm to evaluate the effect of dynamic conditions on aeration characteristics. Non-dimensional numbers related to standard aeration efficiency (SAE) and wire power (P) termed as E and Ne respectively, were introduced. It was found that E and Ne could be well correlated with Froude number (Fr) and Reynolds number (Re) respectively. Power consumption and Standard oxygen transfer rate (SOTR) of Propeller-aspirator pump aerator were evaluated at optimum geometric condition ($\alpha = 75°$) and optimum dynamic conditions (N = 2840 rpm and d = 0.14 m). Further, aeration cost (Rs. 37.73 / kg O_2) of propeller-aspirator pump aerator was estimated for tank volume of 100 m^3.**

***Index Terms*—Aeration cost, dimensionless numbers, positional angle, standard oxygen transfer rate.**

I. INTRODUCTION

Dissolved oxygen (DO) is considered to be the most vital water quality parameter in water and wastewater treatment. Atmospheric oxygen gets dissolved in water through diffusion process. As diffusion is a very slow process, aerators are generally used to maintain desired level of DO in water body. The aerators consume around 60% of the total energy consumption in a typical activated sludge wastewater treatment plant [1]. Presently diffused-air and surface aerators are being popularly used in wastewater treatment plants as well as in lakes and aquacultural ponds.

Various types of aerators have been developed over the years to increase the dissolve oxygen (DO) concentration in the pond. Vertical pump sprayers, propeller-aspirator-pumps, paddle wheels, and diffused-air systems are probably the most widely used aerators in the field of waste water treatment and aquaculture [2]. Paddle wheel aerators were found to be the most efficient aerator in terms of aeration efficiency and circulation [3], [4]. Circular Stepped Cascade Pump Aerator (CSCP) has more brake standard aeration efficiency than the other aerators [5]. However, in small ponds, vertical pump aerators, propeller-aspirator-pump aerators, and diffused-air aerators are more commonly used than the paddle wheel aerators due to economic reason [2]. The propeller-aspirator pumps (1-3 HP) are the least- cost system for small sizes of ponds when compared to other aeration systems [6].

The propeller-aspirator-pump aerator draws atmospheric air through a rotating hollow shaft which is connected to an electric motor at one end and a propeller at the other end which is submerged under water. Basically the propeller accelerates the water to a velocity high enough to cause a drop in pressure over the diffusing surface which forces the air to pass through a diffuser in the hollow shaft and enter into the water as fine bubbles. The fine bubbles thus formed are thoroughly mixed with the water due to the turbulence created by the propeller. The aeration performance of a propeller-aspirator-pump aerator depends on the positional angle, submergence depth and the rotational speed of propeller shaft and the design features of the propeller. Aeration cost depends on aeration efficiency of aerator. Keeping in view the above points, the present study was investigated to determine the effect of various geometric and dynamic conditions on aeration cost of a propeller-aspirator pump aerator.

II. THEORETICAL CONSIDERATIONS

The standard oxygen transfer rate (SOTR) of an aerating device is defined as the mass of oxygen that the device can introduce into a body of water per unit time at standard conditions (20°C water temperature, 0 mg/l initial DO concentration, one atmospheric pressure and clear tap water [7]. It is an important parameter used to compare aerators.

$$SOTR = K_L a_{20} \times (C^* - C_0) \times V = K_L a_{20} \times 9.07 \times V \times 10^{-3} \tag{1}$$

where, SOTR = standard oxygen transfer rate (*kg O_2/h*), $k_L a_{20}$ = overall oxygen transfer coefficient at 20°C (h^{-1}) = $k_L a_T / \theta^{T-20}$, $k_L a_T$ = overall oxygen transfer coefficient at T℃ (h^{-1}), θ = temperature correction factor = 1.024 for pure water, C× = saturation value of DO at test conditions (mg/l), C_0 = DO concentration at time t = 0 (mg/l), 9.07 = saturation value of DO (mg/l) at 20 ℃ and one atmospheric pressure and V = aeration tank volume (*m^3*). A better comparative parameter is the standard aeration efficiency (SAE), which is defined as the SOTR per unit of power [8].

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$$SAE = SOTR/P \tag{2}$$

The total aeration cost (TAC) can be quantified by determining total fixed cost (TFC) and energy cost (EC) associated with aeration devices.

$$TAC = TFC + EC \tag{3}$$

Total fixed cost includes the depreciation cost (DC), maintenance cost (MC), and bank interest (BI).

Energy cost of aeration can be calculated by following equation.

$$EC = ER \times P \times t \tag{4}$$

where, ER = electricity rate (*Rs./kw h*), P = power consumption (*kw*), t = time requires for aeration (*h*) = $[(C_a \times 10^{-3} \times V)/SOTR]$, C_a = concentration of oxygen to be added (mg/l)

Total aeration cost (Rs.) can be estimated by following equation:

$$TAC = t[\, ER \times P + \left(\frac{TFC}{O_h}\right)\,] \tag{5}$$

where, O_h = operating hour of aerator per year.

A. Dimensional Analysis

The basic dimensional analysis of aeration process has been presented by many investigators [9]–[14]. The main parameter of the absorption process is the absorption rate coefficient $k_L a_{20} \times V$, can be expressed as [12].

$$K_L a_{20} \times V = SOTR/\Delta C \tag{6}$$

where, ΔC = DO deficit = C× - C0

The functional relationship between SOTR/ΔC and the variables may be expressed as:

$$SOTR/\Delta C = f_1(\alpha, d, V, N, g, \rho_a, \rho_w, \nu_w, \sigma_w) \tag{7}$$

where, α = positional angle of propeller shaft; *d* = submergence depth of propeller shaft i.e., the distance between the water surface and the water suction hole; *V* = volume of water in the tank; *N* = Rotational speed of propeller; *g* = acceleration due to gravity; ρ_a = mass density of air; ρ_w = mass density of water; ν_w = kinematic viscosity of water and σ_w = surface tension of water.

Based on Buckingham Π theorem, (7) may be expressed as follows:

$$Y = f_2[\alpha, \frac{V}{d^3}, \frac{N^2 d}{g}, \frac{\rho_a}{\rho_w}, \frac{Nd^2}{\nu_w}, \frac{\sigma_w}{g\rho_w d^2}] \tag{8}$$

where, Y = absorption number = $SOTR \times (\nu / g^2)^{1/3} / (\Delta C \times d^3)$, $N^2 d/g$ = Froude number *(Fr)*, Nd^2/ν_w = Reynolds number *(Re)* and $\sigma_w / (g\rho_w d^2)$ = Weber number (W). As the aeration tests were performed on a practically identical system (pure water-air), ρ_a/ρ_w and W remain constant in the aeration tank and subsequently can be omitted from (8).

Aerator power to water volume ratio should be less than 0.1 kW/m^3[15]. Thus in the present study the power consumption of the propeller and water volume were chosen to satisfy the above condition. Hence, the term V/d^3 is also omitted from (8). Thus, simplification of (8) results

$$Y = f_3[\alpha, Fr, Re] \tag{9}$$

The dimensionless quantity, α govern the geometrical similarity of the system and the dimensionless quantities, Fr and Re govern the dynamic similarity of the aeration system.

The power consumption P of a given propeller-aspirator pump aerator is, in general, dependent upon the same parameters as the term SOTR/ΔC. In a similar way, with the help of dimensional analysis the following relationship for power consumption, P is obtained:

$$Ne = f_4[\alpha, Fr, Re] \tag{10}$$

where

$$Ne = Power\ No = P/(\rho_w \times N^3 \times d^5) \tag{11}$$

SAE was also expressed in a non-dimensional form (E) by dividing the absorption number (Y) with power number (Ne) as follows: [13-14].

$$E = Y/Ne = (SOTR/P) \times (\nu_w/g^2)^{1/3} \times (\Delta C \times d^3)^{-1} \times \rho_w \times N^3 \times d^5$$

or

$$E = SAE \times (\nu_w/g^2)^{1/3} \times (\Delta C)^{-1} \times \rho_w \times N^3 \times d^2 \tag{12}$$

or

$$E = f_5[\alpha, Fr, Re] \tag{13}$$

III. MATERIALS AND METHODS

A. Experimental Setup

The aeration experiments were conducted in a brick masonry tank of dimension 5 m × 3 m × 1.5 m. The test aerator consisted of a propeller-aspirator pump aerator operated by a 2 HP, 3 phase high speed induction motor (22 kg, 440 V and 3.3 A) of 2840 rpm. The specifications of the propeller are as follows: i) material – high density polyethylene (HDP), ii) number of paddles – 4, iii) total diameter – 100 mm, iv) inlet and exit angles – 15° and 25°, v) inner and outer width of paddles – 27 and 50 mm and vi) length of paddles – 30 mm. The propeller is attached with the motor through a 700 mm long shaft already fixed with the motor. Aerator was mounted at the centre of the tank on supports fabricated by using four numbers of 40 mm diameter and 1.60 m long G.I pipes (Fig. 1).

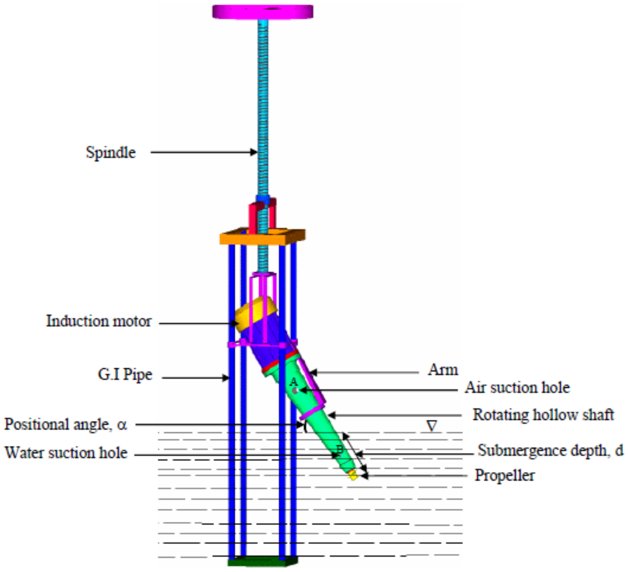

Fig. 1. Experimental setup for testing of propeller-aspirator pump aerator

As the maximum speed of the motor is 2840 rpm and it was desired to evaluate its performance at different speeds, a frequency based speed controller was connected to the motor by a 15 m, 3 phase electric cable to control the speed to desired values.

The positional angle of propeller shaft α (inclination of the shaft with the horizontal water surface) can be changed by changing the position of an arm attached to the supporting structure. The atmospheric air enters through the hole A of the propeller shaft due to suction created by the aspirator. Water drawn through the hole B is thoroughly mixed with the air and is finally splashed into the atmosphere. Thus aeration of the water takes place. The depth of submergence (d) can be changed by rotating the spindle of the structure.

B. *Aeration Test*

Oxygen transfer tests were conducted in a concrete tank using clean tap water. Initially the tap water was deoxygenated using 0.1 mg/l of cobalt chloride and 10 mg/l of sodium sulphite for each 1 mg/l of dissolved oxygen present in water [2]. Thereafter the aerator was operated at the desired conditions as per the experimental design. The dissolved oxygen measurements were taken using two YSI Professional Plus DO meters. Both the DO metres were positioned at mid distances between the propeller and the opposite corners of the tank, at 0.20 m below the water surface [16]. Readings were taken till DO increased from zero to about 80% saturation. At least twenty DO measurements at equal time intervals were taken. The DO deficit was computed for each time. The slope of the best fit line obtained by plotting natural logarithms of DO deficits on Y-axis against the time of aeration on X-axis gave the oxygen transfer coefficient at the test water temperature which was adjusted to 20^{o}C using temperature correction factor. Finally the values of SOTR and SAE were calculated using (1) and (2) respectively.

C. *Effect of Geometric Condition on Oxygen Transfer*

To obtain the optimum geometric condition i.e., positional angle of propeller shaft (α), aeration tests were conducted on propeller-aspirator pump aerator positioned at five different positional angles (α): 90°, 75°, 60°, 45° and 30° keeping the dynamic conditions (rotational speed of the shaft, N and submergence depth of the propeller, d) constants. The rotational speed of the shaft (N) and submergence depth of the propeller (d) were fixed at 2130 rpm and 300 mm respectively. In each case, the volume of water to be aerated (V) was maintained to satisfy: $P/V \le 0.1$ kW/m^3 [15].

D. *Effect of Dynamic Conditions (Fr and Re) on Oxygen Transfer and Power Consumption*

Keeping the optimized value of α (obtained from previous set of experiments) constant, N and d were varied simultaneously to find out the effect of different dynamic conditions on E and Ne. The ranges of variation of N and d were from 1420 to 2840 rpm (at an interval of 355 rpm) and 140 to 460 mm (at an interval of 80 mm) respectively amounting to 25 sets of experiments.

E. *Aeration Cost of Propeller-Aspirator Pump Aerator*

Aeration cost of propeller-aspirator pump aerator was estimated at five different level of C_a from 4 mg/l to 8 mg/l (at an equal interval of 1 mg/l) for 100 m^3 volume of tank.

Aeration cost of aerator depends on the SOTR, power consumption, capital cost, depreciation cost, operating hours per year, and salvage value, useful life of aerator and amount of oxygen concentration to be added.

The relationship among dynamic conditions (Fr and Re), oxygen transfer (E) and power consumption (Ne) were developed. Further, E and Ne were replaced in term of SAE and P by the (12) and (11) respectively to find out the optimum values of N and d. Keeping the optimum values of N and d in (11), power consumption (P) was estimated. Then, optimum SOTR of aerator was calculated using (2).

Capital cost of Propeller-aspirator pump aerator was Rs. 30000. Annual depreciation cost was estimated using the straight line method [6].

$$DC = CC/U_f[1-(SV/100)] \qquad (14)$$

where DC = depreciation cost (Rs./year), CC = capital cost of aerator (Rs.), U_f = useful life of aerator (year), SV = salvage value of aerator (% of capital cost)

The useful life of aeration devices was estimated based on the materials used in the frame and the motor. Useful life of propeller-aspirator pump aerators was estimated for 3 years [6]. Operating hour per day (12 h/day) and maintenance cost (10% of capital cost per year) were estimated for propeller-aspirator pump aerator based on information obtained from manufacturer of electric motors used in aerator.

IV. RESULTS AND DISCUSSION

A. *Determination of Optimum Positional Angle (α) of Propeller Shaft*

Keeping N (2130 rpm) and d (300 mm) as constants, aeration experiments were conducted at different values of positional angles of propeller shaft (α): viz. 30°, 45°, 60°, 75° and 90°. The experimental details along with their results are presented in Table I.

TABLE I: PERFORMANCE OF THE PROPELLER-ASPIRATOR PUMP AERATOR AT DIFFERENT VALUES OF POSITIONAL ANGLE OF PROPELLER SHAFT

α (°)	T (°C)	k_La_T (h^{-1})	k_La_{20} (h^{-1})	SOTR (kg O_2/h)	SAE (kg O_2/ kW h)	E
30	27.0	0.882	0.747	0.061	0.153	0.0117
45	25.3	1.278	1.127	0.093	0.232	0.0178
60	25.6	1.284	1.124	0.092	0.230	0.0176
75	24.8	1.530	1.365	0.112	0.280	0.0214
90	25.3	1.422	1.254	0.103	0.258	0.0198

It is seen from Table I. that the values of k_La_{20}, SOTR, SAE and E increase with the increase in α up to 45 °, but there is a marginal decline in the values between 45 ° and 60 °. No satisfactory explanation can be offered for this discrepancy. However, after 60 ° positional angle, the values increase up to 75 ° where they attend the peak values. After that all the values decrease with the increase in the angle up to 90 °. A typical plot showing the variation of E with α is shown in Fig.

2. It is seen from the figure that all the points could be well fitted by a second order polynomial equation with the variation of α in the range of 30 ° to 90 °.

$$E = -4 \times 10^{-6} \times \alpha^2 + 0.0006 \times \alpha - 0.0017 \quad (15)$$

From the developed relationship, the value of α, at which E reaches the peak value, is found to be 75°. In this case, E is directly proportional to SAE as N and d were kept as constants. Hence the optimum positional angle corresponds to maximum SAE also.

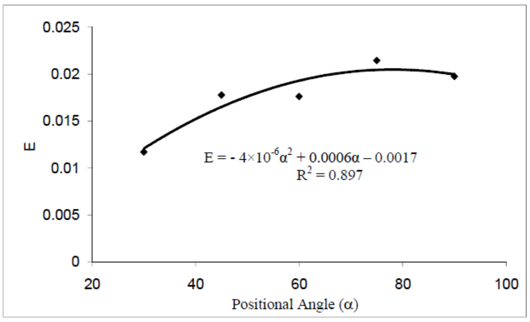

Fig. 2. Variation of E with positional angle of propeller shaft

B. Effect of Dynamic Conditions (Fr and Re) on E

The relationship between E and Fr is shown in Fig.3. It can be seen from Figure that the data points for different submergence depths are close to each other and could be well fitted by the following equation:

$$E = -0.0002 \times Fr^2 + 0.876 \times Fr/(5.28 + 0.0068 \times Fr + 3310/Fr) \qquad R^2 = 0.976 \quad (16)$$

However, no unique relationship could be established between Re and E.

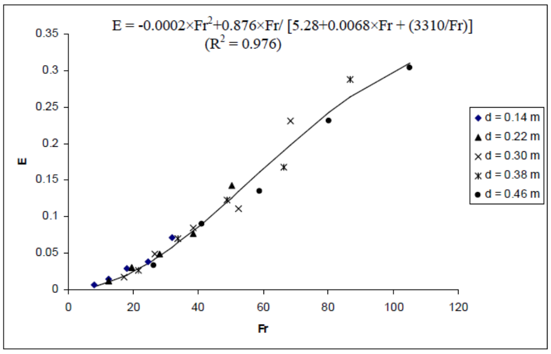

Fig. 3. Effects of Froude criterion on E

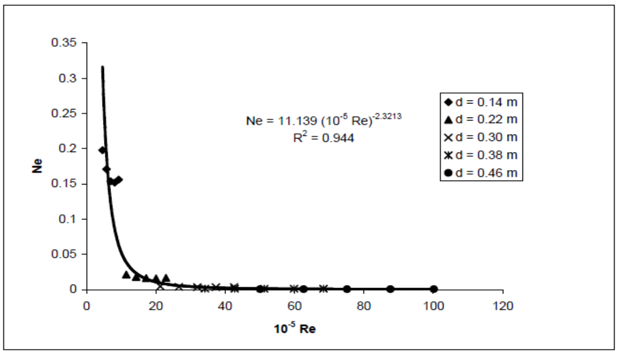

Fig. 4. Effect of Reynolds criterion on Ne.

C. Effect Dynamic Conditions (Fr and Re) on Ne

The relationship between Ne and Re is shown in Fig.4. It can be seen from Figure that the data points for different submergence depths are close to each other and could be well fitted by the following equation:

$$Ne = 11.139 \times (10^{-5} Re)^{-2.32} \qquad R^2 = 0.944 \quad (17)$$

However, no unique relationship could be developed between Fr and Ne.

D. Optimum Dynamic Condition for Propeller-Aspirator Pump Aerator

To arrive at a particular dynamic condition that yields the maximum SAE, E was expressed in terms of SAE as shown in (12). Assuming the water temperature to be 20 ℃, value of g as 9.81 m/s^2, ΔC as 9.07 mg/l, ρ_w as 1000 kg/m^3, equated to (16) and the following expression is obtained:

$$SAE = [-0.0002 \times Fr^2 + 0.876 \times Fr/(5.28 + 0.0068 \times Fr + 3310/Fr)/[240.59 \times N3 \times d3] \quad (18)$$

The above equation is valid subject to $7.993 \leq Fr \leq 105.057$. Substituting Fr = N^{2}d/g in the above equation, an unconstrained nonlinear programming was followed using WinQSB (version 1.00) to determine the values of N and d at which SAE is maximum.

The maximum value of SAE was found to be 0.42 kg O$_2$/kW h at a submergence depth of propeller shaft, d = 0.14 m and rotational speed of N = 2837.59 ≈ 2840 rpm. To calculate the power consumption, (17) can be rewritten by substituting $Ne = P/(\rho_w N^3 d^5)$, $Re = Nd^2/\nu_w$ (assuming water temperature = 20°C), ρ_w = 1000 kg/m^3, N = 2840/60 = 47.33 rps, d = 0.14 m and $\nu_w = 1 \times 10^{-6}$m^2/s as shown below.

$$P = 11.139 \times \rho_w N^3 d^5 \times (10^{-5} Nd^2/\nu_w)^{-2.32}$$

or

$$P = 11.139 \times 1000 \times 47.33^3 \times 0.14^5 \times [10^{-5} \times 47.33 \times 0.14^2/(1 \times 10^{-6})]^{-2.32}$$

or

$$P = 360.81\ W = 0.361 kW$$

Thus, SOTR = SAE × P = 0.42 × 0.361 = 0.15 kg O$_2$ /h

Therefore, a maximum SAE of 0.42 kg O$_2$/kW h and corresponding SOTR of 0.15 kg O$_2$/h can be obtained by operating the propeller-aspirator-pump aerator at a submergence depth, d = 0.14 m and rotational speed, N = 2840 rpm.

E. Fixed cost of Propeller-Aspirator Pump Aerator

TABLE II: DEPRECIATION COST, MAINTENANCE COST, BANK INTEREST AND FIXED COST OF PROPELLER-ASPIRATOR PUMP AERATOR

Depreciation cost (Rs./year)	Maintenance cost (Rs./year)	Bank interest (Rs./year)	Total fixed cost (Rs./h)
9000	3000	3300	3.49

Total fixed cost (Rs./h) was calculated for propeller-aspirator pump aerators (Table II) and 10% of capital cost was considered as a salvage value of aerator to estimate the depreciation cost. The major fixed cost was depreciation cost, while maintenance cost and bank interest were much lower percentage of total fixed cost. However, per year 11 % of capital cost was considered for bank interest. It is observed that TFC is directly proportional to capital cost of propeller-aspirator pump aerator.

F. Effect of C_a on Total Aeration Cost

EC and TAC of propeller-aspirator pump aerator for different values of C_a were calculated using the (4) and (5) respectively, details are presented in Table III. It can be seen from Table that TAC is uniformly increases with the increase in Ca.

Based on commercial rate of electricity as Rs.6/kW h, EC was calculated. Total aeration cost for 100 m^3 volume of tank ranged from Rs. 15.09 to Rs. 30.18 for different level of C_a (4 mg/l to 8 mg/l). TFC of propeller-aspirator pump aerator was 61.76 % of TAC. It shows that capital cost of propeller-aspirator pump aerator is found more significant parameter than EC in case of 100 m^3 volume of tank. Further, aeration cost per kilogram of oxygen was calculated as Rs.37.73*/kg O_2*.

TABLE III: AERATION COST OF PROPELLER –ASPIRATOR PUMP AERATOR FOR DIFFERENT VALUES OF CONCENTRATION OF OXYGEN TO BE ADDED

C_a (mg/l)	TFC (Rs.)	EC (Rs.)	TAC (Rs.)
4	9.32	5.78	15.09
5	11.64	7.22	18.86
6	13.97	8.66	22.64
7	16.30	10.11	26.41
8	18.63	11.55	30.18

V. CONCLUSION

A propeller-aspirator-pump aerator was tested with an aim toevaluate the optimum conditions that would result in maximum efficiency of the aerator, further, aeration cost was estimated at optimum condition. Based on dimensional analysis, nondimensional numbers, E and Ne were proposed for standard aeration efficiency (SAE) and wire power (P), respectively. Keeping the dynamic conditions constant, experiments were conducted at different positional angles (a) of the propeller shaft. From the testing optimum value of α was obtained as 75 °. Further experiments were conducted at different dynamic conditions keeping the geometric condition constant (α = 75 °). The results showed that E and Ne are well correlated with Fr and Re, respectively. Maximum SOTR and SAE are found to be 0.15 kg O_2/h and 0.42 kg O_2/kWh, respectively at rotational speed (N) of 2840 rpm, submergence depth (d) of 0.14 m and positional angle of 75 ° of the propeller shaft. Aeration cost of propeller-aspirator pump aerator was estimated at optimum condition for different level of oxygen concentration and finally the aeration cost was estimated as Rs.37.37 /kg of O_2.

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