A COMPARATIVE STUDY OF DIFFERENT CONFIGURATIONS OF MECHANICAL SURFACE AERATORS

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ABSTRACT

This paper presents a comparative experimental study of different configurations of mechanical surface aerators used in wastewater treatment plants. A laboratory scale tank equipped with different configurations for aeration process was installed to compare the standard aeration efficiency and power consumption ofcurved blade impellers with3, 6, 9, and 12 blades (CBI-3, CBI-6, CBI-9, and CBI-12). Different parameters thought tohavesignificant effects on standard aeration efficiency (SAE) and power consumption, such as submergence depth and rotating speed were studied. Results show that an optimum configuration(9 blades) has the highest aeration efficiency (2.60 Kg. O_2/KW.hr) at 500 rpm. Also, a submersion depth ratio of 0.35 was optimum,giving the highest SAE,as increasing submergence depth ratio above this value causes drop in SAE as a result of inevitableincrease in rated power consumption in this case.

Keywords: Surface Aerators, Oxygen mass transfer, Aeration efficiency, Aeration System.

1 INTRODUCTION

The main objective of an aeration process in water and wastewater treatment plants is to transfer oxygen from the atmosphere to water.Such process is considered an essential part of water treatment. Several types of aeration systems have been used for this purpose. Selection of a proper system depends on many factors such as the function to be performed, type and geometry of the tank, and cost ofinstallation and operationof the system **(Metcalf and Eddy [1])**.
Aeration systems used in water and wastewater treatment plants can be classified into five groups as indicated in fig. (1): (1) Diffused Aeration, (2) Mechanical and Submerged Agitator Aeration, (3) Surface Aeration, (4) Pure Oxygen Aeration, and (5) Cascade Aeration.

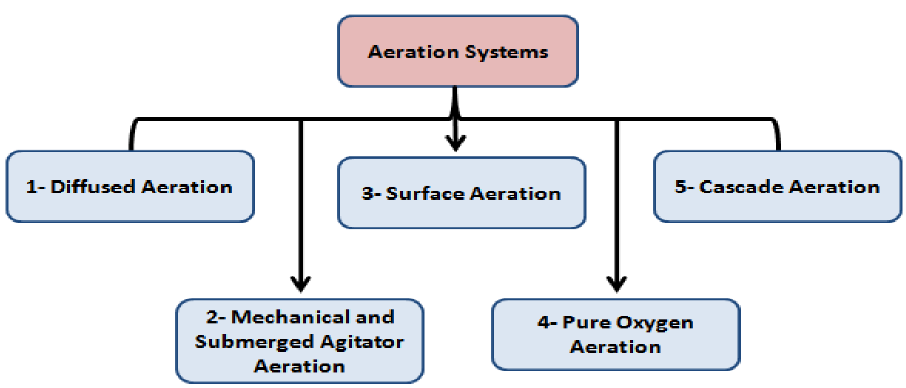

Figure 1.Classification of Aeration Systems

Surface aerators are popular because of their comparable efficiency and ease of operation**.**

One of the most commonly used impellers in stirring tanks is the so-called Rushton rotor. Many researchers investigated the flow field and turbulence induced by such impeller. For example, **Reed et al.[2]** investigated the flow field in a stirring tank equipped with a Rushton type impeller. The flow was investigated using LDA technique. The results showed a ring vortex occurring below the impeller and appearing stronger than that above the impeller. **The authors** noticed also that the presence of baffles had extensive influence on the main flow, emphasizing the existence of strong helical vortices in front of the baffles.

Wu and Patterson [3]studied experimentally the effect of trailing vortices on the velocity measurements in the impeller stream using LDA. The results showed that the flow periodicity resulting from those trailing vortices strongly influenced the root mean square values (rms)of velocities in the impeller stream in the vicinity of the impeller. The largest contribution of the flow periodicity to the total radial and tangential rms velocities occurred in the impeller elevation as well as in the vicinity of the impeller.

Mhetras et al. [4] studied **t**he dispersion mixing intensity for various impeller configurationsusing 15 impeller types in single-impeller configuration. The most common impeller used in aeration process is the Rushton turbine (RT), which imparts a radial flow to the broth. Although it provides an appropriate transfer of oxygen for the process, a disadvantage is that it generates non-uniform mixtures with a high degree of shear near the tips of the blades and mild shear at the periphery of the bioreactor, and also has high power consumption.

Khare [5], **Amanullah [6]**, **Cooke [7]**, **Chen [8]**, **Saito[9**] found that the consumed power by curved blade impellers was less than that consumed by standard Rushton impeller.

A cylindrical mixer agitated by an impeller blade is commonly used for liquid mixing, and it has been observed that the number of blades of the impeller can significantly affect mixing efficiency **(Wu [3])**.

Cancino et al. [10, 11] presented a theoretical design of the rotor using the traditional mass transfer equations and the mechanical approach using the superficial similarities of aerators to axial-flow pumps.A total of 23 different rotor configurations were tested experimentally.The "Kinetic 3" propeller-designed using the criteria of an axial flow pump with a diameter of 94 mm, an inlet angle of 11° and an exit angle of 25°-yielded the highest aeration efficiency at 10°C: 1.769 kg O_2/kWh (SAE =1.805 kg O_2/kWh). The Conrad propeller-designed using other criteria-with a diameter of 104 mm, an inlet angle of 25° and an exit angle of 12°, yielded the highest value for the global mass transfer coefficient at 10°C: 3.249 h^{-1}.

Ochieng et al. [12] presented experimental work and computational fluid dynamics(CFD) computation in a study of the effect of a low clearance Rushton impeller on the mixing time. The laser Doppler velocimeter was used to investigate the hydrodynamics in the tank. Good agreement between the experimental and CFD simulation was observed. Also, it was shown that with low clearance Rushton impeller, a flow field is generated with increased axial flow and reduced mixing time at a constant power number.

Thakre et al. [13] examined the effect of different configurations of mechanical aerators on oxygen transfer and aeration efficiency with respect to power consumption.The variations in overall oxygen transfer coefficient (K_La) and aeration efficiency (AE) for different configurations of aerator were studied by varying the parameters (speed of aerator, depth of immersion, blade tip angles) so as to yield higher values of K_La and AE. Six different configurations of aerator were developed and fabricated in the laboratory and were tested for above mentioned parameters. The curved blade rotor (CBR) emerged as a potential aerator with blade tip angle of 47°. Mathematical models were developed for predicting the behavior of CBR w.r.t k_La and power. In laboratory studies, the optimum value of K_La and AE were observed to be 10.33 h^{-1} and 2.269 kg O_2/ kWh.

Bhuyar et al. [14] designed a high efficiency curved-blade-surface mechanical aerator for oxidation ditch, which was used to treat municipal and domestic sewage. Aeration experiments were conducted in oxidation ditch made up of mild steel sheets to study the design characteristics of curved blade surface mechanical aerator. The standard aeration efficiency (SAE) of CBR was observed to be higher as compared to other aerators used for oxidation ditch

process. Dimensional analysis was used to develop equations that describe the aerator's behavior. Further, a CFD model was also developed for better understanding of the process that takes place inside the ditch.
Devi et al. [15]investigated experimentally the effect of impeller submergence depths on power consumption when arrowhead impeller was used in the process. They found that the optimal range of submergence depth is 0.8 to 0.9 times the impeller diameter.

A 3-D numerical study was performedby **Ryma et al. [16]**to investigate the effects of rotor submergence on aeration of a stirred tank, using CFD techniques. Four submergences were considered while the rotating speed maintained at 250 rpm. It was concluded that to have a good mixing in the tank, we should select the deepest submergence, but the consumed power will be increased. Also, this research did not catch the optimum submergence depth to obtain the less consumed energy.

Scargiali et al. [17] presented an experimental investigation of mass transfer in unbaffled stirred tank equipped with different impellers. It was found that Pitched Blade Turbine (PBT) was suitable for stirring process.

Molnar et al. [18]studied experimentally and numerically the mixing efficiency of a stirred vessel, using different impeller geometries (3- bladed, 4- bladed, 5- blade, and 6- bladed) and rotating speeds. The mixing time, mixing efficiency and the consumed energy were obtained numerically as well as experimentally for all configurations.**Mohammadpour et al. [19]** presented an experimental work to optimize and evaluate efficiency and mixing time in a surface aeration tank. It was concluded that variation of impeller immersion depth had a greater effect on SAE compared to changes in water height.

Ghotli et al. [20] studied the effect of 6-curved blade impellers of different curvature angles and central disk on the aeration performance of stirred tank. The results were compared with that of a Rushton turbine. It was concluded that curved-blade impellers were more economically efficient than Rushton turbine.
It is noted that previous works focused on studying the mixing, turbulence, and numerical simulation of oxygen transfer in stirred tanks. A few researches showed how to develop a new configuration with high AE and low energy consumption. The present work aimed to investigate experimentally different impeller configurations to obtain the optimum operating conditions and the optimum configuration designfor which high aeration efficiency is obtained.

2 MATERIAL AND METHODS

The test rig,as shown in fig. (2),consists of: (1) Tank which is fabricated from steel and coated with epoxy for protectionagainst weather conditions. The tank is of capacity of 1 m^3 and equipped with two beams fabricated from steel sections to mount the driving motor.A drain pipe with valve is provided at the bottom of the tank for water emptying. (2) A.C. Motor manufactured by SIMENS Company with rated power 1100 Watts, 50 Hz, 3 Phase, 1450 rpm and power factor (P.F) 0.8. (3) Variable frequency drive (VFD)to control the aerator speed, manufactured by ABB Company. (4) Wattmeter to measure the electric power of motor. (5) Dissolved oxygen meter. (6) Dissolved oxygen probe that acts as sensor of the oxygen dissolved in the water. (7) Drain pipe with valve.(8) Mechanical surface aerator manufactured locally with different configurations(fig. (3) and detailed dimensions given in table (1)).The uncertaintiesof devices used in the present measurements as given by the operation manual of each device are presented in table (2).

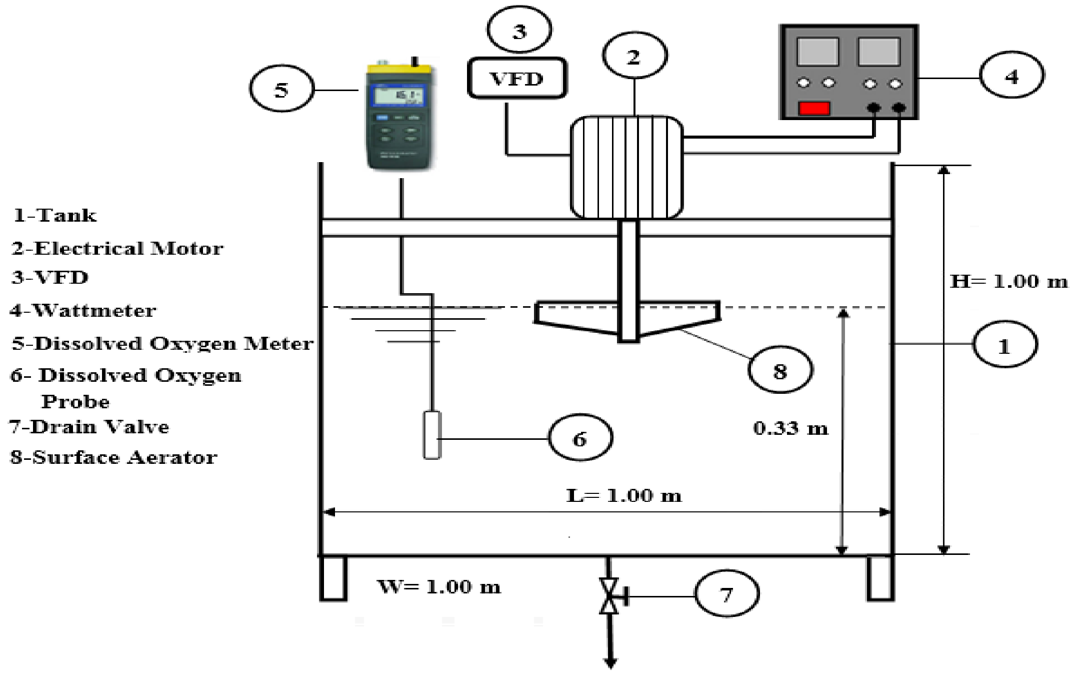

Figure 2. Schematic diagram for the experiment set-up

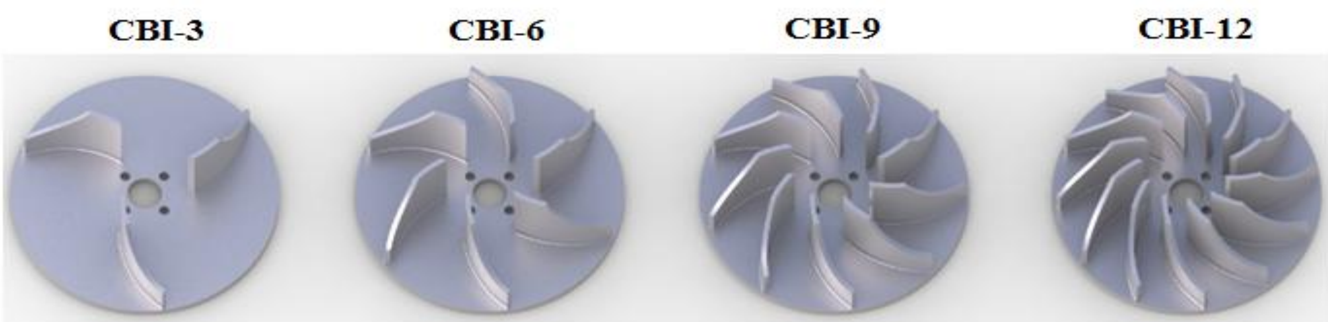

Figure 3.Backward-Curved Blade Impeller (CBI) (4 Configurations)

Table 1.Data of Test Tank andCurved Blade Impellers(CBI).

Item	Data
Tank:	
• Dimensions	1x1x1 m
• Thickness	5 mm
• Aerator Submersion depth ratio (h/D)	0.2 – 0.5
Aerator Impeller:	
• Rotor diameter	156 mm
• Hub diameter	32 mm
• Number of rotor blades	3, 6, 9 and 12
• Blade height at tip	40 mm
• Blade height at hub	15 mm
• Rotor blade angle	48^{o}

Table 2. Uncertainties of devices

Device	Variable	Unit	$Res.$	u_O	u_C	u_d
DO Meter	DO	mg/l	0.10	±0.05	±0.20	±0.21
Temperature meter	Temperature	^{o}C	0.10	±0.05	±0.30	±0.30
Digital tachometer	Speed	rpm	1	±0.5	±0.25	±0.56
Wattmeter	Power	W	0.0	±0.05	±1.5	±1.5

The sulfite method for surface aerator testing described by several previous investigators was adopted in the present work (**Boyd [21], Boyd and Watten[22], Pöpel[23], Wagner [24], ASCE Standard [25] and Stukenberg et al. [26]).**The sulfite method or (unsteady-state test)is conducted by deoxygenating a basin of clean water with sodium sulfite and measuring the change in DO concentration as the water is reoxygenated by an aerator. DO concentrations are measured with a polarographic DO meter at timed intervals while DO increases from 0% saturation to at least 90% saturation.The concentration of dissolved oxygen was detected by means of a YSI oxygen meter sensor which was accurate enough to measure DO at fluid velocities below 0.025 m/s.

Oxygen Mass Transfer Coefficient

Aeration is a mass transfer phenomenonthat occurs between air and water.The variation of oxygen concentration in the water, as a function of time, is given by **Treybal, [27] as**:

$$\frac{dc}{dt} = K_L a_T (C_s - C_T) \quad (1)$$

$$K_L a_T = \frac{\ln(C_s - C_o) - \ln(C_s - C_t)}{t} \quad (2)$$

where, the concentrations C_s, C_0 and C_t are dissolved oxygen (DO) 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 $K_L a_T$ can be obtained as slope of the linear plot between ln (C_s-C_t) and time t.C_s may be computed for different fluid temperaturesfrom equation (3) given by **Boyd, [21]; Pöpel, [23]**as:

$$C_{sT} = 2234.34(T + 45.93)^{-1.31403} \quad (3)$$

In water/air systems, most of the resistance to mass transfer comes from the liquid phase. Therefore, the mass transfer phenomena are controlled by the liquid phase and the overall mass transfer coefficient ($k_L a_T$) can be calculated using the movement of the oxygen in the water **Treybal, [27]**.
In order to compare the coefficients attemperatures other than the standard temperature (20°C) value($K_L a_{20}$)given by Vant-Hoff Arrhenius equation:

$$K_L a_{20\,°C} = K_L a_T \times 1.024^{(20-T)} \quad (4)$$

Based on the obtained oxygen mass transfer coefficient, the standard oxygen transfer rate (SOTR) is computed using the following equation:

$$SOTR = K_L a_{20} C_{s20} V \quad (5)$$

Power Consumption

The consumed power by each aerator is measured directly by a digital Wattmeter of range 0-2.2 KW.

Aeration Efficiency

The aeration efficiency is the most important parameter which is used to evaluate the added oxygen per KWhr. The standard aeration efficiency (SAE)is obtained from the following equation:

$$SAE = \frac{SOTR}{P} \tag{6}$$

The DO values, power consumption, and water temperature were recorded continuously during the experiments. Consequently, the oxygen mass transfer coefficient $k_L a_T$, standard oxygen transfer rate (SOTR), and standard aeration efficiency SAE were calculated and plotted. All procedures of determining the mass transfer coefficient and efficiency were carried out according to ASCE/EWRI 2-06 standard [25].

3 RESULTS AND DISCUSSION

Dissolved Oxygen (DO) concentrations and energyconsumption were recorded during all experiments under a constant water height of 33 cm (determined by practical constraints) and different operating conditions (Submergence depth, rotational speed, and different impellers). Also, effect of different factors on energy consumption and AE were investigated to obtain the optimum aeration efficiency of mechanical surface aerators.

Effect of submersion depth

Figures (4, 5) show the DOpercent versus time for CBI-6 at 200 rpm and CBI-9 at 300 rpm. A submergence depth ratio h/D =0.35 was approximatelythe optimum submergence depth ratio since any further increase in this ratiowould not achieve a significant increase in DO.

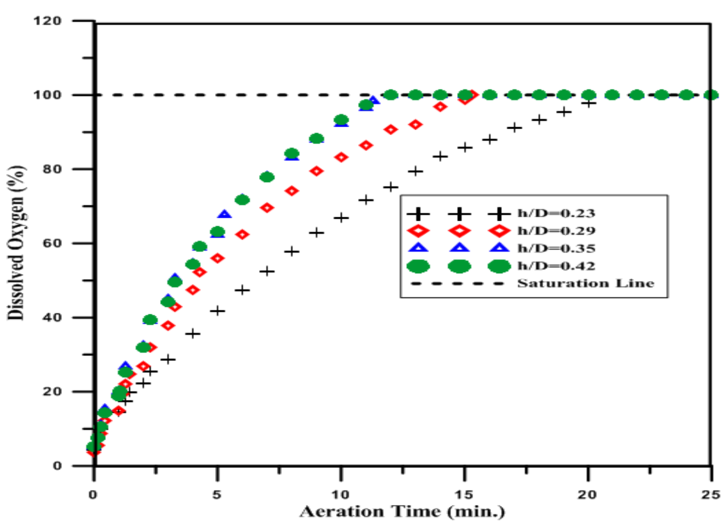

Figure 4. Dissolved Oxygen Versus Time at different depths for CBI-6 at 200 rpm

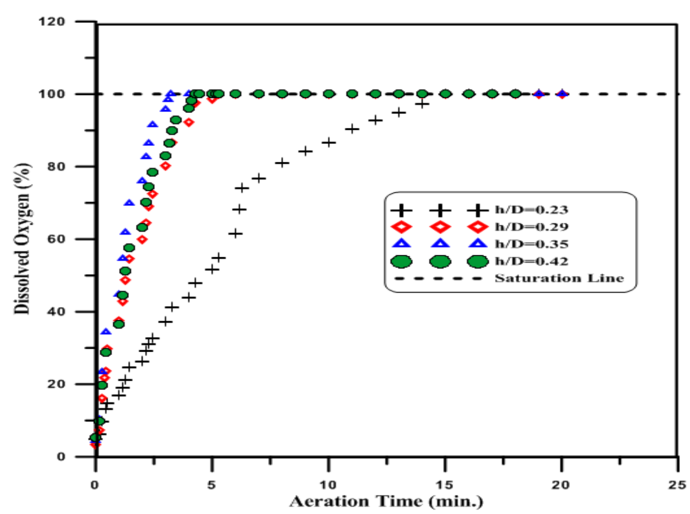

Figure 5. Dissolved Oxygen Versus Time at different depths for CBI-9 at 300 rpm

Figure (6) shows the Oxygen mass transfer coefficient ($K_l a$) versus submergence depth for different configurations at 400 rpm. Submergence depth ratio h/D =0.35was observed to be approximatelythe optimum submergence depth ratio.Further increase in submergence depth is associated with decrease in mass transfer coefficient ($K_l a$) with further more increase in the rated power as indicated by fig. (7).

Figure (8) shows SAE versus submergence depths ratio for different configurations at 400 rpm. A submergence depth ratio h/D =0.35 was observed to be approximatelythe optimum submergence depth since further increase in submergence depth isassociated with decrease in mass transfer coefficient (K_la) with further increase in the rated power and consequently a drop-inSAE.

Effect of Rotational Speed

In the present work,the aerator rotational speed range was varied from 200to 500 rpm.Below this range, DO concentration cannot reach the saturation conditions, and high splashing conditions occur around the tank,above this range.

Rotating speed has a remarkable effect on DO as shown by fig. (9).As the rotational speed increases the time required to reach saturation decreases and consequently the oxygen mass transfer coefficient increases as shown by fig. (10). Also as the aerator speed increases the SAE increases, despite the increase in consumed power as shown by figs. (11, 12).

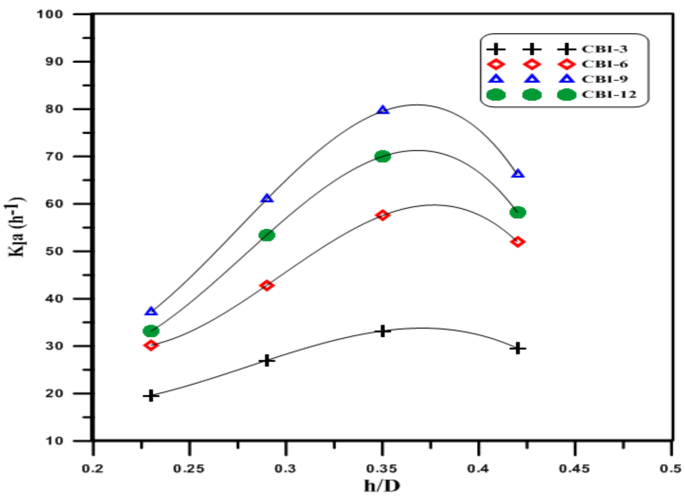

Figure 6. Oxygen mass transfer coefficient (Kla) versus Submersion depth ratio h/D at 400 rpm for various rotors

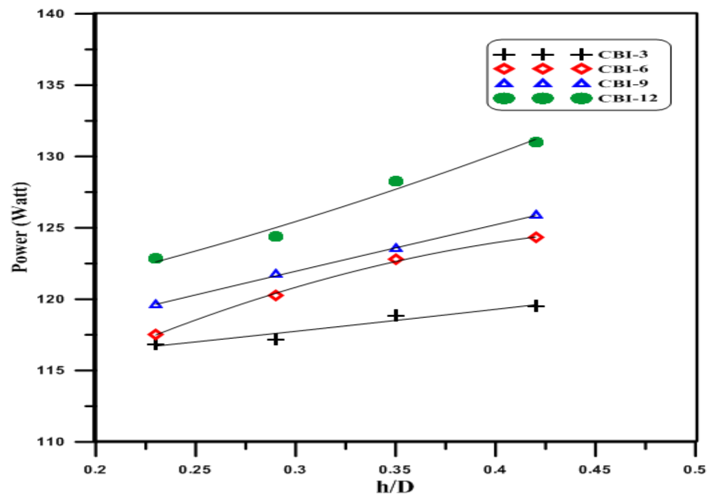

Figure 7. Rated Power Versus Submersion depth ratio h/D at 400 rpm for various rotors

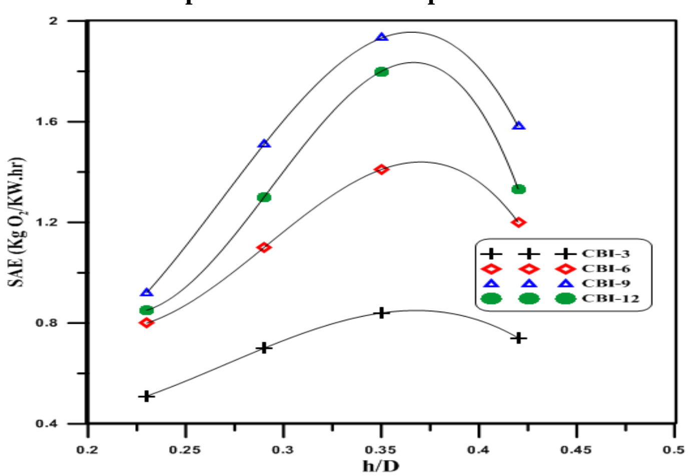

Figure 8. Standard Aeration Efficiency (SAE) versus Submersion depth ratio h/Dat 400 rpm for various rotors

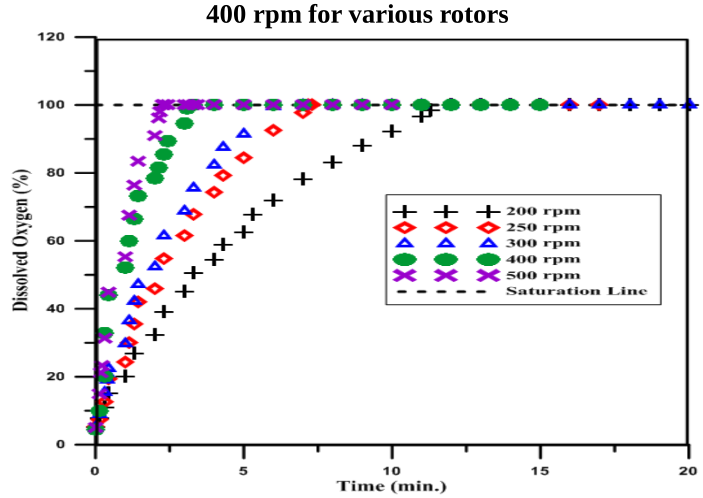

Figure 9.Dissolved Oxygen Versus Time at different speeds for CBI-6 at h/D=0.35

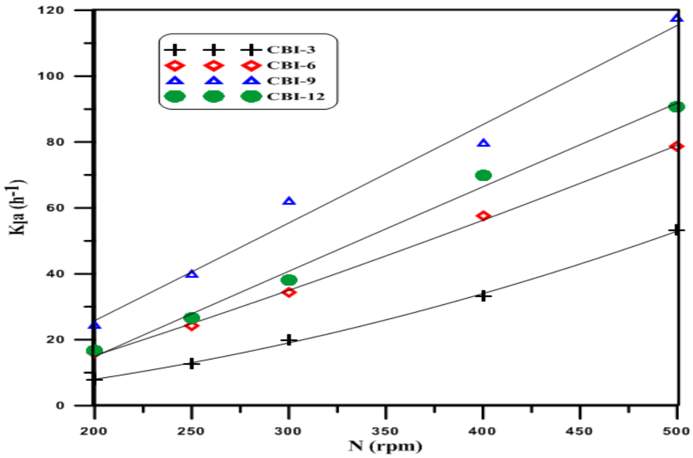

Figure 10. Oxygen Mass Transfer Coeff. (Kla) versus Speed (N) for different Configurations at h/D=0.35 for various rotors

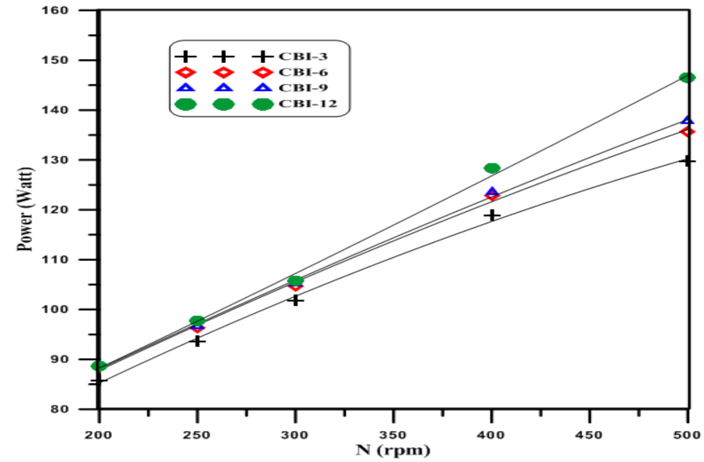

Figure 11.Rated Power Versus Speed (N) for different Configurations at h/D=0.35 for various rotors

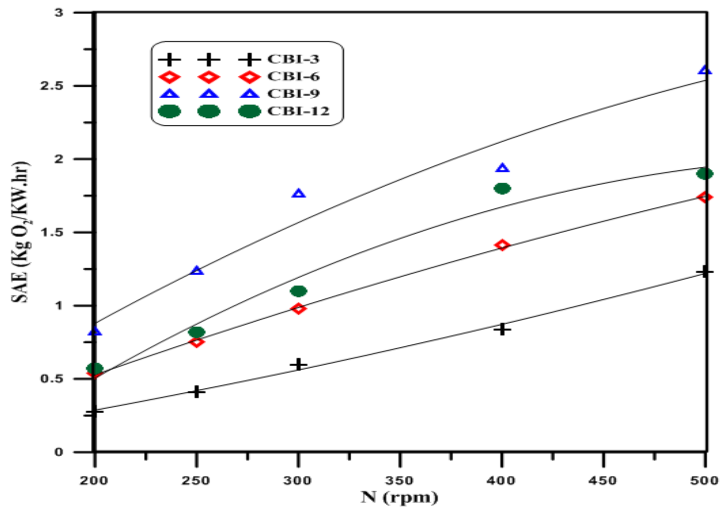

Figure 12. Standard Aeration Efficiency (SAE) versus Speed (N) for different Configurations at h/D=0.35 for various rotors

Effect of number of rotor blades

The effect of number of blades on DO is shown in fig. (13). As the number of blades is higher, the required time for DO to reach saturation decreasesuntil this number becomes 9 blades (CBI-9) above which the DO saturation time is observed to increase.Consequently, a drop-in oxygen mass transfer coeff. (K_la) occurs as shown by fig. (14).

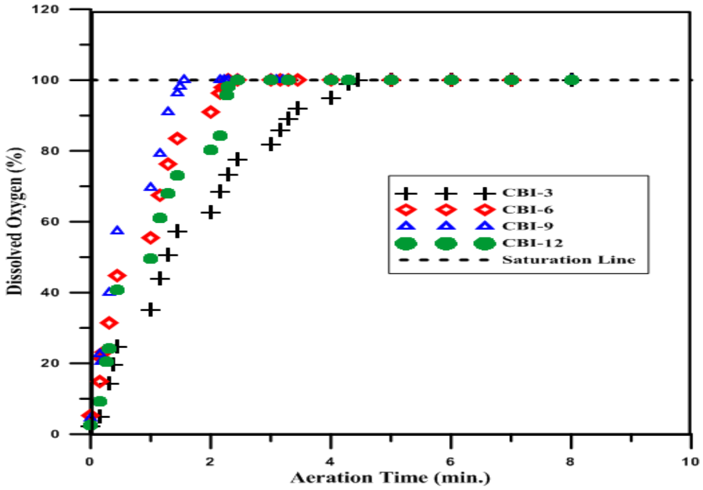

Figure 13.Dissolved Oxygen Versus Time for different Configurations at h/D=0.35 and 500 rpm for various rotors

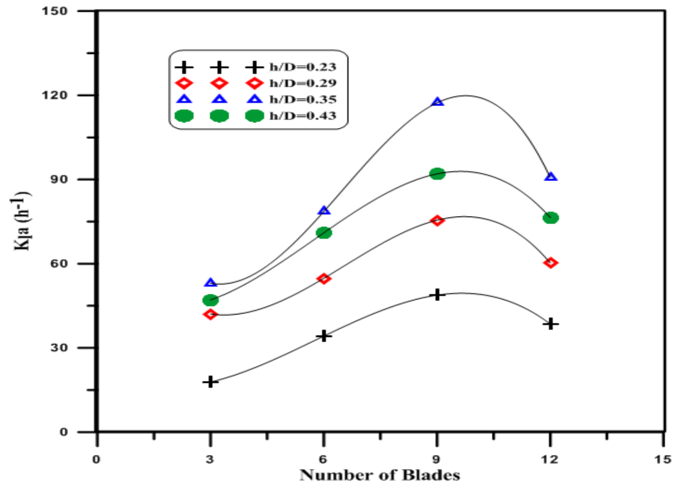

Figure 14. Oxygen Mass Transfer Coeff. (Kla) versus Number of Blades for different Submersion depth ratios (h/D) at 500 rpm

The variation of Oxygen mass transfer coefficient (K_la) with the number of blades for different submersion depth ratios is given by fig. (14).It is indicated that as the number of blades is higher$K_la$gets also highertill the case of 9 blades (CBI-9). A further increase in blade number, leads toa decrease in K_la. The consumed power by the aerator increasesmonotonically with number of blades as shown by fig. (16).

Figure (15) shows the variation of SAE with the number of blades for different submersion depth ratios (h/D). It is noticed that as the number of blades is increased,SAE increases till the case of 9 blades (CBI-9).A further increase in blade number causes adrop-inSAE.

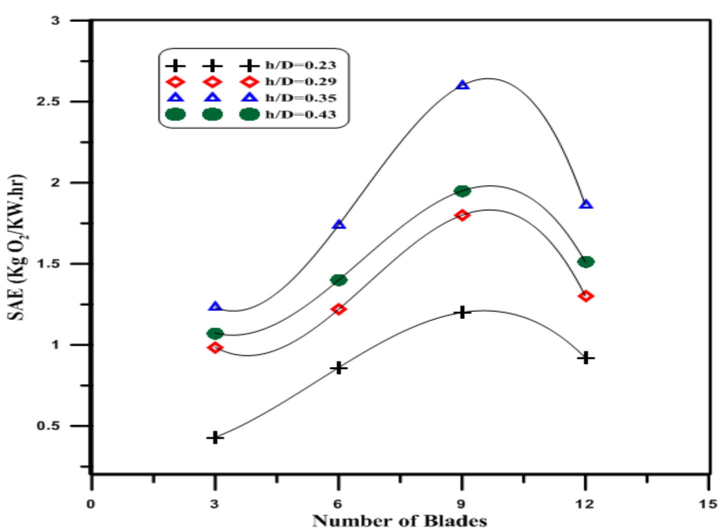

Figure 15. Standard Aeration Efficiency (SAE) versus Number of Blades for different Submersion depth ratios (h/D) at 500 rpm

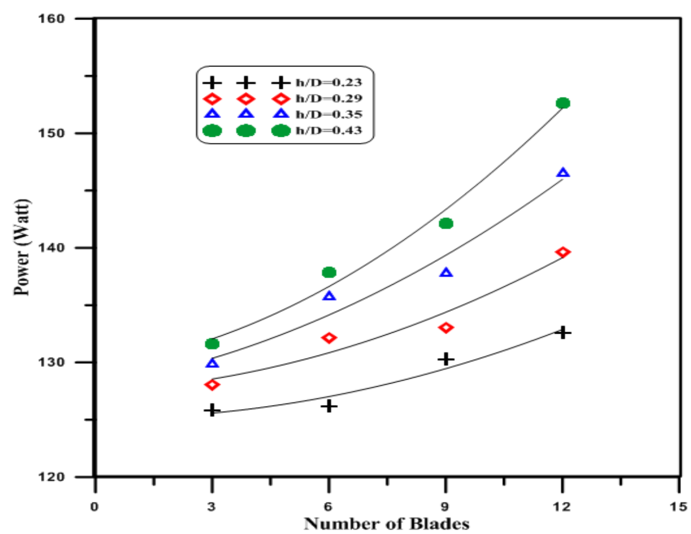

Figure 16. Rated Power versus Number of Blades for different Submersion depth ratios (h/D) at 500 rpm

4 CONCLUSIONS

An experimental study was performed to study the effect of variousaerator parameters on oxygen transfer rate and aeration efficiency. Obtained conclusions are:

1- The optimum number of blades is nine(Curve-blade impeller with 9 blades - CBI-9), achieving the highest standard aeration efficiency.
2- The oxygen mass transfer coefficient and standard aeration efficiency depend on the submergence depth ratio, the optimum value for submergence depth ratio beingapproximately0.35 at whichK_la and SAEare highest.
3- The standard aeration efficiencyincreases with rotating speed.
4- As the number of blades is increased, the Oxygen mass transfer coefficient increases accompanied by a sharp increase in the rated power, hence a dropin standard aeration efficiencySAE.

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NOMENCLATURE

AE	Aeration efficiency	Kg O_2/KWhr
C	Oxygen concentration in water	mg/l
C_s	Saturated oxygen concentration	mg/l
C_o	Oxygen concentration at time t=0 mg/l	
C_t	Oxygen concentration at time t=tmg/l	
C_{sT}	Saturated oxygen concentration at temperature T	mg/l
D	Rotor diameter	mm
DO	Dissolved Oxygen	mg/l
h	Submersion depth	mm
K_la	Overall oxygen transfer rate	hr^{-1}
k_La_T	Overall mass transfer coefficient at the water temperature T	hr^{-1}
k_La_{20}	Overall mass transfer coefficient at 20°C and 1 atmhr^{-1}	
N	Speed	rpm
SOTR	Standard Oxygen transfer rate at 20°C and 1 atmg/m^3/hr	
P	Power of the motor	W
SAE	Standard Aeration efficiency at 20◦C	Kg O_2/kWhr
t	Time	hr
T	Water temperature for the test°C	
T_r	Reference temperature (20 °C)°C	
V	Volume of water tank	m^3

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