ENERGY SAVING USING NEW CONFIGURATION OF MECHANICAL SURFACE AERATOR WITH HIGHER AERATION EFFICIENCY

Mohamed R Shaalan[1], Diaa S El Monayeri[2], Radwan M Kamal[3], M Adel El-Hady[4]*

[1, 3. 4]*Mechanical Power Dept., Engineering Faculty, Zagazig University, Zagazig, Egypt,*
e-mail: **m.adel@zu.edu.eg**
[2]*Environmental Engineering Dept., Engineering Faculty,Zagazig University, Zagazig, Egypt*

ABSTRACT

Energy saving has become a very important in the present time due to the limited resources of energy. Surface aerators used in sewage treatment plants are one important power consumption in such plants. In the present paper, new configuration of mechanical surface aerator with high aeration efficiency was introduced. The new aerator design is based on increasing the oxygen mass transfer coefficient and decreasing the consumed energy by aerator. Three different impellers Rushton Turbine (RT), Pitched Blade Impeller (PBI), and Curved Blade Impeller (CBI) were investigated experimentally. Parameters which affect aeration efficiency and energy consumption were investigated such as submersion depth, and rotational speed. Results show that the CBI with 9 blades achieved an aeration efficiency as high as 2.60 Kg. O_2/KW.hr at 500 rpm.

Keywords:Energy saving, Surface Aerators, Rushton Turbine, Curved Blade aeratorand Aeration System

1 INTRODUCTION

Oxygen transfer process from the atmosphere into the wastewater is an essential part of a number of wastewater treatment processes. This process was called aeration processes. The aeration processfunction is to introduce sufficient amount of oxygen or air for the aerobic micro-organisms which make the biodegradable fraction of the waste be converted into simpler organic or inorganic compounds**Mueller and Boyle [14], Krause et al. [10].**Several types of aeration systems have been used in water and wastewater treatment such as Diffused Aeration, Mechanical and Submerged Agitator Aeration, Surface Aeration, Pure Oxygen Aeration, and Cascade Aeration**Metcalf and Eddy[12]**. However, surface aerators are the most popular because of their easy operation and maintenance **Rao et al. [18]**. **Wesner et al. [24]**Due to the high-power consumption by aeration process which represent 50-90 % of total energy requirement for WWTP, it is become necessary to develop surface aerators with high efficiency and low power consumption.

One of the most commonly used impellers in stirring tanks is Rushton rotor. Many researchers investigated the flow field and turbulence induced by such impeller. For example, **Reed et al.[19]** investigated the flow field in a stirring tank equipped with a Rushton – type impeller. Also, it was noticed that the presence of baffles has extensive influence on the main flow and emphasized the existence of strong helical vortices in front of the baffles.**Lane and Koh [11]** presented a CFD simulation of a Rushton impeller in a baffled tank. Geometry of the tank and Rushton impeller dimensions were chosen according to the previous experimental work. The obtained numerical results were compared with previous work, showing good agreement. **Chapple et al. [6]** examined the effect of impeller and tank geometry on power number for a pitched blade turbine. The results showed that the power number was independent of blade thickness, but dependent on the impeller to tank diameter ratio. **Cancino et al.[4]**, **[5]** 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 had the highest aeration efficiency at 10°C: 1.769 kg O_2/kWh (SAE =1.805 kg O_2/kWh).**DESHMUKH and JOSHI [7]**made experimental and numerical work to study the Power Number, Mass Transfer Coefficient, in pitched blade up flow turbine (PBTU), pitched blade downflow turbine (PBTD) and disc turbine (DT).**Achouri R.** et al., [**26**] presented a CFD simulation for self-inducing turbine and pitched blade turbine at different angles, they found a good agreement between the simulation results and previous experimental in literature. **Thakre et al. [21]**examined the effect of different configurations of mechanical aerators on oxygen transfer and aeration efficiency with respect to power consumption. It was found that the curved blade rotor (CBR) emerged as a potential aerator with blade tip angle of 47° and the optimum value of K_La and AE were observed to be 10.33 h^{-1} and 2.269 kg O_2/ kWh.**Jing et al. [8]** studied the effects of the blade shape on the trailing vortices in liquid flow agitated by four different disc impellers, including the Rushton type, concave blade disk impeller, half elliptical blade disk impeller, and parabolic blade disk impeller. The results showed that the blade shape had great effect on the trailing vortex characteristics. The larger curvature resulted in a longer residence time of the vortex at the impeller tip, bigger distance between the upper and lower vortices and longer vortex life, also leads to smaller and stronger vortices.**Karimi et al. [9]**investigated Oxygen mass transfer characteristics for various twin and single-impeller systems for 6 configurations. Three types of impellers, namely, Rushton impeller, pitched 4-blade and pitched 2-blade impellers with downward pumping have been used to study the oxygen transfer rates from air bubbles generated in the bioreactor. It was shown that twin Rushton impeller configuration demonstrated superior performance (23% to 77% enhancement in K_La) compared with other impeller compositions. Agitation speeds of 400 to 800 rpm were most efficient for oxygen mass transfer.**Molnar et al., [14]** studied experimentally and numerically the mixing efficiency of the stirred vessel by using different impeller geometries (3- bladed, 4- bladed, 5- blade, and 6- bladed) and rotating speeds. The mixing time, mixing efficiency and the consumed power were obtained numerically and experimentally for all configurations.**Achouri R.** et al., **[25**] studied numerically and experimentally the self-inducing turbine aeration capacity at different blade angles and different submersion depths.**Mohammadpour et al. [13]** 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 compare to changes in water height.

It was concluded from the previous researches that the highest aeration efficiency was 2.269 kg O_2/ kWh obtained by **Thakre et al. [21]**and other researches focused on numerical and experimental investigation only. So, the main objective of this study is to present a new design of surface aerator with high aeration efficiency and energy saving. A comparative study between Rushton, Pitched blade, and curved blade aerators will be introduced. Also, different parameters that has a great effect on aeration efficiency and power consumption are investigated experimentally

2 MATERIAL AND METHODS

The experimental test rig consists of tank fabricated from steel with capacity 1 m^3, electrical motor with rated power 1100 Watt, 50 Hz, 3 Phase, 1450 rpm and power factor (P.F) 0.8, and variable speed controller which control the aerator speed by varying the frequency (VFD). Figure (1) shows a schematic diagram for the used tank and different measurements devices. Tap water was used at different operating temperatures that varies from 18–23^{o}c. Water height was kept constant 33 cm during all experiments.

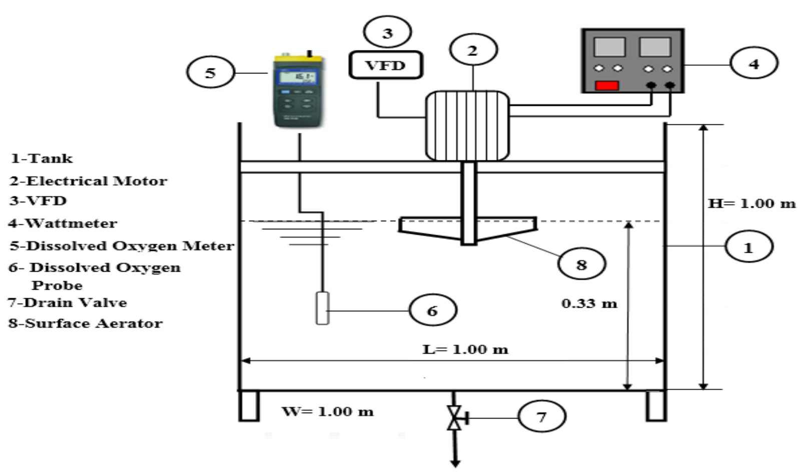

Figure 1. Schematic diagram for the experiment set-up

Surface Aerators

1 Rushton Turbine (RT)

Standard Rushton turbine was tested and investigated during experiments, Rushton impeller diameter was 15.6 cm, the blade height was 4 cm, and the blade length was 5.8 cm with thickness 3 mm. all dimensions and details of Rushton turbine was shown in fig. (2).

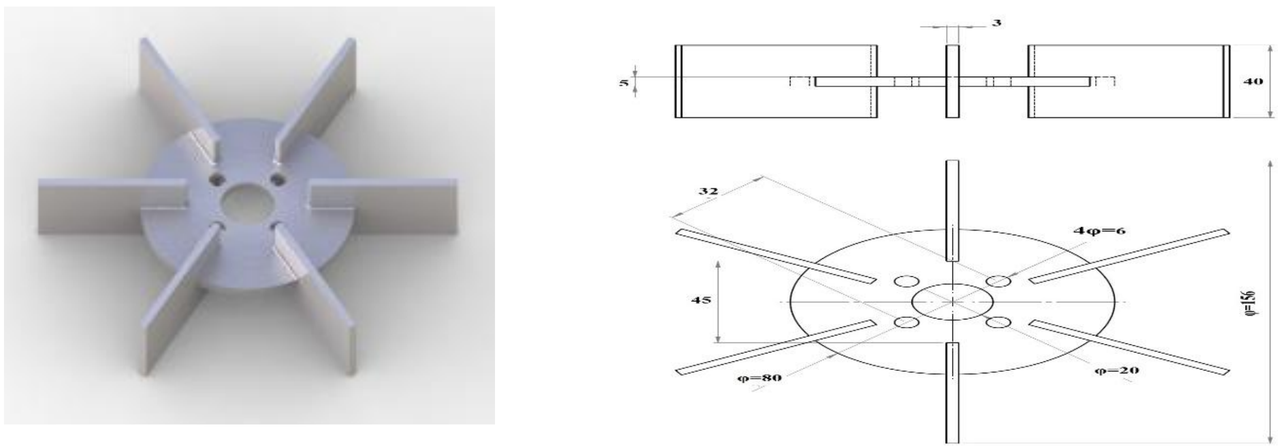

Figure 2. Rushton Turbine configuration and dimensional drawing

2 Pitched Blade Impeller (PBI)

Pitched blade impeller with 4 inclined blades was manufactured with the same diameter 15.6 cm, four inclined blades were welded to the rotor hub at 45^o.each blade had height 4 cm with 3 mm in thickness as shown in fig. (3).

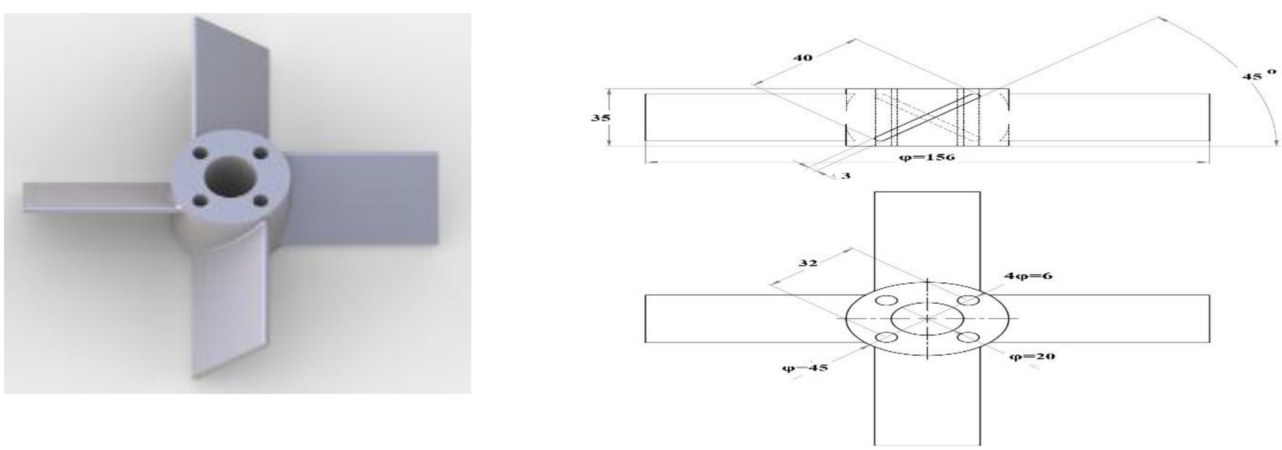

Figure 3. Pitched Blade Impeller configuration and dimensional drawing

Curved Blade Impeller (CBI)

New curved blade impeller was designed on the basis of centrifugal pump, the impeller had 9 curved backward blades with outlet angle 48^o with diameter 15.6 cm. each blade had height 4 cm at hub and 1.5 cm at tip with 3 mm in thickness as shown in fig. (4).

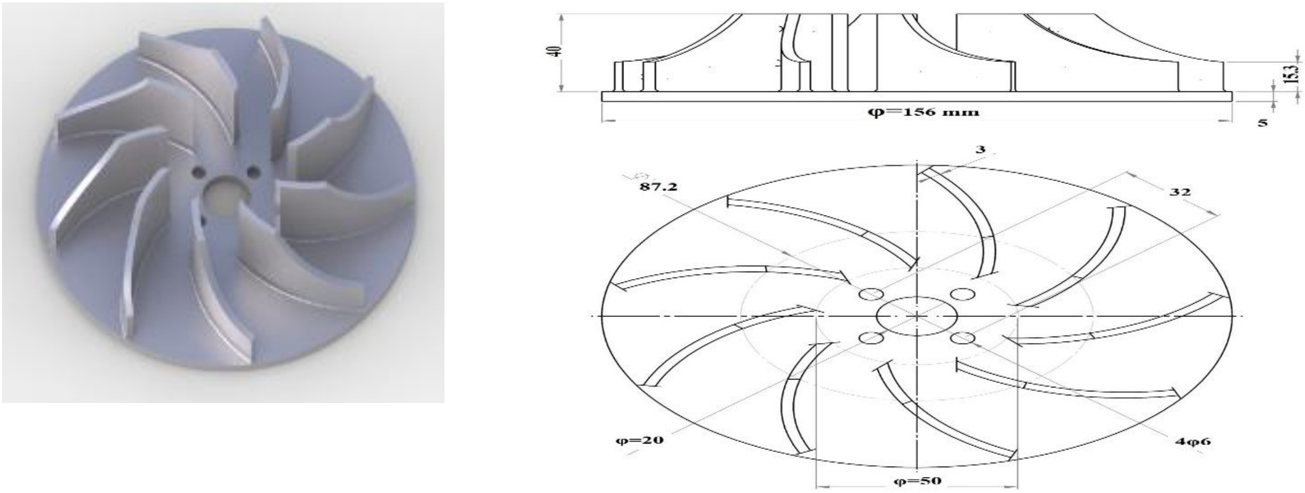

Figure 3. Curved Blade Impeller configuration and dimensional drawing

The sulfite method for surface aerator testing described by several previous investigators was adopted in the present work (**Boyd [3], Boyd and Watten[2], Pöpel[17], Wagner [23], ASCE Standard [1] and Stukenberg et al. [20].**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 measured by means of a polarographic oxygen meter sensor (the sensor used here was an YSI sensor). Such sensor is accurate enough to measure DO at fluid velocities below 0.025 m/s.

Operating Conditions

The following table describes all of the operating conditions as well as the different dimensions for the experiments:

Item	Symbol	Value	Description
Tank Length	L	1.0 m	Const.
Tank Width	W	1.0 m	Const.
Water Height	H	33 cm	Const.
Rotor Diameter	D	156 mm	Const.
Speed	N	From 200-500 rpm	Variable
Submersion depth	h/D	From 0.2-0.45	Variable
Impeller type	--	RT, PBI, and CBI	Variable

Oxygen Mass Transfer Coefficient

Aeration is a mass transfer phenomenon that occurs between air and water. The variation of oxygen concentration in the water, as a function of time, is given by **Treybal, [22] 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 temperatures from equation (3) given by **Boyd, [3]; Pöpel, [17]** 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_La_T) can be calculated using the movement of the oxygen in the water **Treybal, [22]**.
In order to compare the coefficients at temperatures other than the standard temperature (20°C) value (K_La_{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.

Standard 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:

$$SAE = \frac{SOTR}{P} \quad (6)$$

The DO values, power consumption, and water temperature were recorded continuously during the experiments. Consequently, the oxygen mass transfer coefficient k_La_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 [21].

3 RESULTS AND DISCUSSION

Dissolved Oxygen concentrations and energy consumption were recorded for all different impellers (RT, PBI, CBI) under constant water height 33 cm and at different operating conditions (Submergence depth, rotational speed). Also,the 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

The DO percent versus time for RT at speed 300 rpmis shown in fig. (5). It illustrates that with increasing of mixing time (t) the dissolved oxygen concentration increases till reaching its higher possible level near to its saturation dissolved oxygen in water.Also, it demonstrates that with increasing of impeller submersion depth ratio (h/D) the mixing time required to reach the saturation decreases till submersion depth ratio h/D=0.35 even increase in submersion depth ratio lead to decrease in the mixing time.Submergence depth ratio h/D0.35 was the optimum submergence depth because of further increase in submergence depth will not achieve significant increase in DO.

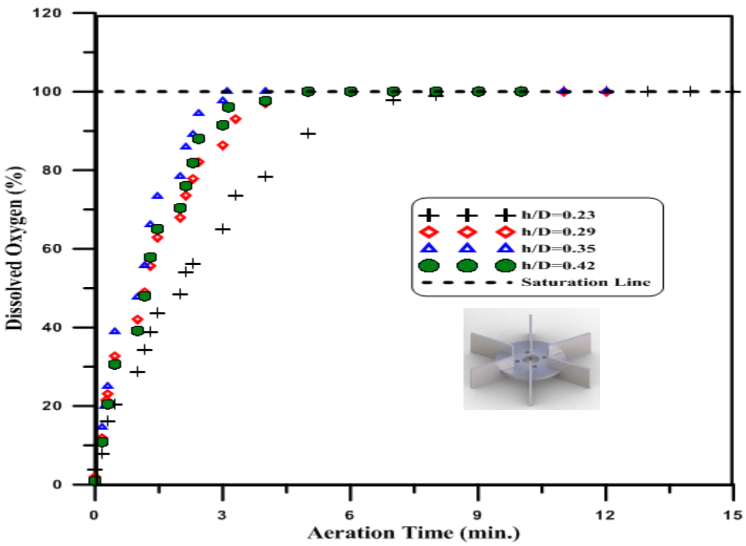

Figure 5. Dissolved Oxygen Versus Time at different depths for RT at 300 rpm

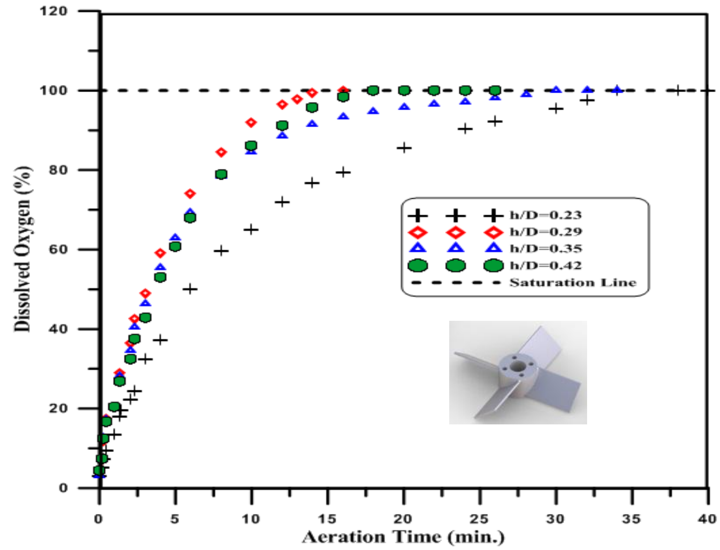

Figure 6. Dissolved Oxygen Versus Time at different depths for PBI at 300 rpm

The DO percent versus time for PBI at speed 300 rpmis shown in fig. (6). Submergence depth ratio h/D0.29 was the optimum submergence depth because of further increase in submergence depth will not achieve significant increase in DO. The DO percent versus time for CBI at speed 300 rpmis shown in fig. (7) shows. Submergence depthratio h/D 0.35 was the optimum submergence depth because of further increase in submergence depth will not achieve significant increase in DO.

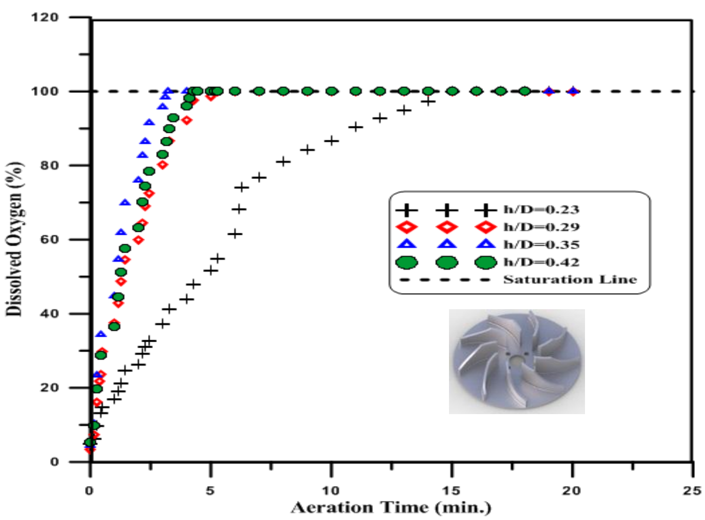

Figure 7. Dissolved Oxygen Versus Time at different depths for CBI at 300 rpm

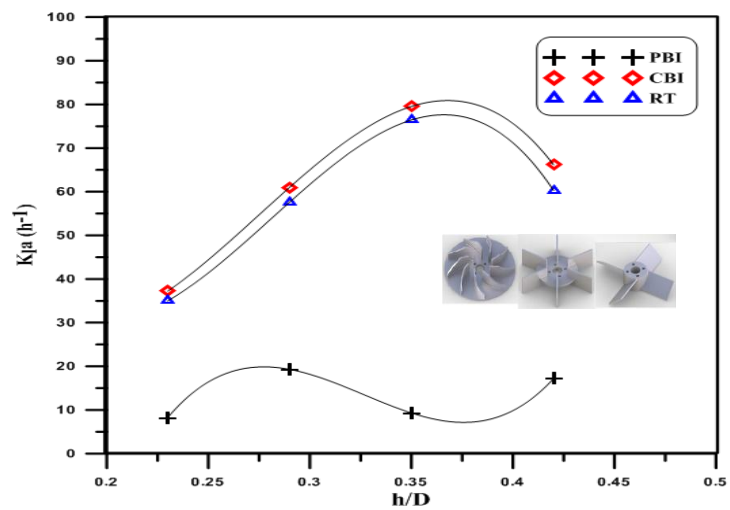

Figure 8. Oxygen mass transfer coefficient (Kla) versus Submersion depth ratio h/Dat 400 rpm

The Oxygen mass transfer coefficient (K_la) versus submergence depth ratios for the three tested impellers at speed 400 rpm is shown in fig. (8).It was found that as the impeller submersion depth ratios h/D increases the oxygen mass transfer coefficient K_La increases in other word the saturated oxygen condition was reached in shorter time up to h/D=0.35, even increase in submersion depth ratio h/D causes drop in the oxygen mass transfer coefficient K_La. This relation can be interpreted that with higher (h/D) more water droplets are thrown into the air, consequently larger interfacial area achieved between air and water and also the flight trip of these droplets goes farther, so as a result the k_La increase. Despite of further increase in h/D over 0.35 leads to increase of drag force which decrease the centrifugal force that is responsible for throwing water droplets into air and consumes more power. Submergence depth ratio h/D0.35 was observed as the optimum submergence depth for RT and CBI because of further increase in submergence depth is associated with decrease in mass transfer coefficient (K_la) while more increase in the rated poweras shown in fig. (9).

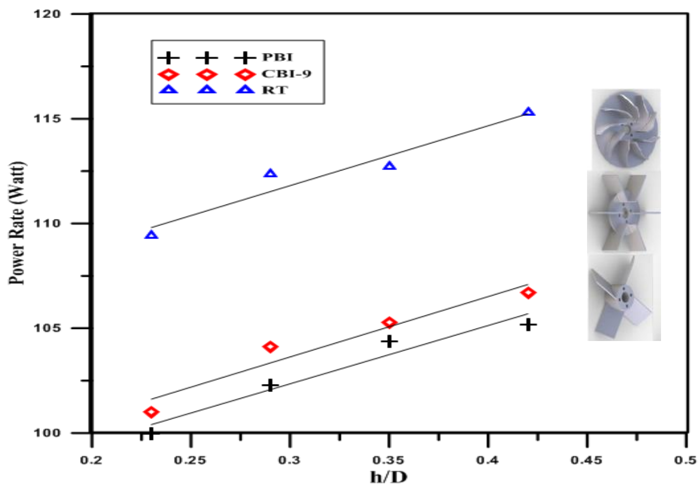

Figure 9. Rated Power Versus Submersion depth ratio h/D at 300 rpm

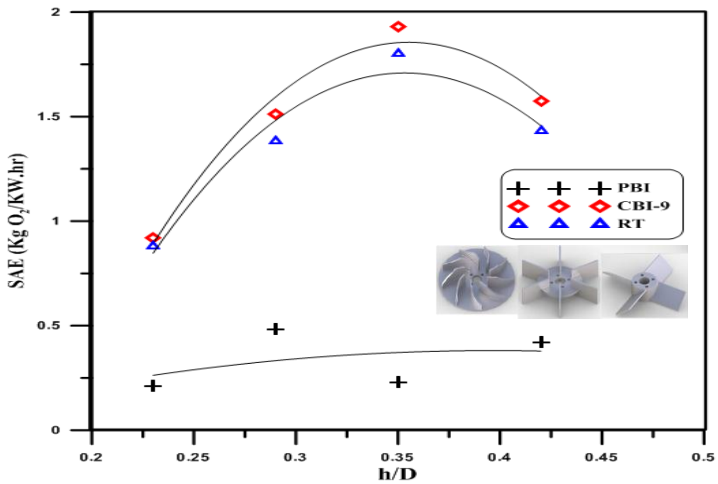

Figure 10. Aeration Efficiency (SAE) versus Submersion depth ratio h/Dat 400 rpm

Standard aeration efficiency SAE versus submersion depth ratios is indicated in fig. (10)for the three tested impellers at 400 rpm. Submergence depth ratio h/D 0.35 was observed asthe optimum submergence depth due to further increase in submergence depth is associated withdecrease in mass transfer coefficient (K_la) while increase in the rated power and consequently drop in AE.

Effect of Rotational Speed

For the present work aerator rotational speed range was 200 -to - 500 rpm since below such range DO concentration cannot reach the saturation conditions, while high splashing conditions occurred around the tank over such range.

Rotating speed has a great effect on DO as shown in fig. (11, 12), as the rotational speed increases the time required to reach saturation decreases and consequently the oxygen mass transfer coefficient increases as shown in fig. (13). Also, the figures show that with increasing of impeller rotation speed (N) the mixing time required to reach the saturation decreases.With higher impeller rotational speeds, higher energy was consumed to achieve efficient mixed condition of the dissolved oxygen in the water bulk, where the dissolved oxygen reaches its equilibrium concentration in shorter time with higher N; for example, after (5 min.) from the beginning of experiment time at (N = 200 rpm) oxygen concentration level was reached (67.3%) (5.22 ml/g), while at (N= 400 rpm) the oxygen concentration level was reached (97.3%) (7.6 ml/g).As the rotational speed increases the DO reaches its saturation in shorter time up to 400 rpm, even increase in rotational speed doesn't achieve a significant increase in DO. Also as the aerator speed increases the SAE increases, despite of increasing in consumed power as shown in fig. (14).

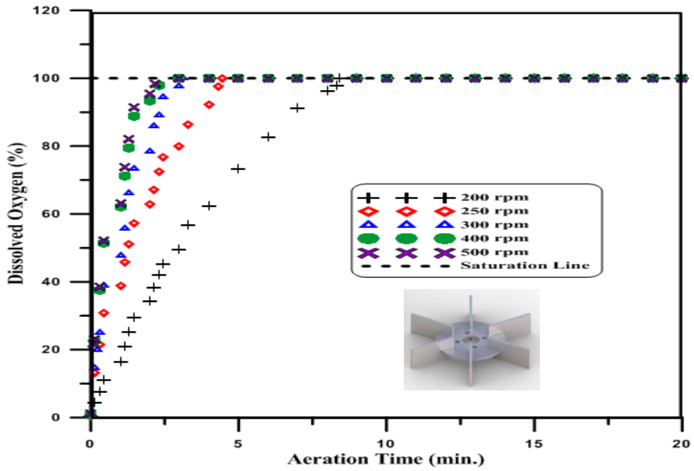

Figure 11. Dissolved Oxygen Versus Time at different speeds for RT at h/D=0.35

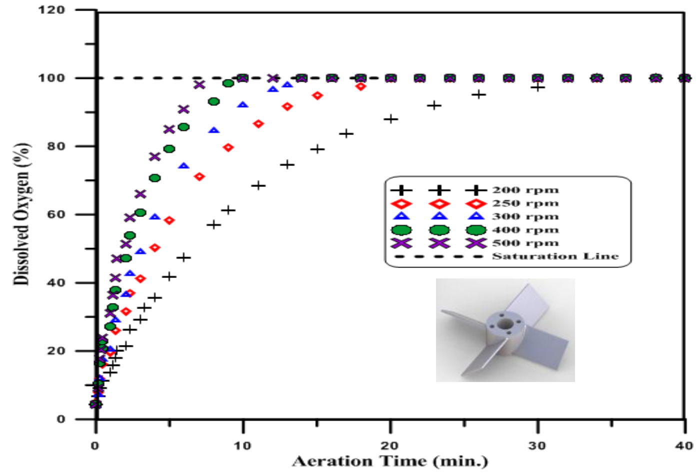

Figure 12. Dissolved Oxygen Versus Time at different speeds for PBI at h/D=0.29

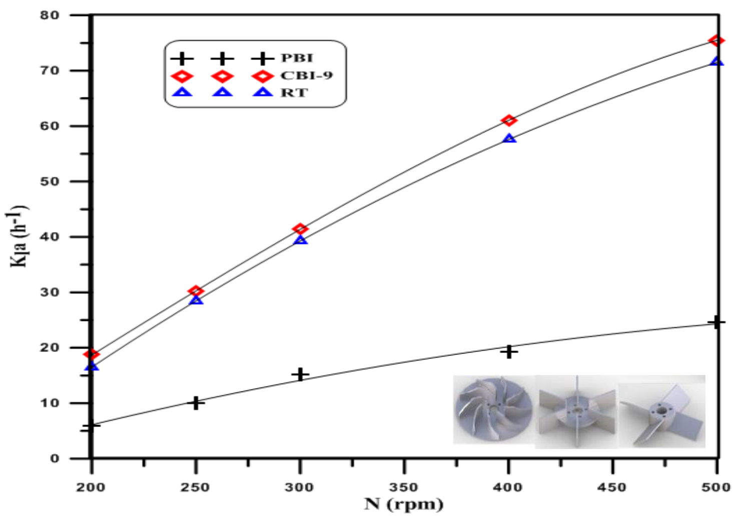

Figure 13. Oxygen mass transfer coefficient (Kla)versus Speed (N) at h/D=0.29

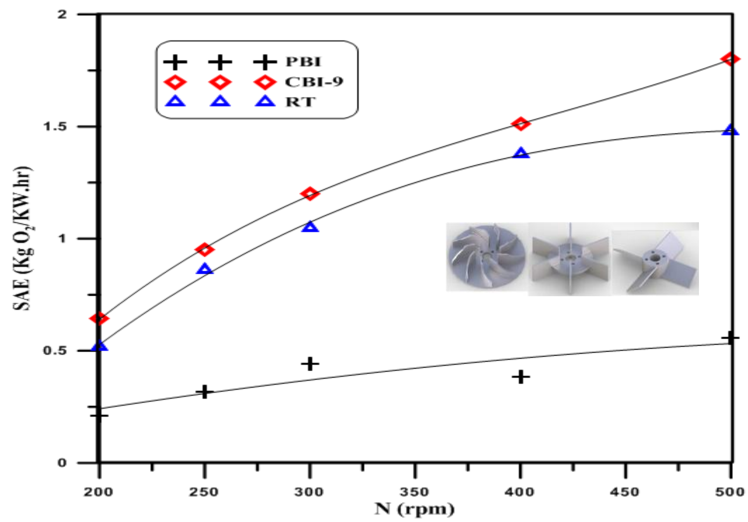

Figure 14. Aeration Efficiency (SAE) versus Speed at h/D=0.29

Three-dimension illustration for Oxygen mass transfer coefficient (K_la) versus the submersion depth ration (h/D) and the aerator speed (N) is shown in fig. (15). It demonstrates that as the impeller submersion depth ratios h/D increases the oxygen mass transfer coefficient K_La increasesup to h/D=0.35, even increase in submersion depth ratio h/D causes drop in the oxygen mass transfer coefficient K_La. on the other hand, as the rotational speed increases the oxygen mass transfer coefficient increases. The same trend occurs for SAE as shown in fig. 16.

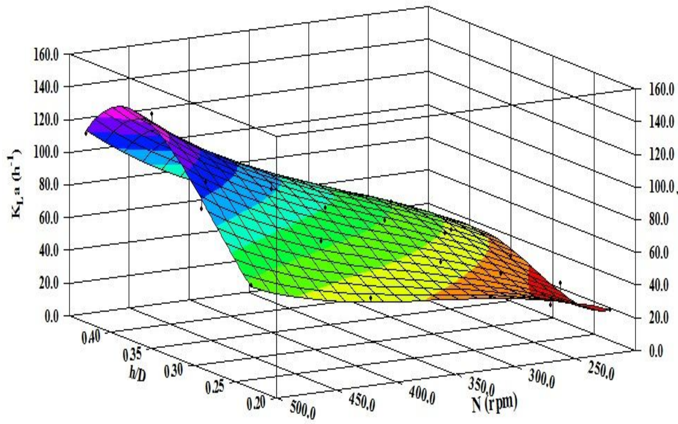

Figure 15. Oxygen Mass Transfer Coeff. (Kla) versus Speed (N) and submersion depth (h/D) forCBI-9

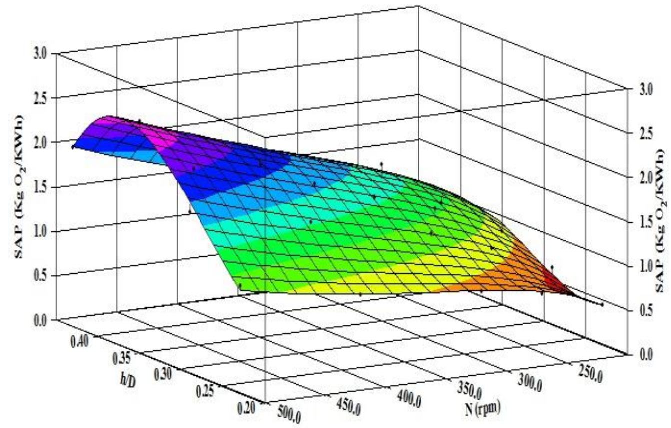

Figure 16. SAE versus Speed (N) and submersion depth (h/D) forCBI-9

Effect of different configurations

Effect of different design of surface aerators on DO has been studied from fig. (17,18), RT and CBI has the same time to reach the saturation state, but the PBI has a great time (30 min) to reach the saturation state.

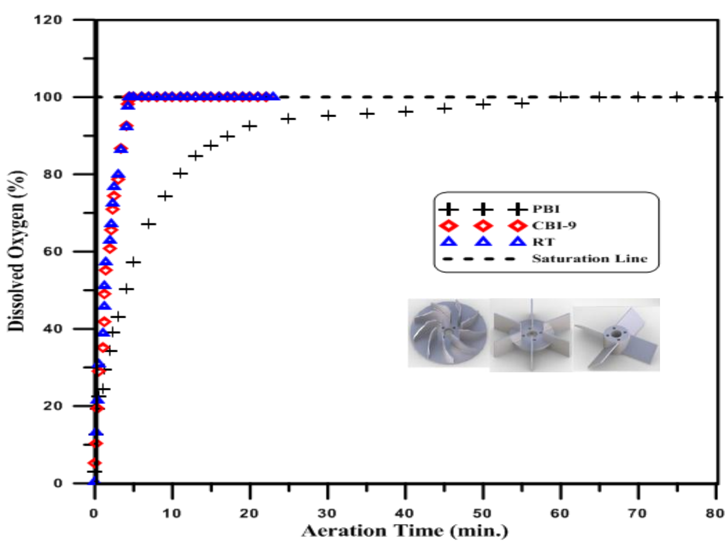

Figure 17.DO Versus Time for different configurations at h/D=0.35 and 300 rpm

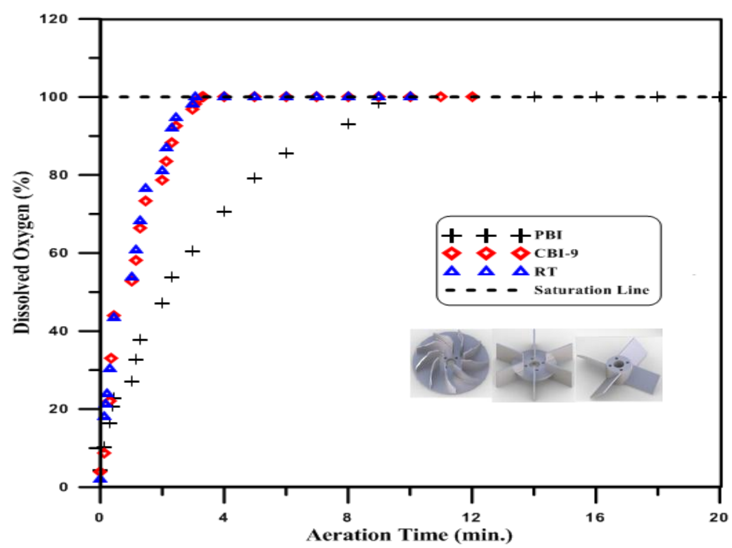

Figure 18. DO Versus Time for different configurations at h/D=0.29 and 400 rpm

The variation of Oxygen mass transfer coefficient (K_la) with the aerator speed for RT, PBI, and CBI is shown in fig. (19). It is clear that CBI has the highest Oxygen mass transfer coefficient (K_la), also PBI has very low Oxygen mass transfer coefficient (K_la). The consumed power by aerators increasesas the rotational speed increases. The consumed power by RT was higher than that is consumed by CBI or PBI as shown in fig. (20).

The SAE versus aerator speed for the different tested impellers is shown in fig. (21). It is clear that CBI achieved the highest SAE (2.60 Kg. O_2/KW.hr) over RT and PBI. Despite of the high K_la achieved by RT, the high-power consumption causes the drop in its AE.

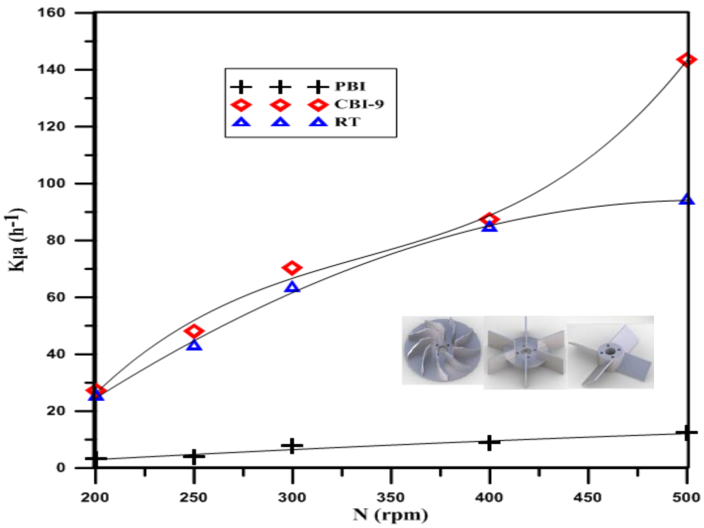

Figure 19. Oxygen Mass Transfer Coeff. (Kla) versus Speed (N) for different Configurations at h/D=0.35

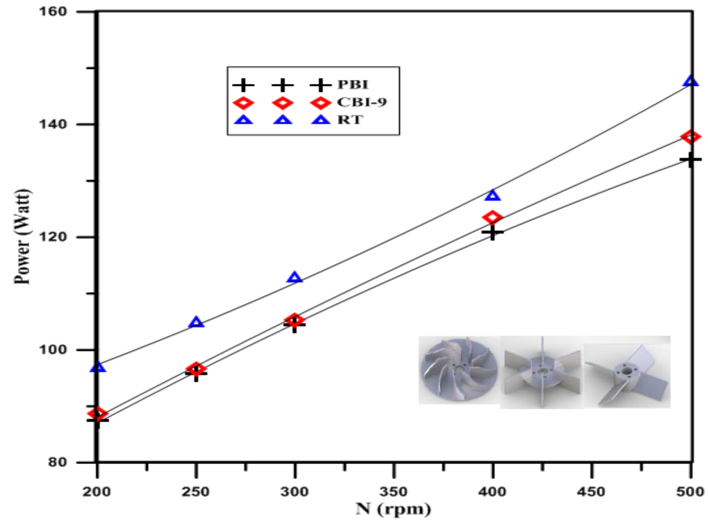

Figure 20. Aerator Power versus Speed (N) for different Configurations at h/D=0.35

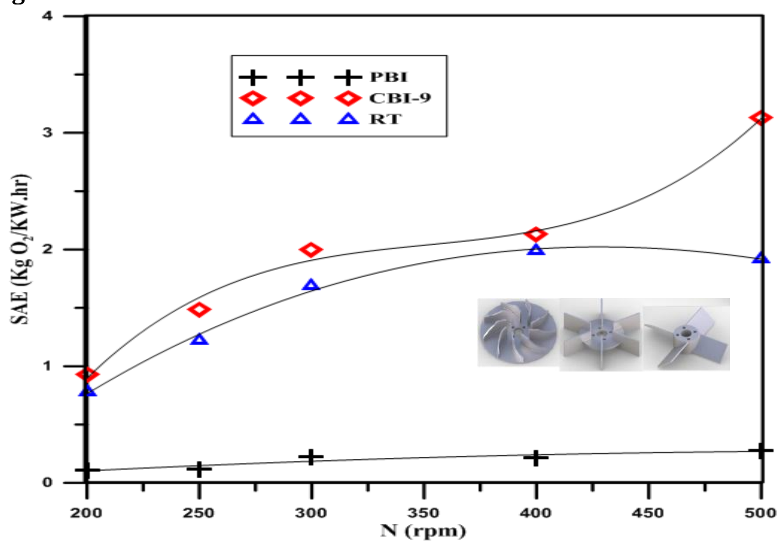

Figure 21.Aeration Efficiency (SAE) versus Speed (N) for different Configurations at h/D=0.35

4 CONCLUSIONS

This paper focused on the design of high aeration efficiencysurface aerator with energy saving. An experimental study was performed to study the effect of different parameters on oxygen transfer rate and aeration efficiency, the following conclusions can be obtained:

1- A new configuration of high energy saving surface aerator was developed (CBI) which achieved the highest SAE (2.60 Kg. O_2/KW.hr) at 500 rpm and 0.35 submergence depth ratio (h/D).

2- Oxygen mass transfer coefficient (K_la) and standard aeration efficiency (SAE) depends on the submergence depth ratio, the optimum value for submergence depth ratio (h/D) was approximately0.35for CBI, and 0.29 for PBI for which the highest value for K_la and SAE were observed.

3- PBI has a very low SAE (0.56 Kg. O_2/KW.hr) at 500 rpm and 0.29 submergence depth ratio, so it is recommended to be used in mixing not aeration process.

ACKNOWLEDGEMENT

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NOMENCLATURE

H	Height of liquid in the stirred vessel	m
D	Rotor diameter	mm
L	Tank length	m
W	Tank width	m
h	Submersion depth	mm
C	Oxygen concentration in water	mg/l
C_s	Saturated oxygen concentration	mg/l
t	Time	hr
T_r	Reference temperature	˚C
T	Water temperature for the test	˚C
C_{sT}	Saturated oxygen concentration at temperature T	mg/l
OTR_{20}	Oxygen transfer rate at 20˚C and 1 atm	$g/m^3/h$
k_La_{Tr}	Overall mass transfer coefficient at the reference temperature	h^{-1}
k_La_T	Overall mass transfer coefficient at the water's temperature for the test	h^{-1}
P	Power of the motor	W
V	Volume of water tank	m^3
AE_{20}	Aeration efficiency at 20◦C	kg O2/kWh
AE	Aeration efficiency	Kg O2/KWh
N	Speed	rpm
K_la	Overall oxygen transfer rate	h^{-1}
DO	Dissolved Oxygen	mg/l
WWTP	Wastewater Treatment Plant	
CFD	Computational Fluid Dynamics	
PBTU	Pitched blade up flow turbine	
PBTD	Pitched blade downflow turbine	
DT	Disc turbine	
CBR	Curved blade rotor	
VFD	Variable frequency drive	
P.F	Power factor	
RT	Rushton Turbine	
PBI	Pitched Blade Impeller	
CBI	Curved Blade Impeller	

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