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Articles

Influence of the angle and perimeter of contact of the blades in a horizontal axis aerator on the transfer of dissolved oxygen

Influencia del ángulo y perímetro de impacto de las aspas en un aireador de eje horizontal sobre la transferencia de oxígeno disuelto

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Abstract

Dissolved oxygen (DO) is a fundamental parameter in water bodies that can be supplied using horizontal axis mechanical agitators. However, blade geometry and operating conditions can influence the process cost. In this work, it is studied the effect of the perimeter and angle of impact of the blades on the water in a prototype of horizontal axis mechanical aeration, starting from the DO transfer analysis. Measurements were made on anoxic water samples using two types of blades with the same area, varying their perimeter and angle of impact. Other parameters that influence the DO transfer process were controlled in this work. The results show the increase in the perimeter, and blade impact angle with the water body, which generates a reduction in the standard aeration efficiency (SAE) up to 30 % in the process. In that way, it is obtained the best results for the prototype Type II blades with a K_La value of 3.69 h^{-1}, and a SAE of 0.47 $kgO_2 \cdot kW^{-1}h^{-1}$ when using an impact angle of 13.5 °. In general, the geometry of the blades is a fundamental design parameter, which influences the transfer of dissolved oxygen in the water. The results of this study can contribute to improving the efficiency of these mechanical systems, reducing the energy consumption associated with oxygenation processes.

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Keywords: Horizontal shaft mechanical aerator, dissolved oxygen (DO), oxygen transfer coefficient, standard aeration efficiency (SAE), blade geometry.

Resumen

El oxígeno disuelto (OD) es un parámetro fundamental en los cuerpos de agua que puede suministrarse por medio de agitadores mecánicos de eje horizontal. Sin embargo, la geometría de las aspas y las condiciones operativas pueden influir sobre los costes del proceso. En este trabajo se estudia el efecto del perímetro y ángulo de impacto de las aspas sobre el agua en un prototipo de aireación mecánica de eje horizontal, partiendo del análisis de transferencia de OD. Las mediciones se realizaron en muestras de agua anóxica utilizando dos tipos de aspas con una misma área, variando su perímetro y ángulo de impacto. Otros parámetros que influyen en el proceso de transferencia de OD se controlaron en este estudio. Los resultados muestran que el incremento del perímetro y ángulo de impacto de las aspas con el cuerpo de agua genera una reducción en la eficiencia de aireación estándar (SAE) en el proceso de hasta un 30 % en este estudio, obteniendo los mejores resultados para el prototipo de aspas Tipo II con un valor K_La de 3.69 h^{-1} y una SAE de 0.47 $kgO_2{\cdot}kW^{-1}h^{-1}$ al usar un ángulo de impacto de 13.5°. De manera general, la geometría de las aspas es un parámetro fundamental de diseño, el cual influye en la transferencia de oxígeno disuelto en el agua. Los resultados de este estudio pueden contribuir en mejorar la eficiencia en estos sistemas mecánicos, disminuyendo el consumo de energía asociado con los procesos de oxigenación.

Palabras clave: aireador mecánico de eje horizontal, oxígeno disuelto (OD), coeficiente de transferencia de oxígeno.

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Introduction

Horizontal axis mechanical aerators are widely used systems to generate circulation and transfer of dissolved oxygen (DO) in bodies of water. Its main use is focused on aerated lagoons, oxidation ditches, aeration channels (Tchobanoglous, Louis-Burton, & Stensel, 2004), although it has also been widely used in aquaculture processes (United States Department of Agriculture & Service, 2011) and water treatment residuals (Barreto *et al*., 2018; Rojas-Romero, 2010).

Mechanical aerators have a cylinder with steel or plastic bristles, angles, or sheets, which promote air circulation by introducing it into a body of water, presenting a transfer rate that varies between 1.5 to 2.1 $kgO_2 \cdot kW^{-1}h^{-1}$ under standard conditions, and from 0.5 to 1.1 $kgO_2 \cdot kW^{-1}h^{-1}$ under field conditions (Tchobanoglous *et al*., 2004). During this process, the device can provide a sufficient amount of oxygen in the medium to maintain the necessary conditions to generate aeration (Barreto *et al*., 2018; Tahri, Bahafid, Sayel, & El-Ghachtouli, 2013).

DO is probably the most critical element of water quality in different processes due to the need for its existence for the survival of aquatic organisms (United States Department of Agriculture & Service, 2011). However, the energy consumption involved in the aeration stages during water treatment implies a cost between 50 and 90 % of the total energy requirement of the process (Daw, Hallett, DeWolfe, & Venner, 2012). Likewise, DO transfer is affected by various environmental factors (Itano *et al*., 2019; Ren, Chai, Xue, Anderson, & Chavez, 2018); physical (Bao, Peng, Zhou, Zhu, & Ye, 2018), and microbial (Torres, Quintero, & Atehortúa, 2018), so on, making it difficult to transfer oxygen from the atmosphere to bodies of water (Arora & Keshari, 2018; Bao *et al*., 2018).

The characteristics of the aeration system such as the geometry, type and arrangement of the blades also have a great influence on DO transfer (Bahri, Setiawan, Hermawan, & Junior, 2015), *e.g.* although larger blade sizes tend to generate greater aeration, they require greater power consumption due to a greater drag force, increasing the operating cost of the process, including electricity and fuel consumption (Qiu *et al*., 2018; Samsul-Bahri & Wawan-Hermawan, 2015).

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The objective of this work is focused on studying the influence of the impact perimeter, maintaining the same area value, of two different types of blades; controlling the rotation speed (RPM), as well as the angle of impact on the body of water. The tests were carried out on a laboratory scale, focusing mainly on the effect that the variation of the blade perimeter can generate on the DO transfer.

Materials and methods

The tests were carried out under controlled conditions using 44 l samples of drinking water, maintaining a contact area with the atmosphere of 0.1924 m^2 and a depth of 0.24 m. The oxygen desaturation concentration in the water samples was 7.5 $mg \cdot l^{-1}$ (C_s), obtained by means of a Hach-flexi HQ30d-US oximeter at an ambient temperature of 17 °C, atmospheric pressure of 740 hPa and a height of 2 800 msnm This value is comparable to the temperature and atmospheric pressure in the measurement area (Sander, 2015). Other parameters of water such as conductivity, salinity, temperature and pH were controlled in an experimental process. OD removal was carried out by applying 3.35 g of sodium sulfite (Na_2SO_3) and 0.05 $mg \cdot l^{-1}$ of anhydrous cobalt chloride

($CoCl_2$) as a catalyst agent (Engineers, A. S. of C., 2007; Uby, 2019). Weights were measured on an Ohaus SPX123 balance with a precision of 0.001 g. The fluid was stirred at 10 RPM to ensure total oxygen removal.

The aeration assembly is presented in Figure 1. An interchangeable blade support built by 3D printing was used, using PETG (polyethylene glycol terephthalate). The system was started using a Greartisan DC 12V geared motor with a maximum rotational speed of 50 RPM. The blades used in the test were made of galvanized zinc sheet with a thickness of 0.6 mm. The first type of blade is made up of three sections of 18 cm x 2.2 cm each (Type I) and an impact perimeter of 114.6 cm. The second type of blade is one-piece with a dimension of 18 cm x 6.6 cm and a perimeter of impact with water of 42.6 cm (Type II). The system configuration was made to impact the blades with the water surface at 180 ° (parallel with the water surface) and 13.5 °, varying the direction of rotation. The maximum power necessary to stop the operation of the system was calculated from a rotation speed of 20 ± 1 RPM, seeking to avoid fluid losses due to spills or splashes, which are not very effective in DO transfer processes (Bahri, Jufriadi, & Anwar, 2019).

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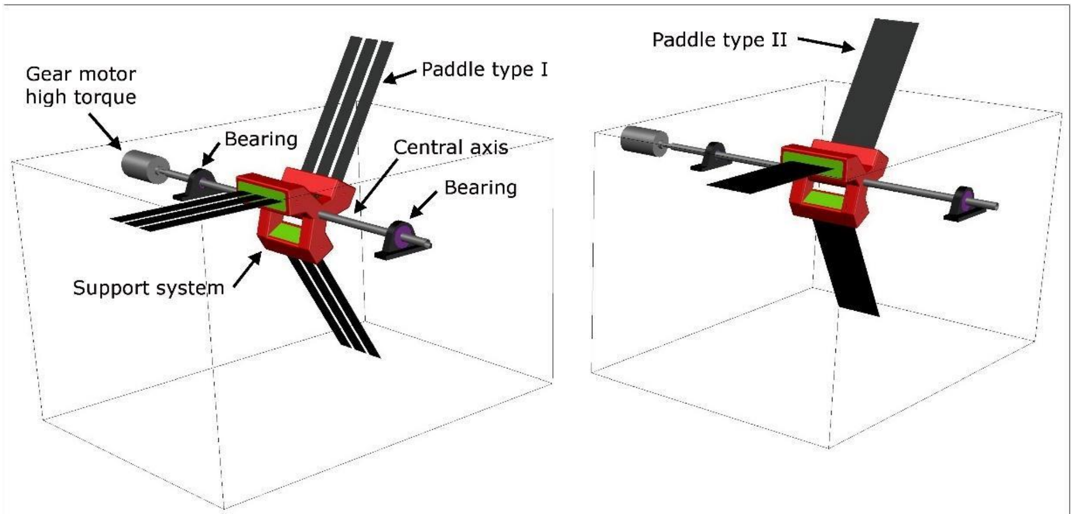

Figure 1. Schematic of the horizontal axis mechanical aerators used in this study using the Type I blade system (left) and the Type II blade system (right).

DO concentration in the water samples was measured with an oximeter in 5 minutes intervals for one hour and subsequently in 15 minutes interval until reaching a saturation concentration of 98 % of the initial concentration (Engineers, A. S. of C., 2007). Measurements were made on the opposite diagonals of the mount for each measurement time at a depth of 5cm. 6 replications were made for each trial in order to ensure the validity and replicability of the process.

The data obtained in this study were analyzed using non-linear regression models, evaluating the performance of the aeration process. The DO transfer rate (SOTR), the transfer coefficient (K_La), and the standard aeration efficiency (SAE) were performed through the calculations presented by Rojas-Romero (2010), and Roy, Moulick and Mal (2017), using a temperature correction factor for the value of K_La. The transfer can be expressed as follows:

$$\frac{dC}{dt} = K_L a(C_\infty^* - C) \quad (1)$$

Where,

$K_L a$ = Volumetric mass transfer coefficient (1/T).

C_∞^*= Final DO concentration average in an infinite time (mg·l^{-1}).

C= Average effective concentration of DO in the liquid phase.

The integrated form becomes:

$$ln \frac{C_\infty^* - C_o}{C_\infty^* - C} = K_L a(t - t_0) \quad (2)$$

$$C = C_\infty^* - (C_\infty^* - C_0) \cdot exp\, exp\, [K_L a(t - t_0)] \quad (3)$$

Where,

C_0 = Initial DO concentration, when $t = t_0$.

Equations (2) and (3) are used for tests in clean water, in non-steady state, to determine the transfer capacity of aeration equipment and can be applied to different aeration systems (Liu, Shi, Wang, Fan, & Shi, 2013). Since the temperature varies during the experimentation process, the volumetric mass transfer coefficient K_La must be converted to standard temperature (T = 20°C) by means of equation 4:

$$K_L a_{20} = 1.024^{(20-t)} \tag{4}$$

The standard oxygen transfer rate ($SOTR_{20}$ $kgO_2 \cdot h^{-1}$) indicates the amount of oxygen transferred per hour under standard conditions, which can be calculated based on the following equation:

$$SOTR = K_L a_{20} \cdot C_{s,20} \cdot V \tag{5}$$

Where,

$K_L a_{20}$ = Volumetric mass transfer coefficient (1/T) at 20 °C.

$C_{s,20}$ = Saturation concentration for a steady state at 20 °C.

V = volumen of the liquid.

The standard aeration efficiency (SAE) is expressed as the oxygen transfer per unit of power, as indicated in the following equation:

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

Where,

$SOTR =$ Standard oxygen transfer rate ($kgO_2 \cdot h^{-1}$).

$Power =$ Power consumed (kW).

The power in watts [W] of the gear motor was calculated as the product of the electrical voltage (voltage) multiplied by the intensity of the electrical current (amperage); based on the following equation:

$$P = V \cdot A \quad (7)$$

Where,

P= Power in watts.

V= Voltage

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A= Current.

Results and discuss

DO transfer measurements were made in anoxic water bodies using two types of blades that contained the same surface area but a different contact perimeter, with an impact angle of 180 ° and 13.5 °. The results obtained allowed the analysis of the data from graphs and mathematical relationships that determine the efficiency of the transfer process carried out for each type of sample.

A high rate of DO transfer is observed during the first minutes in the water samples, gradually reducing until reaching a maximum saturation value generating a stabilization phase. The handling of water samples under anoxic and hypoxic conditions experiences a higher oxygen saturation rate in its initial stage due to the difference between the partial pressure of DO in water and atmospheric O2 (Abdelrahman & Boyd, 2018; Sander, 2015). Upon reaching the point of maximum DO saturation concentration in the water, the oxygen transfer rate will be reduced, generating an Arrhenius-type behavior until reaching a point of equilibrium, penalizing the energy consumption of the aerator system (Bahadori & Vuthaluru, 2010).

Figure 2 shows the variation of the DO concentration of the water, as a function of the stirring time. The blades rotate and impact the water with an entry angle of 13.5° and 180°. Values close to 95 % of the initial DO concentration were obtained during the first 60 minutes, in that way to generate a gradual attenuation in the DO transfer rate until achieving 98 % (7.35 mg·l^{-1}) of the initial concentration at 120 minutes of starting the experiment.

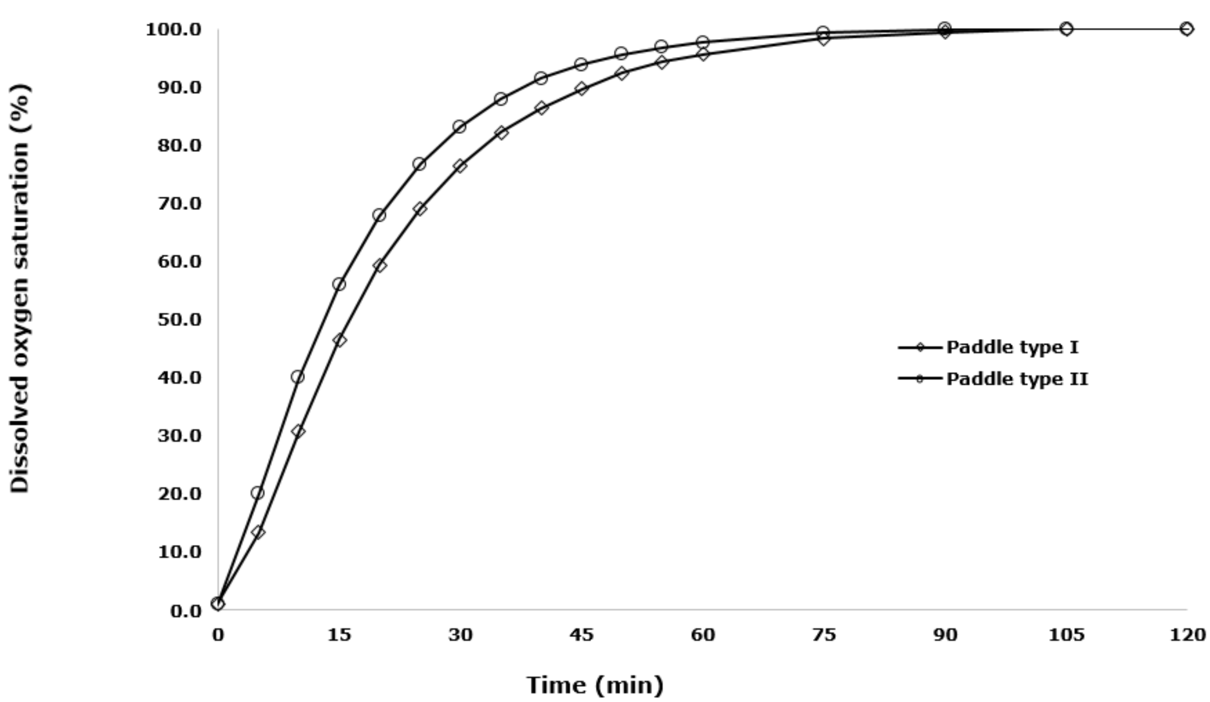

Figure 2. DO saturation percentage curves in the water samples worked with an impact angle of 13.5° and 180°.

By using a 180° angle, Type II blades generates greater water displacement when submerged. This situation favors greater agitation, trapping and transport of air within the body of water, as shown in Figure 2. On the other hand, the application of blades with a greater contact perimeter reduces the possibility of trapping and transporting a greater quantity of air into the water body, reducing the rate of DO transfer per unit time.

Reducing the angle at which the blades impact the water allows an increase in the rate of DO transfer in the fluid. DO transfer relationship as a function of time can be seen in Figure 3. The force exerted per unit area is reduced by partially impacting the blades with the body of water, requiring a lower energy supply to keep the system working at a constant rotational speed. An inclination of the blades can contribute to a greater trapping of air within the system in a manner comparable to that presented by Tian, Xu, Chen, Liu and Zhang (2018). This reduction in the force exerted is reflected in the energy required by the system to maintain a stable rotational speed (Bahri *et al*., 2015; Bahri *et al*., 2019).

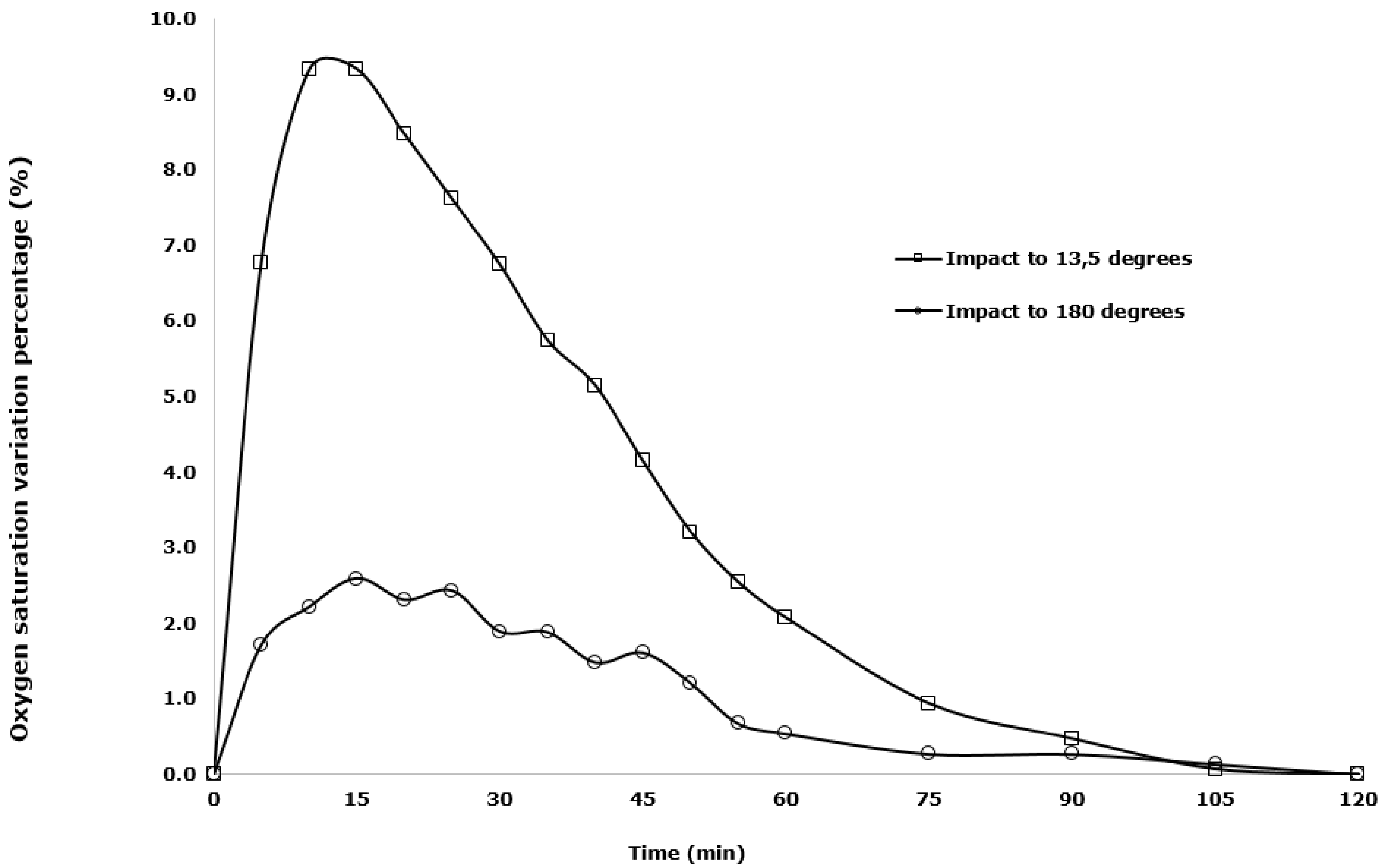

Figure 3. Variation in the percentage of DO transfer per measurement time, between the two systems worked with an impact angle of the blade of 13.5° and 180° respectively.

The volumetric mass transfer coefficients K_La (h^{-1}) were calculated using the non-linear regression method (Engineers, A. S. of C., 2007). These data made it possible to determine the efficiency of the transfer process based on energy consumption. The summary of the values obtained in this study is presented in Table 1. A K_La coefficient is observed for the Type I blade system with an equivalent value of 3.00 h^{-1} and 2.87 h^{-1} with an impact angle of 13.5° and 180°, respectively. The K_La values obtained using Type II blades show a value of 3.69 h^{-1} (23 % higher) and 3.06 h^{-1} (6.6 % higher) in relation to the first device. Regardless of the variation in power supplied, the geometry of the blades is a very important design parameter that can have a transcendental influence on the agitation of the water and the transfer of dissolved oxygen.

Table 1. Summary of the data obtained in this study for the aeration systems with Type I and Type II blades.

Impact angle	**I-type blade**		**II-type blade**	
	13.5°	**180°**	**13.5°**	**180°**
Voltage (V)	6	6	6	6
Current (Å)	0.46	0.53	0.53	0.63
Power (W)	2.76	3.18	3.18	3.78
K_La (h^{-1})	3.00	2.87	3.69	3.06
Velocity (RPM)	21	20	21	20
dc/dt ($g \cdot h^{-1}m^{-3}$)	27.62	26.41	33.98	28.19
SOTR ($kgO_2 \cdot h^{-1}$)	1.22	1.16	1.49	1.24
SAE ($kgO_2 \cdot kW^{-1}h^{-1}$)	0.44	0.37	0.47	0.33

The SAE values were also obtained in this study, allowing to observe the effect in the variation of the perimeter and impact angle of the blades on energy consumption that involves transferring DO to the water bodies. The surface area of the blades for the two experimental situations was the same; however, Type II blades required a higher energy consumption when impacting and breaking the water surface. This energy consumption is reduced by using an impact angle of 13.5°, obtaining power values similar to those obtained in the system with Type I blades and 180° impact angle.

The reduction in force exerted to maintain a constant rotational speed was considerably reduced, improving SAE by 19 and 42 % for systems with Type I and Type II blades, respectively, by reducing the angle of impact. It is presumed that the gaps between the Type I blades allow less resistance to the advance of the water flow during the moment of impact. This situation reduces the force necessary for these blades to penetrate the surface of the water, thus reducing the energy consumption associated with this situation while maintaining a constant rotation speed of the system.

The SOTR depends on the number of blades, as well as the rotation speed of the aerator (Roy *et al*., 2017). However, in this case we can see that the type and geometry of the blade can affect this value. The SAE values show that the best performance was obtained for the Type II blade configuration with an impact angle of 13.5°. while the worst behavior can be observed in the same system by varying the angle to 180°.

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The study allowed observing the behavior of the blades when submerging in the body of water. Air entrapment is observed during immersion of the blades into the body of water. The images obtained are presented in Figure 4. This behavior remains independent of the angle of impact of the blade, the shape of the blade being of greater importance.

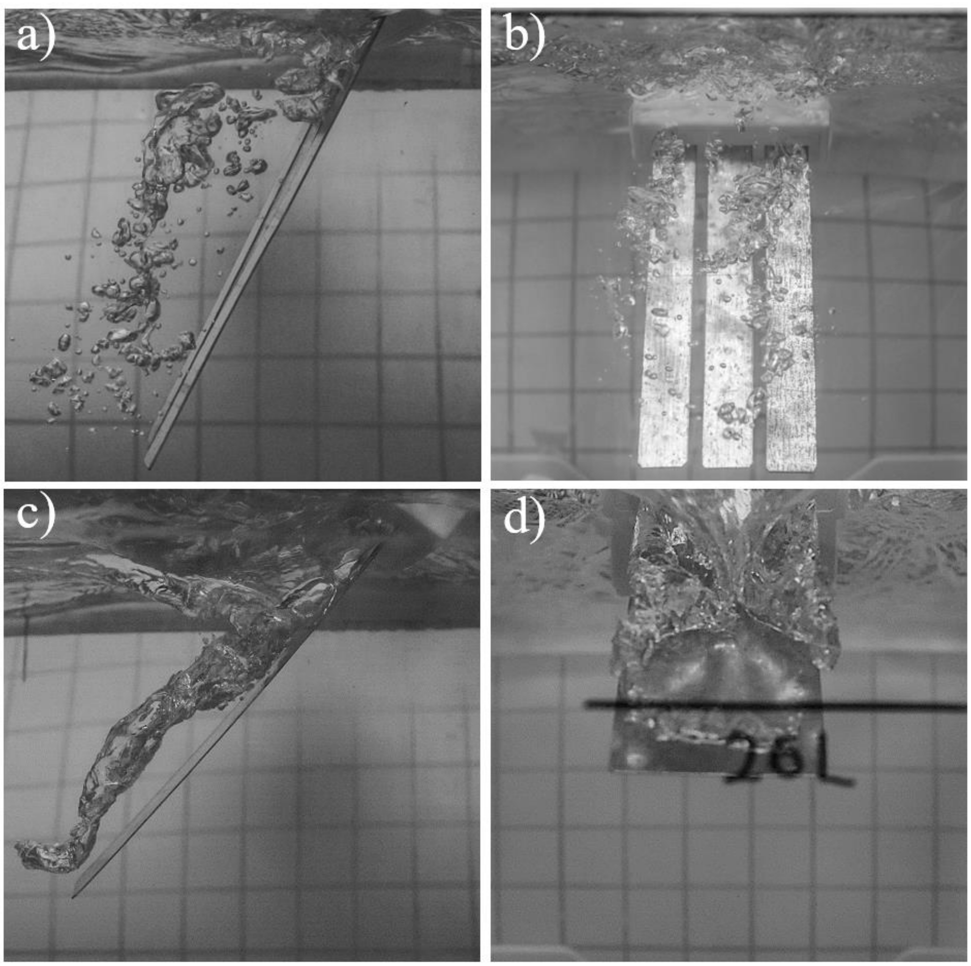

Figure 4. Behavior of air trapped under water in the worked blade systems. a-b) Type I blade systems and c-d) Type II blade system.

Depending on the type of blade used, this behavior presents a variation in air trapping, i.e. In Figures 4-c and 4-d, a vortex-shaped entrapment is seen when applying a Type II blade system. These blades, having a greater width, generate a greater depression at the moment of impact and submerge in the body of water, concentrating the return of the water to its original state through the lateral edges. On the other hand, the trapped air takes the form of several vortices that are located at the ends of the blades. The vortices are displaced within the water by the inertial rotational movement that the system maintains. In the case of the Type I blade system (Figure 4-a and 4-b), the trapped air ends up colliding, disintegrating itself, to form clusters of bubbles, which end up reaching the surface of the water. A better understanding of this situation can favor the design of mechanical aerator systems that are more efficient in terms of energy consumption and with a higher DO transfer rate.

Conclusions

The effect of the edge and contact angle in two types of blades used in a horizontal axis mechanical aeration system in anoxic water bodies has been studied. It was observed that the importance of the geometry and variation of the blade contact perimeter, as well as the angle at the moment of impact with the body of water have a great influence on the DO transfer process, as well as energy efficiency, in terms amount of DO transferred due to energy consumption during the aeration process.

The transfer of atmospheric oxygen in DO was generated only by the phenomen of surface agitation and the trapping of air within the body of water. The transfer effects given by lifting and splashing the fluid above the water surface were eliminated by maintaining a low rotational speed. The geometry of the blades in a horizontal axis mechanical aerator can generate a predictable behavior of the air trapped within a body of water, even when agitation or turbulence occurs on the same surface of the fluid.

The effect of the perimeter and angle of impact of the blades on the body of water are reflected in the efficiency and energy consumption of the process. The reduction of the contact angle generates an improvement in the process in energy costs, mainly in Type II blade systems. Additionally, the formation of vortices and trapping of air bubbles within water bodies were observed, which can contribute to the transfer process. This effect is expected to be studied further in future research.

The authors express their motivation in the development of this research, which is related to the effects that climate change can have on water bodies, such as deoxygenation due to increased temperature. This problem could strongly affect aquatic ecosystems in different environments, as well as commercial activities carried out in ponds and lagoons, such as aquaculture processes. The research and development of new technologies can help to mitigate these problems associated with bodies of water.

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