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AERATION SYSTEM POWERED BY SAVONIUS WIND TURBINE

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Abstract. *The energy potential of wind turbines, considering their different formats, brings countless application possibilities as technological alternatives for different emerging sectors. Among these sectors is aquaculture, the productive activity of aquatic life organisms, which is expected to be the next major world frontier in food production, in where Brazil has potential protagonist, being among the world's largest fish producers. Thus, Brazilian aquaculture is experiencing a technological intensification of crops where, among the main applied technologies, is aeration, an important factor to increasing of crop densities in fish farming. Given the above, abroad and unrestricted overview of the needs present in the environment, coupled with knowledge of existing technologies and their applications, make it possible to allocate not widely explored technologies as alternatives for carrying out works where their constructive characteristics sum up to the environment, filling technological gaps and meeting two needs that are still not much observed. From this perspective, the present work proposes the project for the construction of a Savonius wind turbine for the use of wind energy as a propellant for an aeration device to the aeration of ponds in aquaculture, thus constituting a renewable and clean energy source applied to the development of the rural environment. Theoretically calculated values indicate that the proposed wind-powered aerator meets the demand of 0.5 kg O_2/h, with the wind turbine operating with winds of the order of 10 m/s and power around 180 W.*

Keywords: *savonius wind turbine, aeration, fish farming, dissolved oxygen, renewable energy.*

1. INTRODUCTION

Incentives for family farming, through United Nations programs (UN, 2020) presents themselves as gateways for energy efficiency and sustainable energy generation projects, which carry great possibilities for the development of urban and rural areas.

Aquaculture, on the other hand, pointed out as the next world frontier in food production in 2014, according to FAO (2016), presented world fish production at the mark of 73.8 million tons, with 561 thousand tons coming from Brazil, which ranks 13th in the general ranking of the largest fish producers. In this context, FAO – the United Nations arm for the promotion of agricultural production, gives Brazil the role of potential protagonist in aquaculture production, attributing to the country an expected production of 20 million tons/year by 2030, (WORLD BANK, 2013).

Thus, Brazilian aquaculture experiences a fast professionalization due to the technological intensification of crops where, among the main technologies applied to the production in fish farms, is the aeration an important factor to increase of crop densities, which is defined as the transfer of oxygen present in the atmosphere to the water body. The aeration process, however, is carried out by equipment powered by the electrical grid and many times often expressive values of cost due to energy consumption.

The conversion of the energy contained in the winds into useful energy has been recorded since antiquity, when boats and also grain mills use the energy of the winds to propel their sails, converting the kinetic energy of the fluid mass in motion into mechanical energy and work, what is known today as wind energy.

Currently, the mechanical architecture used in capturing of wind energy is, preferably, aimed at obtaining of electrical energy, although the energy potential of these technologies is not limited exclusively to this.

Recent works such as Mahmudov et al., (2019) propose the aeration of ponds for small scale fish production given through wind energy, while Tien et al., (2019) presents the environmental impacts that can be reduced by adopting renewable energy sources for aeration in shrimp farming, an activity that demands high consumption of electricity, and Kirke (1995) addresses the importance of aeration applied to different scenarios such as, for example, the lakes stratification.

Therefore, it is necessary to adopt a broad and unrestricted view of the whole allied to the understanding of the needs present in the environment, as essential characteristics in engineering research because by knowing not only limitations but also advantages of certain technologies, it is possible to design them as alternatives to carrying out diverse of works, in different areas or environments, in which their constructive and mechanical characteristics are added to the environment, filling existing technological gaps, meeting needs that still no much observed and thus contributing to human development.

From this point of view, this work presents the project for the construction of a Savonius micro wind turbine able to, with appropriate dimensioning, compose an accessible and mechanically efficient system, as an alternative and renewable energy source for the aeration by diffused air in fish farms. Therefore, contributing economically to the development of the aquaculture sector with the reduction of costs arising from the consumption of electricity.

2. METHODOLOGY

2.1 Project Methodology

Diffused air oxygenation is a technique that uses an air compressor connected to a submerged injector nozzle witch, in turn, connects to a bubble diffuser device, constituting one of the best techniques for oxygenation. Due to the formation of bubbles that can be thin, medium or large, there is an increase in the gas exposure surface to the water body and a consequent increase in the oxygen transfer rate, presenting itself as an aeration mechanism suitable for different depths, in addition to contributing to reducing the organic matter decomposition at the bottom of pond (Von Sperling, 1997).

Aeration through an air compressor powered by a wind turbine, proposed in this work, is an alternative technology, not presenting previous references of predecessor devices for direct comparison of performance or efficiency. Thus, the methodology applied for the development of this wind-powered aerator device assumes, as design parameters, the comparison of this developing technology with existing technology on the market, in this case, an industrial aerator commonly applied for diffuse air aeration, powered by electric energy, as a reference device.

The Aeromack model CRE-MINI industrial aerator, which has a nominal power output of 248 W, and an air flow rate of 1.1 m³ / min is allowed (Aeromack, 2020), is therefore admitted.

2.2 Dimensioning of the wind turbine

Vertical axis wind turbines, also known as VAWT, are characterized by their rotation axis that's perpendicular to the wind speed and ground, and by providing low angular speed and high torque. Designed by Sigurd J. Savonius in 1922, the Savonius wind turbine is regarded as one of the simplest models among vertical axis wind turbines and operates due to the aerodynamic drag forces. Generally composed of two blades – as originally designed, this model of wind machine has its geometry very similar to the letter "S", making its blades less resistant to the opposite movement to the flow than in favour of this, which results in the conversion of the amount of movement contained in the winds into mechanical torque on its axis (Menet, 2004).

The dimensioning of the wind turbine, proposed in this work, is based on the expected performance of the equipment and on the structure of the installation and operation site, where its proximity to the water body ensure lower values of pressure drop, from the distance between the equipment and the aeration point. Therefore, dimensional design values are assumed as shown in Tab. 1.

Table 1. Savonius wind turbine dimensions.

Turbine area	A	1.6	m²
Diameter	D	0.8	m
Height	H	2.0	m
Eccentricity	e	0.08	m
End plate	D_O	0.88	m
Radius	R	0.40	m
Chord	c	0.44	m
Aspect ratio	RA	2.50	-
Eccentricity ratio	R_E	10.0	%
Number of blades	N	2	-
Solidity	σ	2.20	-

According to Akwa (2010), design values referring to the aspect ratio *RA* in Savonius turbines, can be admitted for continuous torque and good power performance, which can be seen in Eq. (1).

$$RA = \frac{H}{D} \tag{1}$$

where *H* represents the height of the turbine and *D* its diameter.

Values for R_E eccentricity ratio, on the other hand, avoid the increase of flow recirculation in the central region of the wind turbine rotor and consequent reduction of performance, according to Eq. (2).

$$R_E = \frac{e}{D}.100 \tag{2}$$

where *e* represents the eccentricity between the turbine blades.

This design approach seeks to obtain the most optimal use of the wind potential available in the environment and, based on the torque coefficient C_T, achieve results for continuous torque and satisfactory values of power delivered to the turbine shaft, intended for air compressor work.

The final geometry of the wind turbine, according to the methodology applied in the project, is illustrated in Fig. 1.

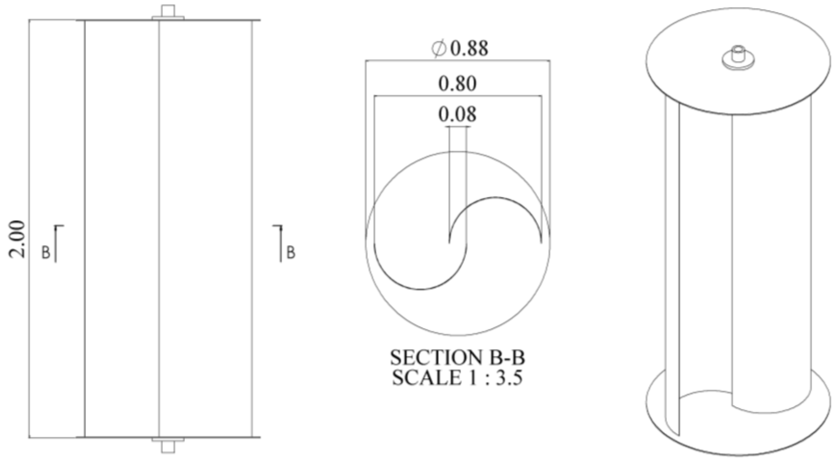

Figure 1. Savonius wind turbine geometry [m].
(Authors)

A projection for torque values in a Savonius wind turbine can be obtained by taking into account the turbine geometry, the wind speed and the torque coefficient (Burton, et al., 2011) through Eq. (3).

$$C_T = \frac{Torque}{\frac{1}{2}.\rho.V_\infty{}^2.A.R} \quad \rightarrow \quad Torque = C_T.\frac{1}{2}.\rho.V_\infty{}^2.A.R \tag{3}$$

where C_T represents the torque coefficient and V_∞ the wind speed.

Approximate values of torque coefficients, for Savonius turbines, can be found in the literature, where they are presented as a function of the tip speed ratio (TSR), taking as reference for torque calculation, the maximum values for C_T (Fig. 2).

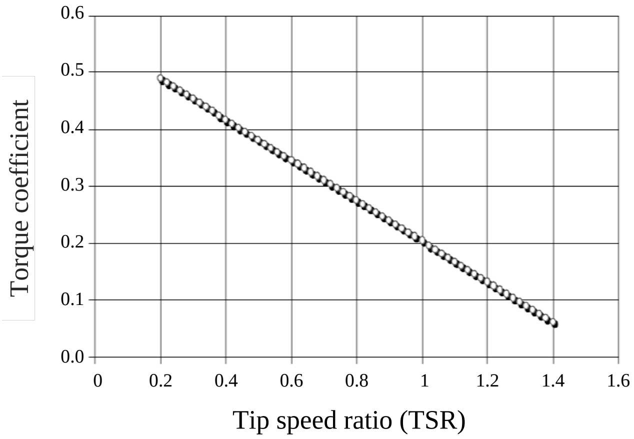

Figure 2. Torque coefficient as a function of the tip speed ratio (TSR)
(Adapted from ALÉ, Jorge A. V. – Small Wind Turbines Workshop, 2012.)

The wind speed V_∞ is the current speed of the wind without the interference of the turbine. Since the proposed wind-powered aerator will operate close to the ground, average wind speed values for *surface winds*, at a height of 10 m from the ground, allow for the proposed scenario. In this case, the Climatological Table of the International Airport Salgado Filho (SBPA) - Porto Alegre/RS is adopted, where historical measurements between the years 2001 and 2010 point to winds with an annual average speed of approximately 4.3 m/s and gusts of 14 m/s, as provided by Redemet (2020). The value adopted for wind speed is shown in Tab. 3.

The power extracted from a wind turbine, that is, it's useful power, is taken as the product of the available power in the wind by its power coefficient (Burton, et al., 2011) and can also consider the extracted power as a product of torque by the frequency or angular speed, on the wind turbine shaft (Eq. 4).

$$C_P = \frac{P_E}{P_D} = \frac{T.\omega}{\frac{1}{2}.\rho.V_\infty{}^3.A} \quad \rightarrow \quad P_E = C_p.\frac{1}{2}.\rho.V_\infty{}^3.A \tag{4}$$

where C_P represents the power coefficient, P_E the extracted power by the wind turbine and V_∞ the wind speed.

Approximated values of power coefficients of Savonius wind turbines can be found in the literature, where they are presented as a function of the tip speed ratio (TSR) taking as reference maximum values for C_P (Fig. 3).

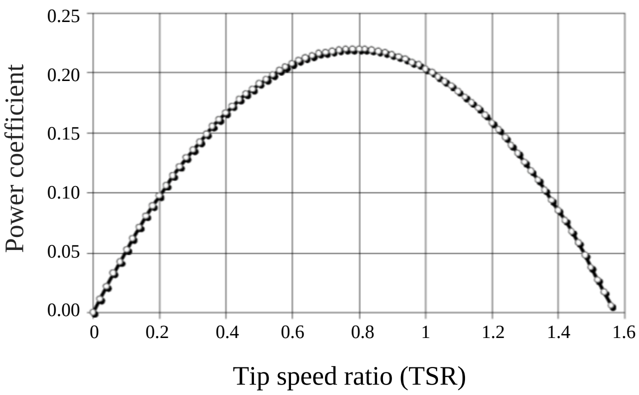

Figure 3. Power coefficient as a function of the tip speed ratio (TSR).
(Adapted from ALÉ, Jorge A. V. – Small Wind Turbines Workshop, 2012)

The tip speed ratio TSR is the ratio of the tangential velocity V_T, in the wind turbine blade, by the wind speed V_∞ and, therefore, directly related to the angular velocity of the turbine ω, as well as its geometry, being represented in Eq. (5).

$$TSR = \frac{V_T}{V_\infty} = \frac{\omega . R}{V_\infty} \tag{5}$$

where R represents the distance between the center of the shaft to the tip of the blade, that is, the radius of the wind turbine.

Since values of torque coefficient C_T and power coefficient C_P can both be expressed as a function of TSR values, such magnitudes are proportional, as observed in the following expression (Eq. 6).

$$C_P = \frac{P_E}{P_D} = \frac{T . \omega}{\frac{1}{2} . \rho . V_\infty{}^3 . A} = \frac{T}{\frac{1}{2} . \rho . V_\infty{}^2 . R} \; . \; \frac{\omega . R}{V_\infty} = C_T \, . TSR \tag{6}$$

2.3 Dimensioning of the air compressor and diffusers

For air injection, an air compressor model CRE-MINI of Aeromack brand is chosen with a nominal power of 250 W and a maximum flow rate of 1.1 m³/s. Its connection to the wind turbine is given shaft-to-shaft coupling, discarding energy losses by gearboxes (Aeromack, 2020).

Two Armax model P-25 plate-type flat diffusers with a maximum flow rate of 284 L/min each area allowed for the project. The efficiency allowed for the diffusers is about the order of 7 % of the injected oxygen volume per meter of depth of the diffusers. Calculated values of efficiency and pressure drop can be seen in Tab. 4.

The connection between the equipment that makes up the aeration system is given according to the diagram in Fig. 4.

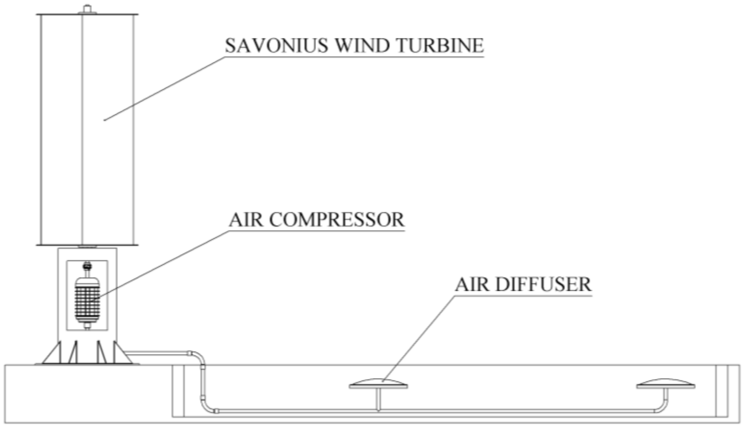

Figure 4. Connection diagram of the aeration system.
(Authors)

3. RESULTS AND DISCUSSION

3.1 Proposed scenario for analysis

To calculate the performance of the wind aerator an analysis environment is proposed as a pond under operating conditions, where the equilibrium during the aeration process is related to the saturation concentration of the gas C_S in the liquid phase, i.e., to the maximum of oxygen that can be dissolved by the water body, according to atmospheric pressure and temperature, observed in Eq. (7).

$$C_S = K_D \, . D_V \, . (P_A - P_V) \, . \left[\frac{P_m}{(R.T)} \right] \tag{7}$$

where D_V is the volumetric distribution of Oxygen in atmospheric air, P_m the molecular weight of oxygen, P_A the *in loco* atmospheric pressure, P_V the water vapor pressure as a function of temperature, R the universal gas constant and T the temperature.

The oxygen concentration in the pond C_O represents the initial concentration of the gas within the liquid mass, and a zero value is adopted for the analysis, i.e., it represents a scenario of total absence of dissolved oxygen in the water.

According to Arana (2017), the atmospheric pressure affects the efficiency of the aerators, since, at sea level, the aerators have their maximum performance due to the greater solubility of the atmospheric oxygen at this pressure and, therefore, there is a considerable drop in the solubility of the gas with the increase in altitude, reducing the efficiency in aeration, which can be observed in Eq. (8).

$$f_H = \frac{C_{S'}}{C_S} = 1 - \left(\frac{A_{LT}}{9450}\right) \tag{8}$$

where f_H is the correction fator for C_S according to altitude H. Therefore, an ideal condition for the analysis environment is established, suggesting a fish farm located at sea level.

The oxygen concentration is also affected by salinity or the concentration of dissolved salts in the liquid environment, and a correction factor is adopted, considering a salinity of 35 %. The mass transfer rate of diffusion of gas molecules to water in the liquid phase through an exposure area is given by the Fick's Law (Eq. 9), where

$$\frac{dM}{dT} = -D \,.\, A \,.\, \frac{dC}{dx} \tag{9}$$

where D is the molecular diffusion coefficient, A is the interfacial area of exposure, x the distance of interface and dC/dx the concentration gradient.

Therefore, the rate of gas absorption to the liquid environment occurs according to the *Penetration Theory* of mass transfer, (Eq. 10),

$$\frac{dM}{dT} = A.(C_S - C_O) \,.\, \sqrt{\frac{D}{(\pi.t)}} \quad \rightarrow \quad \frac{dM}{dTA} = (C_S - C_O) \,.\, \sqrt{\frac{D}{(\pi.t)}} \tag{10}$$

where M is the mass of absorbed gas per unit of area A during the exposure time t and C_O the initial concentration of the gas within the liquid mass. The depth of gas penetration into the liquid mass (Eq. 11) is given by

$$X_P = \sqrt{(\pi.D.t)} \tag{11}$$

The aeration kinetics, that is, the variation of the gas concentration within the liquid mass in time C, are given by the volumetric or global coefficient of oxygen transfer K_{LA} *(s^{-1})* that under stationary conditions is given by Eq. (12),

$$K_{LA} = 2 \,.\, \sqrt{\frac{D}{(\pi.t)}} \,.\, \left(\frac{A}{Q_{AR}}\right) \tag{12}$$

where Q_{AIR} is the flow rate.

Assuming that the mass of gas absorbed at the time M as the product of the variation in gas concentration at time t, by the flow rate, has the Eq. (13), where

$$\frac{dC}{dt} = K_{LA} \,.\, (C_S - C) \tag{13}$$

and the lower the oxygen concentration or the higher the deficit *(CS – C)*, the higher the transfer rate dC/dt, resulting in Eq. (14),

$$C = C_{máx} - (C_{máx} - C_O) \,.\, 10^{-K_{LA}\,.(t-t_o)} \tag{14}$$

finding that the highest value that can be reached by oxygen concentration is lower than saturation, which is observed in the graph of Fig. 5.

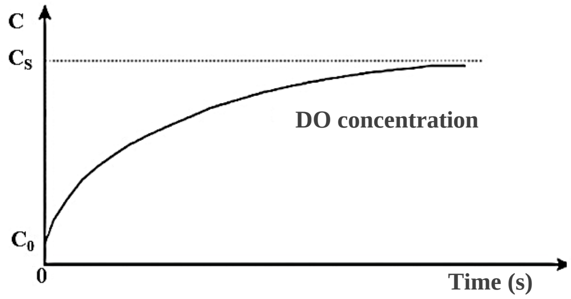

Figure 5. Time progression of OD concentration during aeration process.
(Adapted from Von Sperling, 1997)

Oxygen transfer is influenced by temperature, where the change in saturation concentration C_S occurs and, consequently, change the mass transfer coefficient K_{LA}. This influence can be represented by Eq. (15),

$$K_{LA\,(T)} = K_{LA\,(20°\,C)}\,.\,\Theta^{(T-20)} \tag{15}$$

where Θ is the temperature coefficient, commonly adopted of 1,024.

In turn, considering that the greater the amount of dissolved oxygen present in the liquid environment *OD*, the lower the transfer rate, has an influence on oxygen transfer *OD*, thus admitting a correction factor for concentration *OD* (Eq. 16), as being

$$OD = \frac{(c_S - C_L)}{C_{S\,(20°\,C)}} \tag{16}$$

Oxygen transfer is also influenced by the oxygen concentration maintained in the pond C_S, since the latter influences the oxygen transfer coefficient, K_{LA}. Thus, a correction factor β is admitted for the influence of C_S in K_{LA}, according to Equation (17)

$$\beta = \frac{C_S}{C_{S\,(20°\,C)}} \tag{17}$$

and, consequently, for the influence of K_{LA} on the oxygen transfer, a correction factor is established α, obtained by Eq. (18).

$$\alpha = \frac{K_{LA}}{K_{LA\,(20°\,C)}} \tag{18}$$

The total oxygen transfer demand in the pond DTO_2 represents the need of dissolved oxygen replacement in the water in kilograms per hour, based on fish respiration and other organisms; while the standard oxygen transfer rate *SOTR* (Eq. 19), is the amount of oxygen that should be transferred to the water body considering DTO_2, the physical conditions inside the pond, as well as correction factors for altitude, presence of salts, particulate matter, degree of mixing and temperature during operation.

$$SOTR = \frac{DTO_2\,.\,C_{S\,(20°\,C)}}{\{[\beta\,.\,f_H\,.\,(C_S - C_O)]\,.\,\alpha\,.\,\Theta^{(T-20)}\}} \tag{19}$$

The summary of the physical operating conditions of the proposed scenario for analysis is shown in Tab. 2.

Table 2. Physical conditions of water inside the pond.

Approximate area	A_T	430	m²
Approximate depth	P	2	m
Water temperature	T	20.0	°C
Altitude	A_{LT}	sea level	
Salinity	S_{AL}	35	%
Oxygen saturation concentration	Cs	9.20	mg/L
Concentration of oxygen inside the pond	Co	0.00	mg/L
Total Oxygen Demand	TOD	0.50	kg O_2/h
Standard Oxygen Transfer Rate	$SOTR$	0.88	kg O_2/h

3.2 Torque, power and efficiency of the wind turbine

As referred in item 2.2, the projection of torque and power values of the turbine is based on the wind speed V_∞, the turbine geometry (Tab. 1) and the torque coefficient C_T. The calculated values are shown in Tab. 3.

Table 3. Calculated torque and power values for turbine as a function of C_T.

Wind speed	V_∞		10,0		m/s
Mass flow rate	Qm		19,27		kg/s
		Minimum	Medium	Maximum	
Rotation	R_T	35.0	20.0	23.4	RPM
Angular velocity	ω	35	20	5	rad/s
Tip speed ratio (TSR)	λ	1.4	0.8	0.2	
Torque coefficient	C_T	0.06	0.28	0.49	
Torque	T	2.31	10.60	18.88	N.m
Available wind power	P_D		963.3		W
Power coefficient	C_P	0.084	0.220	0.098	
Power extracted by the wind turbine	P_E	80.9	211.9	94.4	W

3.3 Efficiency of the wind-powered aerator system

Taking as a reference theoretical values of the torque delivered on the turbine shaft, it is possible to calculate the air compressor flow rate adopted for the aeration work and, according to the conditions of the environment or scenario proposed for analysis, is given the calculated values for oxygenation efficiency *SAE* and the efficiency in the transfer of oxygen *SOTR* of the wind turbine - air compressor set, that is, to the proposed wind-powered aerator system, as shown in Tab. 4.

Table 4. Calculated values to the wind turbine efficiency, considering a wind speed of 10 m/s.

Specific mass of water	ρ	1000	kg/m³
Gravity acceleration	g	9.81	m²/s
Power delivered by the wind turbine	P	211.9	W
Ari compressor flow rate	Q_{AR}	0.00757	m³/s
Diffusers Efficiency in oxygen transfer	η_D	14	%
Head loss in the diffusion system	ΔH	0.45	m
Immersion depth of air diffusers	Di	2	m
Power required for diffused air aeration	P_A	182	W
Standard Oxygen Transfer Rate	$SOTR$	0.881	kg O_2/m³ AR
Standard Aeration Efficiency	SAE	4.84	kg O_2/kWh

The adequate interpretation of the obtained values is based not on expressive results of nominal power, but on the capacity that the equipment presents in the transference of oxygen to the liquid environment and the energy consumed during the process. Therefore, four essential factors are considered, they are: *TOD* - which is the oxygen demand inside the pond, considering the breathing of the animals and other organisms, *STOR* - standard oxygen transfer rate of the aerator, and aims at meeting the oxygen demand in the pond according to the physical conditions of the environment, P_A - which refers to the power required for aeration, in this case, by diffused air, and the *SAE* - which indicates the oxygen transfer rate per unit of power consumed.

The *SAE* points out that equipment that presents high power, delivering higher flow, does not necessarily constitute equipment of greater efficiency for aeration. This is explained by the fact that the absorption of oxygen injected into the water body by the liquid mass occurs according to the capacity of the environment to absorb such quantity of the delivered gas, during a given operating time and exposure area, a phenomenon explained by Fick's Law (Eq. 11).

Consequently, a good aeration efficiency equipment is considered to be one whose its flow rate meets the oxygen demand inside the pond but also allows that the amount of injected oxygen is effectively transferred to the liquid mass, respecting its capacity to absorb such quantities of gas, with the minimal energy consumption.

4. CONCLUSIONS

Calculated theoretical values indicate that the wind powered aerator meets the total oxygen demand *TOD* established in the proposed environment, according to the equipment’s standard oxygen transfer rate *SOTR* and power of the order about 180 W, supplied by the projected wind turbine, in operation with wind speed around 10 m/s.

The use of oxygen delivered by the wind-powered aerator, in terms of effectively transferred oxygen to the liquid mass, is based on the *SAE* of the equipment, which indicates good aeration efficiency operating exclusively with the power delivered by the wind turbine, without power consumption from the electrical grid.

Thus, it can be said that it is possible to build an aeration system powered by a wind turbine for application in aquaculture ponds, contributing as an alternative, renewable and clean source of energy, with the use of the amount of movement contained in the winds, through its conversion into useful mechanical energy.

5. FUTURE WORKS

Future works aim to addressing the dynamics of the aeration process, obtaining values referring to the amount of effectively transferred oxygen to the liquid mass over the time and according to the evolution of the gas concentration within the liquid mass and its penetration. Thus, it is possible to calculate the actual oxygen supply capacity delivered by the designed aerator system, to a known area of the pond. Such an approach enables not only the adequate sizing but also a good plan for the diffuser’s distribution along the pond, ensuring better control of the process, as well as efficiency values closer to a real operating condition.

In order to obtain experimental values of the equipment’s efficiency and the performance of the designed wind turbine, there is the construction of the wind turbine and the carrying out of experimental tests on site, under real operating conditions. This proposal makes it possible to compare the calculated theoretical values with those measured experimentally, thus resulting in obtaining real values of efficiency and performance of the system.

6. ACKNOWLEDGEMENTS

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