COMPUTATION OF PERFORMANCE AND EFFICIENCY OF THE WATER OXYGENATION PROCESS IN NON-STATIONARY CONDITIONS

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ИЗЧИСЛЯВАНЕ ХАРАКТЕРИСТИКИТЕ НА ПРОЦЕСА НА АЕРАЦИЯ НА ВОДИ В НЕСТАЦИОНАРНИ УСЛОВИЯ

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Abstract: The paper presents a method for computing the performance and efficiency of the water oxygenation process. The method can be used when the concentration of dissolved oxygen increases in function of the duration of the process of introducing in the water. The theoretical results are verified by experimental researches.

Keywords: oxygen dissolved in water, oxygenation efficiency.

1. INTRODUCTION

Oxygen dissolved in water is known as dissolved oxygen DO (Fig. 1) and is conventionally measured in mgO_2/l.

It can be noticed from Fig. 1 that every molecule of water consists of a molecule of oxygen connected to two molecules of hydrogen. Oxygen molecules that constitute the dissolved oxygen can be found among water molecules [1]. The maximum quantity of oxygen that can be dissolved in water depends on a number of physical and chemical parameters [2...9]: atmospheric pressure or pressure exerted on water, water temperature, water salinity, water clearness. Water temperature represents an important parameter: warmer the water, less concentration of DO. Therefore: at t=10°C fresh water can absorb up to 11.3 mgO_2/l; at t=25°C only 8.3 mgO_2/l are absorbed.
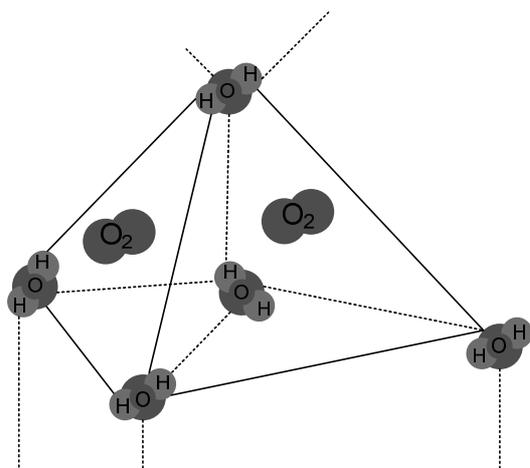

Fig.1. View of the molecular structure: oxygen dissolved in water

The parameters leading to the decrease of the DO concentration are: high temperature of water, oil pollution of water, detergents, presence of ice, water depth.

Water oxygenation processes can be found in treatment and purification plants for residual waters, in food industry, fishing farms and chemistry.

2. NUMERICAL INTEGRATION OF THE DIFFERENTIAL EQUATION THAT COMPUTES THE TRANSFER SPEED OF O_2 DISSOLVED IN WATER

Numerical methods used for the integration of ordinary differential equations are classified in two categories [10]:

- The first category consists of methods with separate steps, namely the methods that require knowing the coordinates of the previous point (x_i, y_i) and the step h in order to compute the ordinate of the point y_{1+1}. These methods issue from the Taylor series expansion of the function in the neighborhood of a point:

$$(1) \quad y(x_{1+1}) = y(x) + h \cdot y'(x_i) + \frac{h}{2!} \cdot y''(x_i) + ...$$

- The second category consists of the methods with connected steps, that require knowing the coordinates of a number of previous points: $(x_i, y_i), (x_{i-1}, y_{i-1}),...$ and the step h in order to compute the ordinate of the point y_{1+1}. These methods issue from the use of the definition formula of the definite integral:

$$(2) \quad y(x_{i+1}) - y(x_{i-j}) = \int_{x_{i-j}}^{x_{i+1}} y'(x)dx$$

where $y'(x)$ is approximated by an interpolation polynomial.

There are a number of numerical methods used for the integration of the ordinary differential equations [10]: the Euler method, the Runge-Kutta method, the Adams-Bashford method, the Milne method, the finite differences method, etc. The Euler method will be used in order to numerically integrate the equation that specifies the transfer speed of the DO in water [11]:

(3) $\dfrac{dC}{dt} = ak_L(C_s - C)$

where:

dC/dt –transfer speed of the dissolved oxygen [$kg/m^3 \cdot s^1$];

ak_L – volumetric factor of the mass transfer [$1/s$];

C_s – mass concentration of the component transferable at saturation (at equilibrium) in liquid phase [kg/m^3];

C – current mass concentration of the component transferable in liquid phase [kg/m^3].

In order to theoretically establish the increase of the dissolved oxygen concentration in function of the duration of the water oxygenation process, one must know the following values:

-initial oxygen concentration for a given water temperature $t=19°C$, $C_1=5.12mg/l$;

-saturation concentration $C_s=9.2mg/l$ for the same water temperature;

-duration of the oxygenation process: $\tau=120min$;

-integration step $h=1min; n=120$ values for C.

From specialty literature [11] for a blown air flow rate of $540 l/h$, kept constant, a value of 0.09 is adopted for ak_L (Fig.2); researched porous diffusers produce fine air bubbles, like the studied fine bubbles generator (FBG).
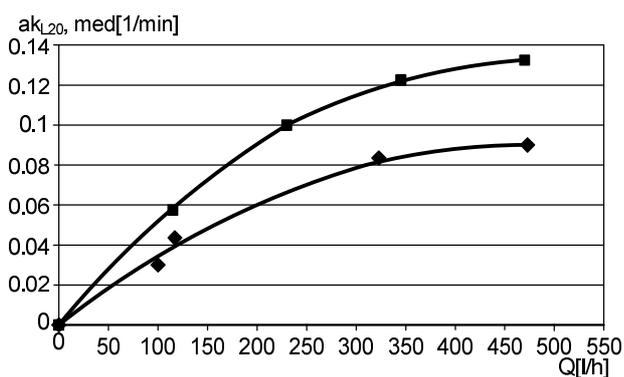

Fig.2. Variation of $ak_{L\,20}$ in function of air flow rate in standard conditions. porous diffusers $\Phi50mm$: ♦ ceramics; ■ glass.

120 points of the curve $C=f(\tau)$ were obtained using the computation software whose logical scheme was presented above. The graphical representation of these points leaded to the curve presented in Fig. 3.
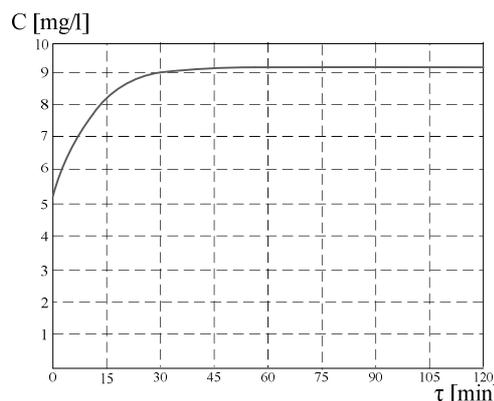

Fig.3. Relation $C=f(\tau)$ established by numerical integration of the differential equation of the transfer speed of O_2 in water

3. EXPERIMENTAL RESEARCHES REGARDING THE FUNCTIONING OF A NEW TYPE OF FINE BUBBLES GENERATOR

3.1. The experimental setup for measuring the concentration of oxygen dissolved in water

After purchasing the oxygen meter from the manufacturer HANNA INSTRUMENTS it was noticed that the instruction manual required that, in order to obtain accurate measurements, water must flow with a minimum speed of $0.3m/s$. This would lead to an important water consumption in the laboratory, thus it was established that the probe must be moved with a speed of:

(4) $v = \dfrac{S}{t} = \dfrac{pd}{t}$

where: d – diameter of the circle on which the probe moves; the circle is situated at the midway between the tank side and the tank axis, $d=0.25m$; τ – duration of a complete rotation of the probe; $\tau=2s$.

The speed of the probe will be:

(5) $v = \dfrac{p \cdot 0.25}{2} = 0.3925m/s$

The experimental plant (Fig..6) includes:

a) A transparent plexiglass rectangular tank, with a volume of: $0.5 \times 0.5 \times 1.6 = 0.4\ m^3$;

b) A compressed air pipe that supplies the fine bubble generator (FBG);

c) Device for driving in circular movement the probe for the measurement of DO concentration;

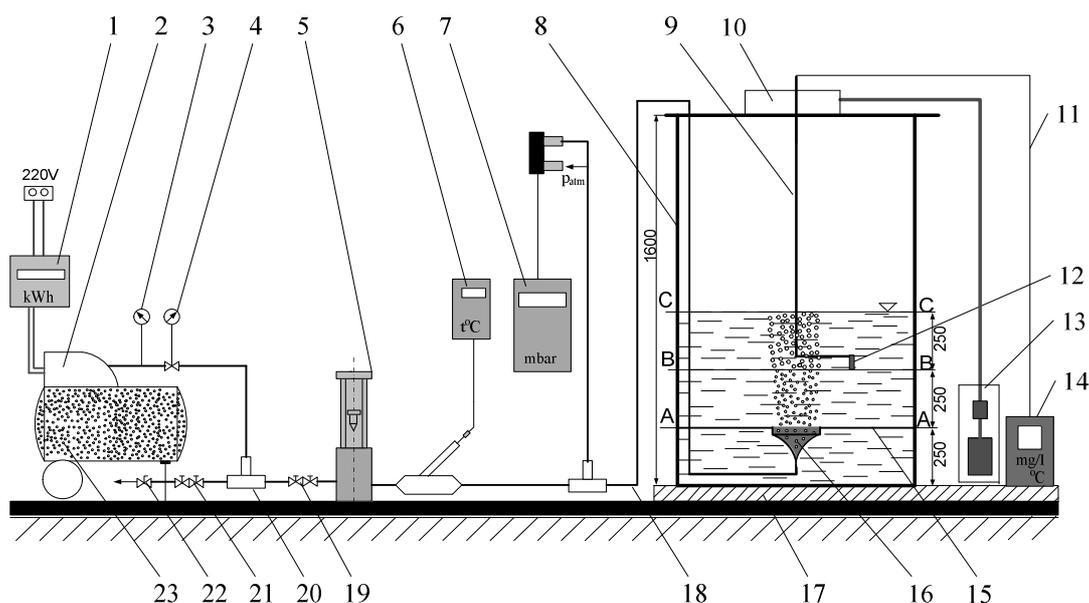d) Connection cable between the probe and the oxygen meter;

Fig.4. Sketch of the stand for experimental researches regarding the water oxygenation.
1 – energy meter; 2 – compressor; 3 – manometer; 4 – pressure reducer; 5 – rotameter; 6 – digital thermometer; 7 – digital manometer; 8 – transparent plexiglass tank; 9 – carrying rod of the probe; 10 – device for rod driving; 11 – connection cable between the probe and the oxygen meter; 12 – oxygen meter probe; 15 – separation plate; 16 – fine bubble generator (FBG); 17 - support plate; 18 – compressed air pipe; 19 – valves for regulating the air flow to FBG; 20 – branch pipe; 21 - valves for regulating the discharged air flow; 22 – closing valve; 23 – compressed air tank.

e)   Oxygen meter of type HI 9146;
f)   Measuring instruments of the parameters of the air blown in the tank:

- Rotameter for air flow rate measuring;

- Digital manometer for measuring the air pressure;

- Digital thermometer for measuring the air temperature.

Pressure of the compressed air and air flow rate were measured; these values were kept constant during measurements.

- In the experimental stand, a column of water of height $H=500mmH_2O$ lies above the perforated plate. The pressure generated by the surface tension [11] is equal to:

$$(6) \quad p_{ts} = \frac{2s}{r_0} = \frac{2 \cdot 8 \cdot 10^{-2}}{0.25 \cdot 10^{-3}} = 620 N/m^2$$

$$(7) \quad \Delta h_{ts} = \frac{p_{ts}}{r_{H2O} \cdot g} = \frac{620}{10^3 \cdot 9.81} = 0,063 mH_2O$$

Hereupon the first gas bubbles will appear if the digital manometer will display:

$$(8) \quad \Delta h_1 > H + \Delta h_{ts} \Rightarrow \Delta h_1 > 563 mmH_2O$$

Fig.5. FBG in function; $\Delta h_1 = 60 mbar = 611 mmH_2O$

- Previous researches [12][13] proved that the air pressure at the entrance to FBG had to be equal to $611\ mmH_2O > 563\ mmH_2O$, therefore the FBG functioned normally (Fig. 5).

3.2. Methodology of measurements

The measurements are performed in eight stages.

I) The first measurement is illustrated in Fig. 4 where the water column above the FBG is of $h_{H_2O} = 500mm$ and the probe situates at $h_{probe}=250mm$, the initial concentration of DO being $C_0=5.12$ mg/l, the indication of the energy meter $E_0=31.6$ kWh and the water temperature $t=19.5°C$. The pressure and the rate of the air flow that enters the FBG are measured: $p_1=611mmH_2O$; $\dot{V}_1 = 540l/h$, values that are maintained constant during the measurements. After the FBG functions for a time period of $\Delta\tau_1=15'$, it is stopped and the O_2 concentration is measured by rotating the probe in section B-B in the water (Fig..4).

II) The FBG is started again. Air is introduced in water during 15', leading to a total functioning time of $\Delta\tau_2=30'$. The O_2 concentration is measured in section B-B. Similarly we arrive at $\Delta\tau_3=45'$, $\Delta\tau_4=60'$, $\Delta\tau_5=75'$, $\Delta\tau_6=90'$, $\Delta\tau_7=105'$, $\Delta\tau_8=120'$.

Finally the concentration of the O_2 dissolved in the water is measured after a functioning time of the FBG of two hours. Table 1 presents the measured values.

Table 1. O_2 concentration in function of the functioning time of the FBG.

Concentration of O_2 dissolved in water [mg/l]				
$\tau=0'$	$\Delta\tau_1=15'$	$\Delta\tau_2=30'$	$\Delta\tau_3=45'$	$\Delta\tau_4=60'$
5.12	6.57	7.16	7.63	7.97
Concentration of O_2 dissolved in water [mg/l]				
$\Delta\tau_5=75'$		$\Delta\tau_6=90'$	$\Delta\tau_7=105'$	$\Delta\tau_8=120'$
8.22		8.35	8.44	8.48

Data presented in Table 1 allow constructing the graph $C_{O_2} = f(t)$, curve 2 (Fig. 6). The first point of the graph represents the concentration of O_2 dissolved in water at the beginning of the measurements ($\tau=0'$); after each functioning stage of the FBG, the concentration of dissolved O_2 will be represented by the curve 2.

Fig. 6 proves a good coincidence between the theoretical values and the experimental results. The error is small (< 1.8 %). The oxygen transferred to the clean water (from the plant supply) was not consumed neither as consequence of the microorganism metabolism nor by the fishes, thus the concentration of oxygen in water increased in proportion as air was blown in the water tank.
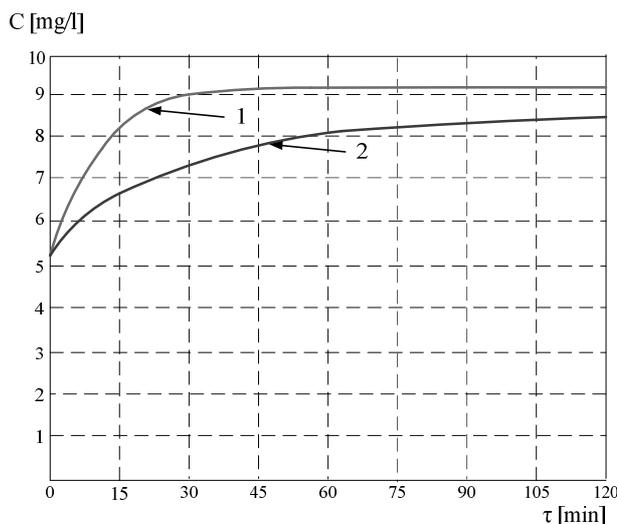

Fig.6.Concentration of oxygen dissolved in water in function of time.
1-theoretical values; 2-experimental values

3.3. Establishing the performance and the efficiency of the oxygenation process

It is known from specialty literature [11] that the performance of the water oxygenation is defined as ratio between the oxygen dissolved in water and the oxygen introduced in water:

$$(9)\ h_{ox} = \frac{V}{\dot{m}_{O_2}} \cdot \frac{dC}{dt} = \frac{V}{r_{O_2} \cdot \dot{V}_{O_2}} \cdot aK_l(C_s - C)$$

where: V – volume of the water subjected to oxygenation $V=0.125m^3$; $\dot{m}_{O_2}$ – flow rate of oxygen introduced into water.

The oxygenation performance can be established in two situations:

I) In stationary conditions, the amount of oxygen introduced in the tank is consumed by the fishes and other creatures living in water; in this case $dC/d\tau=ct$, the transfer speed of the dissolved oxygen is constant.

Mathematically, the variation of the concentration of DO in function of time has a sole validity point (*i*), for instance:

$$(10)\ \left(\frac{dC}{dt}\right)_i = \frac{\Delta C}{\Delta t} = ct$$

This value stays constant in the case of stationary conditions. Thus in the case of stationary conditions the oxygenation performance is constant.

II) In the case of non-stationary conditions a quantity of air (thus O_2, 21%) is introduced. The concentration of oxygen dissolved in water varies in time, namely increases.

In the case of non-stationary conditions, the performance will be equal to:

(11) $h_{ox} = \dfrac{V}{\dot{m}_{O_2}} \cdot \dfrac{dC}{dt}$ or:

(12) $h_{ox} = \dfrac{V}{\dot{m}_{O_2}} \cdot \dfrac{dC}{dt} \cdot 100$ [%]

The slope between two successive points is given by the relation:

(13) $\dfrac{\Delta C}{\Delta t} = \dfrac{C_{i+1} - C_i}{t_{i+1} - t_i}$

Using the graph presented in Fig. 6, curve 2, the value DC/Dt from the first stage of the oxygenation time is successively computed:

(14) $\left(\dfrac{dC}{dt}\right)_{t_1} = \dfrac{C_1 - C_0}{t_1 - t_0} = 0.1611 \cdot 10^{-5} \left[\dfrac{kg}{m^3} \cdot \dfrac{1}{s}\right]$

The flow rate of the oxygen introduced in water is computed this manner: from specialty literature [11] it is known that:

(15) $\dot{m}_{O_2} = 0.233\, \%\, m_{aer}\, [kg/s]$

(16) $\dot{m}_{O_2} = r_{aer} \cdot \dot{V}_{aer}$

(17) $r_{aer} = \dfrac{p_{aer}}{RT_{aer}}$

Air overpressure:

(18) $\Delta p_{aer} = 60\,mbar = 60 \cdot 10^{-3}\,bar = 6000\,N/m^2$

(19) $p = p_{atm} + \Delta p_{aer} = 107325\,N/m^2$

(20) $T_{aer} = t_{o_C} + 273.15 = 295.15\,K$

(21) $R_{aer} = 287\,j/kgK$

(22) $r_{aer} = \dfrac{107325}{287 \cdot 295.15} = 1.267\,kg/m^3$

(23) $\dot{V}_{aer} = 540\,l/h = 15.0 \cdot 10^{-5}\,[m^3/s]$

(24) $\dot{m}_{aer} = r_{aer} \cdot \dot{V}_{aer} = 0.19 \cdot 10^{-3}\,kg/s$

(25) $\dot{m}_{O_2} = 0.23 \cdot \dot{m}_{aer} = 0.0437 \cdot 10^{-3}\,kg/s$

In non-stationary conditions, the oxygenation performance for the first functioning stage will be:

(26) $h_{ox} = \dfrac{V}{\dot{m}_{O_2}} \cdot \dfrac{dC}{dt} = 0.46 \cdot 10^{-2}$ or:

(27) $(h_{ox})_{1-2} = 0.46\,[\%]$

Water oxygenation efficiency indicates the quantity of oxygen transferred to the water for a certain consumption of electric power; for the first stage ($\Delta\tau_1 = 15'$) it is obtained that:

(28) $E = \dfrac{kgO_2}{kWh} = 0.262\,kgO_2/kWh$

The performance is computed for each time interval accordingly to (26). The computed values are given in Table 2.

Table 2. Performance of the oxygenation process in non-stationary conditions

The computed values of the performance of O_2 dissolved in water *[mg/l]*							
τ	$\Delta\tau_1=15'$	$\Delta\tau_2=30'$	$\Delta\tau_3=45'$	$\Delta\tau_4=60'$	$\Delta\tau_5=75'$	$\Delta\tau_6=90'$	$\Delta\tau_7=105'$	$\Delta\tau_8=120'$
$\eta_{0x}\%$	0.46	0.18	0.15	0.10	0.08	0.04	0.02	0.01

Fig. 7 presents the chart of the performance in function of the functioning time of the FBG:
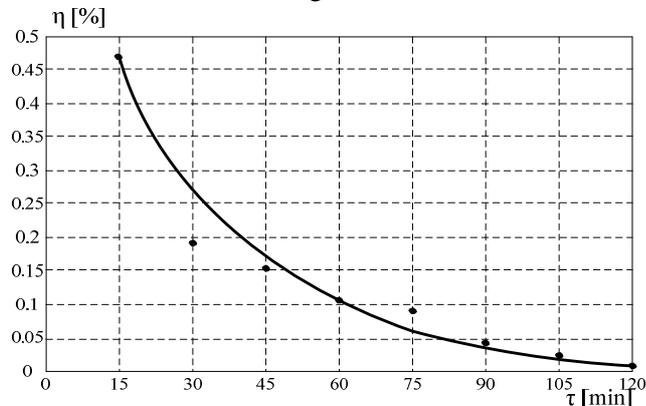

Fig.7. Performance of the oxygenation process in function of the FBG functioning time

CONCLUSION

1. The developed computation software is based on the Euler method, often found in calculations specific to technical processes.

2. The performance of the oxygenation process is reduced because the height of the water layer above the FBG is small (H= 500 mmH$_2$O); besides, the initial concentration of O_2 dissolved in water at $\tau=0$ is high (C$_0$ = 5,12 mg/l).

3. The theoretical and experimental results prove a satisfying coincidence.

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