ISSN 1453 – 7303 **"HIDRAULICA" (No. 1/2019)**
Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics*

The Correlation between the Composition of the Gas Mixture Injected into Water and the Concentration of Dissolved Oxygen in Water

PhD Student **Nicoleta Dorina ALBU**[1], As. Dr. Eng. **Elena Beatrice TĂNASE**[1], PhD Student **Nicolae Vlad SIMA**[1], Prof. Dr. Eng. **Nicolae BĂRAN**[1], Eng. **Corina MOGA**[2]

[1] Politehnica University of Bucharest, n_baran_fimm@yahoo.com

[2] DFR Systems SRL, Bucharest, corinamoga@yahoo.com

Abstract: *The paper presents three versions of gas mixtures: atmospheric air, atmospheric air and oxygen from a cylinder, air with low nitrogen content supplied by oxygen concentrators. These mixtures are successively introduced into a water tank and the theoretical and experimental determination of the change in the dissolved oxygen concentration in water is determined. The most favourable option for water oxygenation is chosen.*

Keywords: *Water aeration, oxygen dissolved in water, water oxygenation.*

1. Introduction

The process of water oxygenation is based on a transfer between air and water; the oxygen in the air is transferred by various processes to the water. The air bubbles generated by the installations that form them are introduced into a water volume. The most effective water oxygenation systems are those that generate very fine bubbles. A classification of the gas bubbles is shown in Figure 1.

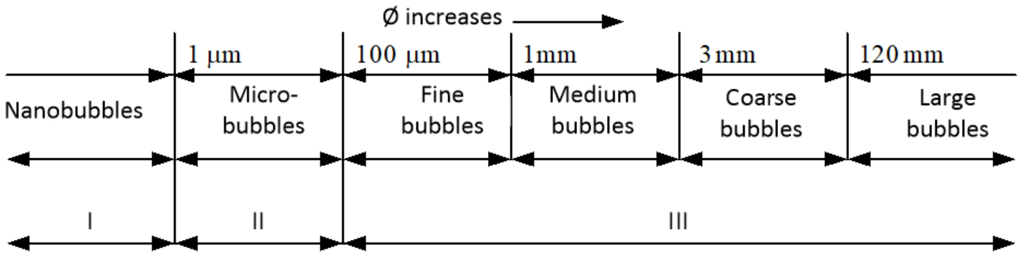


Fig. 1. Classification of gas bubbles according to their diameter
I - the area where the gas bubbles can be observed under the microscope;
II - the area where gas bubbles can be observed with difficulty;
III - the area where gas bubbles can be observed with the naked eye.

In the water treatment and purification processes, oxygenation, referred to as aeration in some specialty works, is the basic operation in ensuring proper water quality. As a result of the researches carried out in the laboratories of POLITEHNICA University of Bucharest, it was found that the two processes should be distinguished:
I) Water Aeration;
II) Water oxygenation.
- In the case I) only atmospheric air (21% O_2 + 79% N_2) is introduced into the water.
- In the case II), a mixture of gases consisting of:
• air + oxygen from a cylinder in different volumetric volumes;
• air with low nitrogen content supplied by oxygen concentrators.
Aeration is used:
- In water treatment processes, removal of dissolved inorganic substances or chemical elements such as iron, manganese, etc., by oxidation and formation of sedimentable compounds or which may be retained by boiling;
- In the biological treatment of wastewater, either through the activated sludge process or with bio filters;

- In the disinfection processes, by ozonizing the raw water captured from a source for the purposes of its drinking;
- In separating and collecting emulsified fats from wastewater.

Water oxygenation is a mass transfer process with wide application in water treatment and purification. Oxygenation equipment's are based on the dispersion of one phase into the other, for example, a gas into liquid, an energy consuming process.
Dissolved oxygen is an important parameter in assessing water quality due to its influence on living organisms in a water volume. In Limnology (the study of lakes), dissolved oxygen is an essential factor [1]. A too high or too low dissolved oxygen level can affect water life and affects water quality.

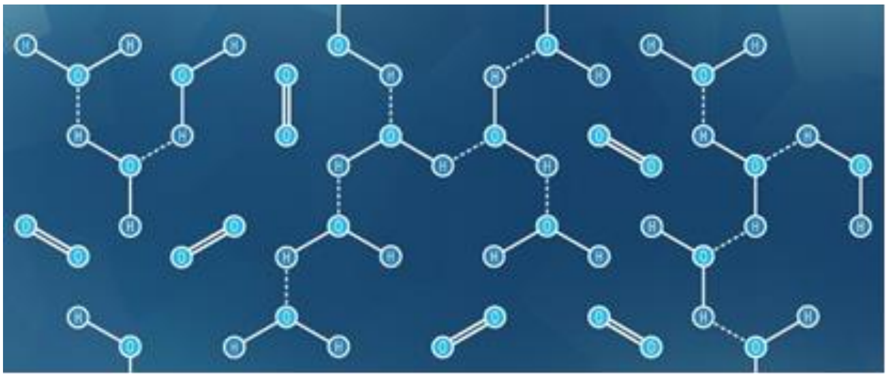
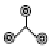


Fig. 2. Non-bonded oxygen molecules in water

 **-** oxygen molecule bound in water;  - oxygen dissolved in water.

Non-compound oxygen or free oxygen is the oxygen that is not bound to any other element (Fig. 2). Dissolved oxygen is the presence of those free oxygen molecules into water. Water-bound oxygen molecules (H_2O) are a compound and are not considered in the determination of dissolved oxygen level [2].

2. The introduction of gas mixtures in water to increase the dissolved oxygen concentration in water

These gas mixtures can be made in the following versions:
I - Atmospheric air (21% O_2+ 79% N_2);
II - Atmospheric air + oxygen from a cylinder (the following cases are considered:
case 1: r_{O2} = 25%;
case 2: r_{O2} = 50%;
case 3: r_{O2} = 75%;
case 4: r_{O2} = 100%;
r- volumetric participation).
III - Air with low nitrogen content (95% O_2 + 5% N_2) supplied by oxygen concentrators.
In the studied versions, the concentration of oxygen dissolved in water (C_{O2}) will increase in time.
The gas mixture is continuously fed into the tank for 120 minutes, so the regime is non-stationary and the initial concentration of oxygen dissolved in water increases in time.
In non-stationary regime the measured amount is the concentration of dissolved oxygen in water, in time.
The water tank in which the researches are carried out is shown in Figure 3.

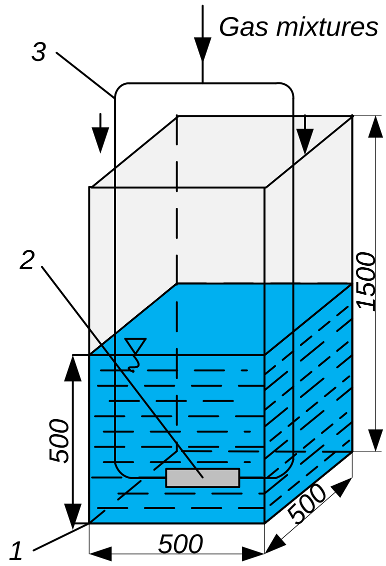


Fig. 3. Water tank into which the microbubbles generator is inserted; the generator is fixed
$V_{useful} = 0.375\ m^3$; $V_{H2O} = 0.125\ m^3$
1 - transparent plexiglass tank; 2 - microbubbles generator (M.B.G.); 3 - different gas mixtures supply pipes.

The following are measured: water and air temperature, gas flow rate at the inlet to the tank and gas pressure in the body of the microbubbles generator [1].

3. Numerical integration of the equation of oxygen transfer rate into water

The oxygen transfer speed equation in water is [1]:

$$\frac{dC}{d\tau} = a \cdot k_L \left(C_s - C\right) \qquad (1)$$

where:
C - The dissolved oxygen concentration at the time τ;
ak_L -The volumetric mass transfer coefficient;
C_s -The oxygen concentration in water at saturation.
The values of ak_L and C_s are constant with time. If the boundary conditions $C = C_0$ for $\tau = 0$ are imposed, the equation (1) can be integrated [2]:

$$\frac{dC}{C_s - C} = a \cdot k_L\, d\tau \qquad (2)$$

Assuming $C < C_s$, after integration, results:

$$-\ln\left(C_s - C\right) = a \cdot k_L \cdot \tau + ct \qquad (3)$$

The ct. term is obtained from the limit condition:

$$C = C_0 \text{ for } \tau = 0 \qquad (4)$$

and has the value

$$ct = -\ln\left(C_s - C_0\right). \qquad (5)$$

Inserting (5) into (3):

$$-\ln\left(C_s - C\right) = a \cdot k_L \cdot \tau - \ln\left(C_s - C_0\right), \qquad (6)$$

$$\ln\left(C_s - C\right) = \ln\left(C_s - C_0\right) - a \cdot k_L \cdot \tau, \qquad (7)$$

$$\ln\left(C_s - C\right) = \ln\left(C_s - C_0\right) + \ln e^{-a \cdot k_L \cdot \tau}, \qquad (8)$$

$$\ln\left(C_s - C\right) = \ln\left(\left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau}\right),$$

$$C_s - C = \left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau} , \quad (9)$$

$$C = C_s - \left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau} , \quad (10)$$

initial: $\tau = 0$.

In this equation the following values must be known: C_0 - the initial concentration of dissolved O_2 in water; C_s - saturation concentration of dissolved O_2 in water for a given water temperature; ak_L - the volumetric mass transfer coefficient [s^{-1}] or [min^{-1}] determined by one of the chemical or electrical methods. The values of C = f (τ) are calculated based on a computing program presented below (Fig. 4) [4] [5]:

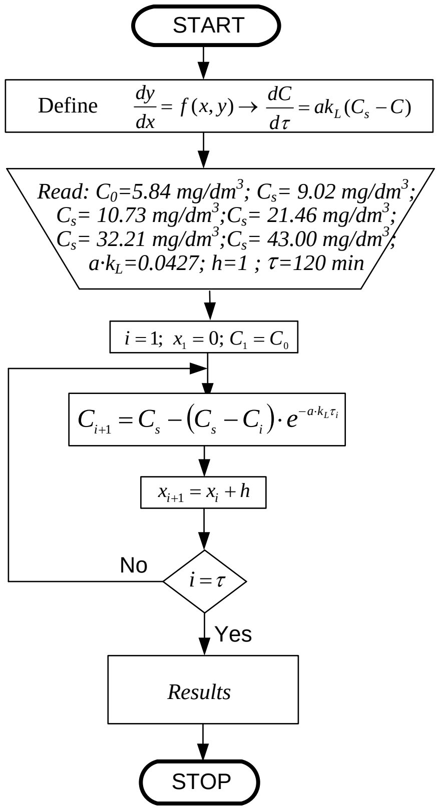


Fig. 4. The logical scheme for the function: C = f (τ) in the case of the injection of some gas mixtures into the water tank

This logical scheme is completed for each studied variant, i.e. separately:
- air ($O_2 + N_2$);
- air / oxygen mixture (air + O_2);
- air with low nitrogen content.

4. Data on the analysed gas mixtures

In the theoretical study, the following assumptions are made:
- the air flow rate or the mixing rate (air + oxygen), (air with low nitrogen content) is equal to 600 dm^3/h;
- gas mixture pressure 573 mm H_2O;
- the height of the water layer remains constant: H = 500 mmH_2O;
- working time, i.e. duration of an experiment: τ = 120 minutes;
- water temperature, t_{H2O} = 23.7 °C;
- the value of the initial dissolved oxygen concentration in the water is to be the same: C_0 = 5.84 mg / dm^3.

Theoretically, the following versions of gas mixtures in water are analysed:
Version I: air (21% O_2 + 79% N_2);

Version II: gas mixture: air + gas cylinder gas ($r_{O_2} = 25\ \%, r_{O_2} = 50\ \%, r_{O_2} = 75\ \%, r_{O_2} = 100\ \%$);
Version III: air with low nitrogen content (95% O_2 + 5% N_2) air.
For the three gas mixtures, some input data into the computation program are the same. It is specified that the value of oxygen concentration at saturation is different in each version I, II, III.

5. Computation results regarding the introduction of gas mixtures in the water

5.1 Version I. Injection of atmospheric air into the water

Input data in the computation program: C_0 = 5.84 mg / dm^3; H = 500 mmH_2O; t_{H2O} = 23.7 ^oC, t_{air} = 24.1 ^oC; $\dot{V} = 600$ dm^3/h; τ = 120 min, C_s = 8.4 [mg / dm^3].
To represent the evolution of dissolved oxygen concentration in water, computational programs were performed using the MatLab simulation program and the results obtained were displayed graphically.

Table 1: Theoretical operating conditions of the fine bubble generator in version I

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{air}$ [dm^3/h]	600	600	600	600	600	600	600	600	600
$\dot{V}_{IO_2} = 0.21 \cdot 600 = 126$ [dm^3/h]	126	126	126	126	126	126	126	126	126
$\dot{V}_{O_2}$ from other sources	0	0	0	0	0	0	0	0	0

Based on the theoretical data in Table 1 and the obtained results following the computation program, the function C = f (τ) was represented in figure 5.

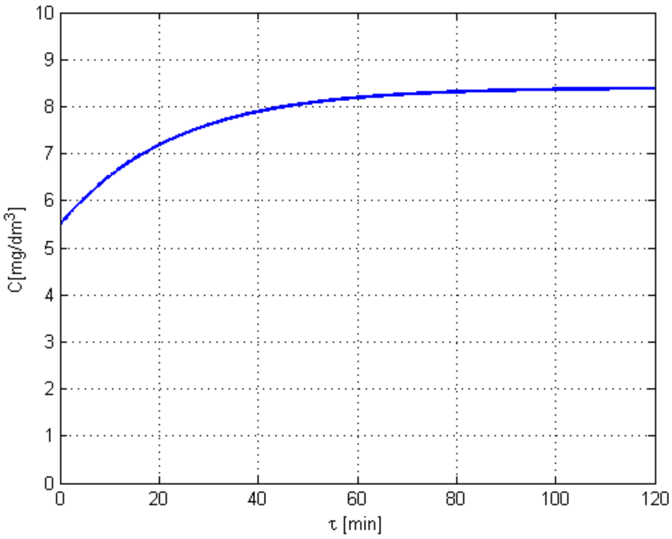


Fig. 5. Graphical representation of the variation of dissolved oxygen in water in version I.

5.2 Version II. Injection of a mixture of atmospheric air and oxygen from a cylinder

When oxygen-enriched air is used for oxygenation, the saturation concentration is corrected by the factor "k" according to the relation [8], [9]:

$$C_s = C \cdot \frac{k\ \%}{21\ \%}\ , \qquad (11)$$

where k% is the oxygen concentration in the diffusing gas.

For t = 20 ^oC and p = 760 torr, for water, the saturation concentration is C = 9.02 mg / dm^3.

Taking into account the evolution of saturation concentration of dissolved oxygen in water for different values of the gas mixture between air and pure oxygen results: case I: - for k = 25% result:

$$C_{s,25} = C \cdot \frac{k\,\%}{21\,\%} = 9.02 \cdot \frac{25}{21} = 10.73 \text{ mgO}_2/\text{dm}^3 \tag{12}$$

C_s for case 2, 3, 4, the results are shown in table 2.

Table 2: Saturation concentration values C_s for the four cases of version II

Nr. crt	$\dot{V}$ [dm^3/h]	$\dot{V}_{air}$ [dm^3/h]	r_{i,O_2}	$\dot{V}_{O_2}$ [dm^3/h]	C_0 [mg/dm^3]	C_s [mg/dm^3]
1	600	450	25	150	5.84	10.73
2	600	300	50	300	5.84	21.46
3	600	150	75	450	5.84	32.21
4	600	0	100	600	5.84	43.00

The following are theoretical calculation results for the four cases of version II.
1. Version II, case 1 (r_{O2} = 25%)
Atmospheric air $\dot{V}_1 = 0{,}75\,\% \cdot V_I = 0.75 \cdot 600 = 450$ dm^3/h and oxygen $\dot{V}_{O_2,b}$ =150 dm^3/ h from a cylinder of with the same pressure are injected. As a result, the oxygen flow rate introduced into water is (Table 3).

$$\dot{V}_{1,O_2} = 0.21 \cdot \dot{V}_1 + \dot{V}_{O_2,b} = 0.21 \cdot 450 + 150 = 94.5 + 150 = 244.5 \text{ dm}^3/\text{h}$$

Table 3: Theoretical operating conditions of the fine bubble generator in case 1

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{air}$ [dm^3/h]	450	450	450	450	450	450	450	450	450
$\dot{V}_{1O_2} = 0.21 \cdot \dot{V}_{air} = 94.5$ [dm^3/h]	94.5	94.5	94.5	94.5	94.5	94.5	94.5	94.5	94.5
$\dot{V}_{O_2}$ from a cylinder [dm^3/h]	150	150	150	150	150	150	150	150	150
$\dot{V}_{O_2,total}$ [dm^3/h]	244.5	244.5	244.5	244.5	244.5	244.5	244.5	244.5	244.5

Based on the data in Table 3 and the obtained results following the computation program, the graph in Figure 6 was plotted.

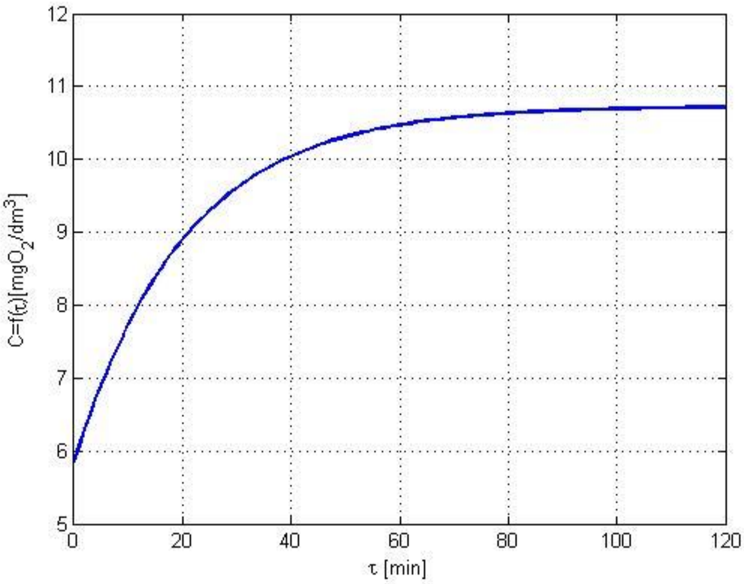


Fig. 6. Graphical representation of the variation of dissolved oxygen concentration in water in case 1.

The obtained values are similar to the data from the literature [10], [11].
2. Version II, case 2 (r_{O2} = 50%)
Atmospheric air is introduced: $\dot{V}_2 = 0.5\,\% \cdot V_I = 0.5 \cdot 600 = 300$ dm^3/h t_{air} = 24.10 ° C, t_{H2O} = 23.7 ° C and $\dot{V}_{O_{2,b}} = 300$ dm^3/h. As a result, the oxygen flow rate introduced into water is (Table 4):

$$\dot{V}_{2,O_2} = 0.21 \cdot \dot{V}_2 + \dot{V}_{O_2,b} = 0.21 \cdot 300 + 300 = 63 + 300 = 363 \text{ dm}^3\text{/h}$$

Table 4: Theoretical operating conditions of the fine bubble generator in case 2

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{air}$ [dm^3/h]	300	300	300	300	300	300	300	300	300
$\dot{V}_{2O_2} = 0,21 \cdot \dot{V}_{air} = 63$ [dm^3/h]	63	63	63	63	63	63	63	63	63
$\dot{V}_{O_2}$ from a cylinder [dm^3/h]	300	300	300	300	300	300	300	300	300
$\dot{V}_{O_2,total}$ [dm^3/h]	363	363	363	363	363	363	363	363	363

Based on the data in Table 4 and the obtained results following the computation program, the graph in Figure 7 was plotted.

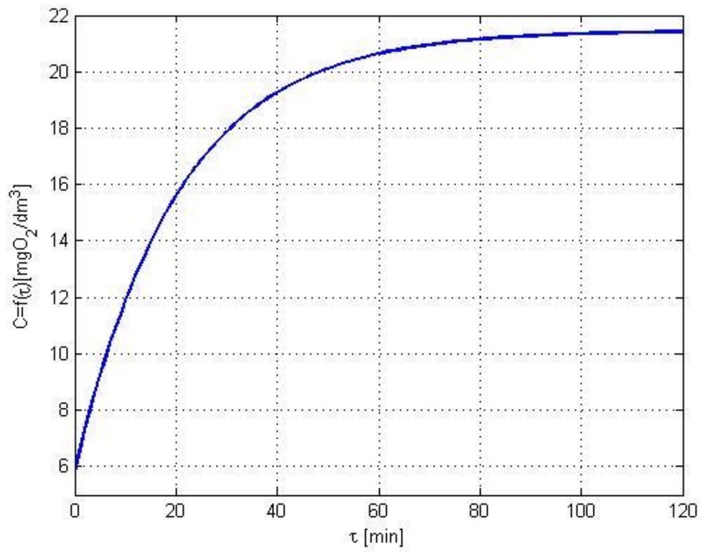


Fig. 7. Graphical representation of the variation of dissolved oxygen concentration in water in case 2.

3. Version II, case 3 (r_{O2} = 75%)

Atmospheric air is introduced: $\dot{V}_3 = 0.25\,\% \cdot V_I = 0.25 \cdot 600 = 150$ dm^3/h and $\dot{V}_{O_{2,b}} = 450$ dm^3/h. As a result, the oxygen flow rate introduced into water is (Table 5):

$$\dot{V}_{3,O_2} = 0.21 \cdot \dot{V}_3 + \dot{V}_{O_2,b} = 0.21 \cdot 150 + 450 = 31.5 + 450 = 481.5 \text{ dm}^3\text{/h}$$

Table 5: Theoretical operating conditions of the fine bubble generator in case 3

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{air}$[dm^3/h]	150	150	150	150	150	150	150	150	150
$\dot{V}_{3O_2} = 0.21 \cdot \dot{V}_{air} = 31.5$ [dm^3/h]	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5
$\dot{V}_{O_2}$ from a cylinder [dm^3/h]	450	450	450	450	450	450	450	450	450
$\dot{V}_{O_2,total}$ [dm^3/h]	481.5	481.5	481.5	481.5	481.5	481.5	481.5	481.5	481.5

Based on the data in Table 5 and the obtained results following the computation program, the function C = f (τ) (figure 8) was represented.

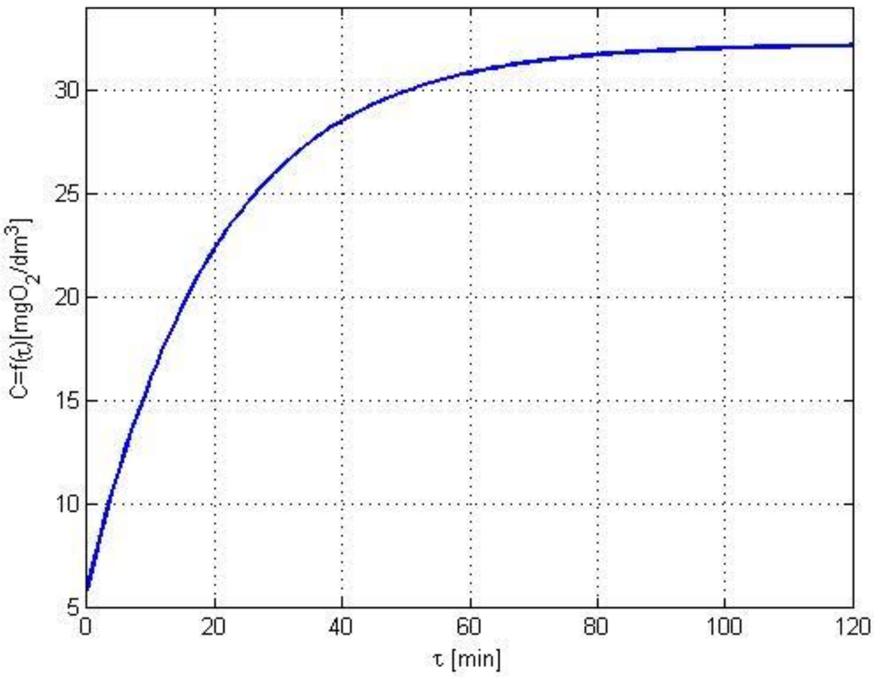


Fig. 8. Graphical representation of the variation of dissolved oxygen concentration in water in case 3.

4. Version II, case 4 (r_{O2} = 75%)

Atmospheric air is introduced: $\dot{V}_4 = 0$ dm^3/h and $\dot{V}_{O_{2,b}} = 600$ dm^3/h. As a result, the oxygen flow rate introduced into water is (Table 6):

$$\dot{V}_{4,O_2} = 0 + \dot{V}_{O_2,b} = 0 + 600 = 600 \text{ dm}^3/\text{h}$$

Table 6: Theoretical operating conditions of the fine bubble generator in case 4

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{air}$ [dm^3/h]	0	0	0	0	0	0	0	0	0
$\dot{V}_{4O_2} = 0.21 \cdot \dot{V}_{air} = 0$ [dm^3/h]	0	0	0	0	0	0	0	0	0
$\dot{V}_{O_2}$ from a cylinder [dm^3/h]	600	600	600	600	600	600	600	600	600
$\dot{V}_{O_2,total}$ [dm^3/h]	600	600	600	600	600	600	600	600	600

Based on the data in Table 6 and the obtained results following the computation program, the function C = f (τ) (figure 9) was represented.

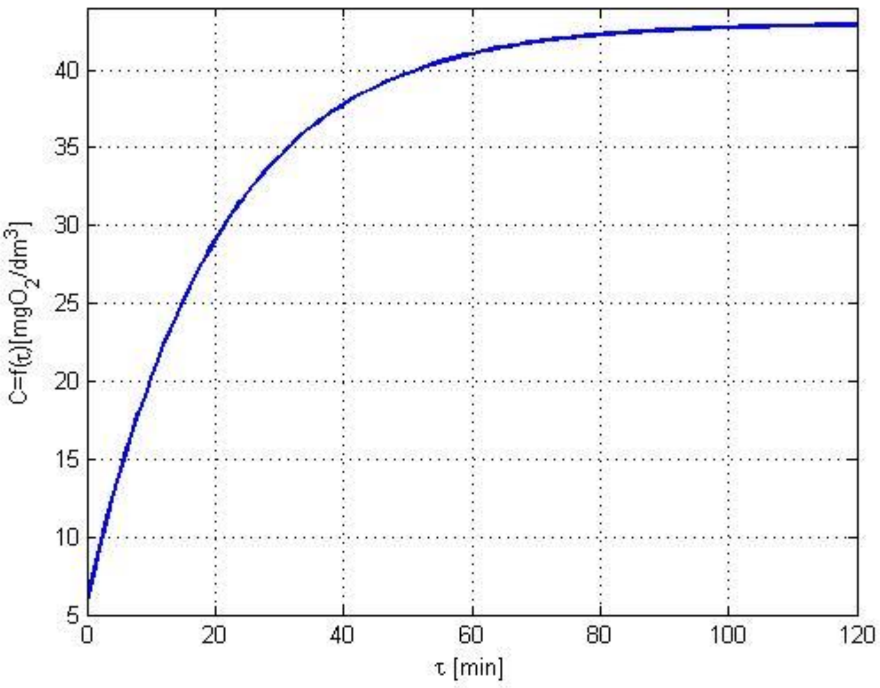


Fig. 9. Graphical representation of the variation of dissolved oxygen concentration in water in case 4.

The comparison of the C = f (τ) function for version I and the four cases of version II presented above can be seen in Figure 10.

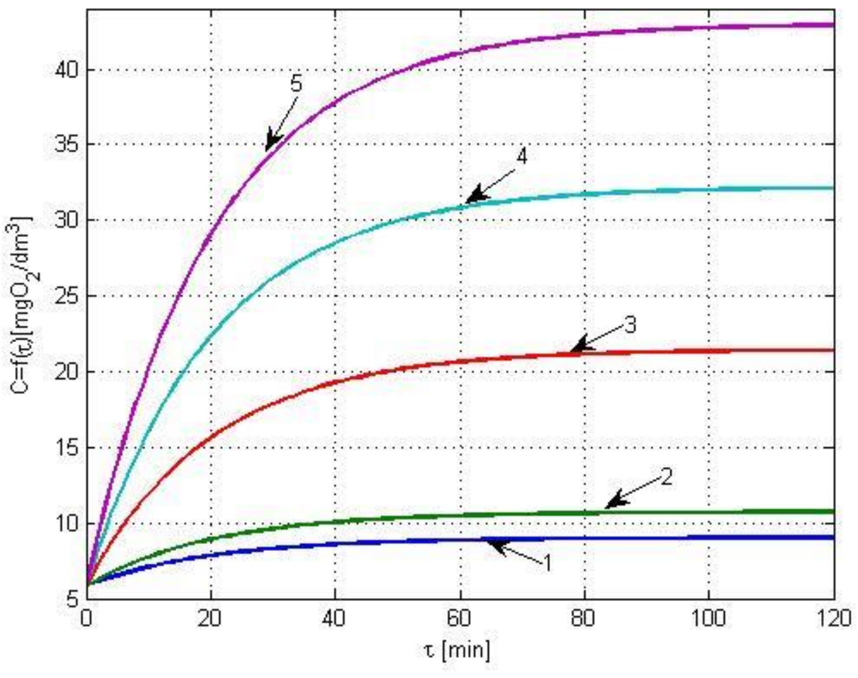


Fig. 10. The graphical representation of the variation of dissolved oxygen concentration in water for the I version and the four cases of version II
1 - the I version; 2 - version II, case 1; 3 - version II, case 2; 4 - version II, case 3; 5 - version II, case 4.

Figure 10 shows that with the increase in oxygen from the cylinder, the amount of dissolved oxygen in water increases.

5.3 Injection of air with low nitrogen content (version III)

In the process of water oxygenation, the use of air with low nitrogen content is investigated.
For t = 29 ºC and p = 760 torr, the saturation concentration is 7.7 mg / dm³.

$$C_s = 7.7 \cdot \frac{95\ \%}{21\ \%} = 34.8\ \text{mg O}_2/\text{dm}^3\ . \qquad (13)$$

The values C = f (τ) are shown in Table 7.
Of the total of 600 dm³ / h, 95% is O_2 (i.e. 570 dm³ / h), and 5% (i.e. 30 dm³ / h) is nitrogen.

Table 7: Theoretical operating conditions of the fine bubble generator in version I

τ [min]	0	15	30	45	60	75	90	105	120
$\dot{V}_{N_2}$ [dm³/h]	30	30	30	30	30	30	30	30	30
$\dot{V}_{O_2} = 95\ \%$[dm³/h]	570	570	570	570	570	570	570	570	570

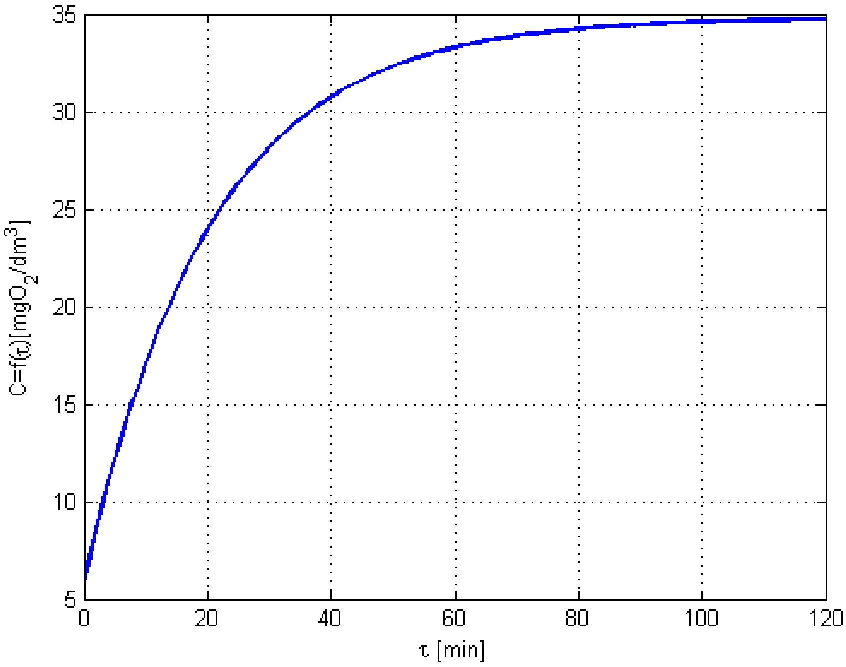


Fig. 11. Graphical representation of the variation of dissolved oxygen in water in version III.

Following the running of the computation program, the graph in Figure 11 was plotted.

6. Conclusions

- The most advantageous method of water oxygenation is presented in version II, case 4, when pure oxygen is pumped into the water.
- The variation speed, namely the increase of the dissolved oxygen concentration in water, increases from the version I to the version II, case 4.
- An efficient oxygenation process is also achieved with the use of air with low nitrogen content.
- Following an economic calculation, it can be determined which process is most effective among the most advantageous solutions, namely:
a) Case 4 when pure oxygen is introduced or a mixture of air and oxygen from the cylinder;
b) Version III where air with low nitrogen content is introduced.
Taking into account the costs of purchasing oxygen and operating costs, it was concluded that the most cost-effective water oxygenation process consists of introducing into the water a mixture of atmospheric air and 25% oxygen from a cylinder.

References

[1] Tănase, Elena Beatrice. *Influenţa compoziţiei gazului insuflat în apă asupra conţinutului de oxigen dizolvat*. PhD. Thesis. Bucharest, Politehnica University of Bucharest, 2017.
[2] Oprina, G., I. Pincovschi, and Gh. Băran. *Hidro – gazo – dinamica sistemelor de aerare echipate cu generatoare de bule fine*. Bucharest, Politehnica Press, 2009.
[3] Pătulea, Al.S. *Influenţa parametrilor funcţionali şi a arhitecturii generatoarelor de bule fine asupra eficienţei instalaţiilor de aerare*. PhD. Thesis. Bucharest, Politehnica University of Bucharest, 2012.
[4] Călușaru, I. *Influenţa proprietăţilor fizice ale lichidului asupra eficienţei proceselor de oxigenare*. PhD. Thesis. Bucharest, Politehnica University of Bucharest, Faculty of Mechanical Engineering and Mechatronics, 2014.
[5] Căluşaru-Constantin, M., E.B. Tănase, N. Băran and Rasha Mlisan-Cusma. "Researches Regarding the Modification of Dissolved Oxygen Concentration in Water." *IJISET - International Journal of Innovative Science, Engineering & Technology* 1, no. 6 (August 2014): 228-231.
[6] Căluşaru, I., N. Băran and A. Pătulea. "The influence of the constructive solution of fine bubble generators on the concentration of oxygen dissolved in water." *Advanced Materials Research* 538-541 (July 2012): 2304-2310.
[7] Băran, N., A. Pătulea, and M. Căluşaru. "Computation of performance and efficiency of the water oxygenation process in non-stationary conditions." Paper presented at the Sixième édition du Colloque Francophone sur L'Energie –Environnement- Economie et Thermodynamique COFRET 2012, Sozopol, Bulgaria, June 11-13, 2012.
[8] Tănase, E.B., N. Băran, and R. Mlisan. "An Efficient Solution for Water Oxygenation." *Asian Engineering Review* 1, no. 3 (2014): 36-40.
[9] Barnhart, E.L. "Transfer of oxygen in aqueous solutions." *J. Sanit. Eng. Div.* 95, no. 3 (1969): 645 – 661.
[10] Băran, N., M. Vlăsceanu, M. Băran, and E.B. Tănase. "Increasing the performance of oxygenation installations." *Termotehnica* 18, no. 1 (2014): 16-21.
[11] Vlăsceanu, M., N. Băran, and M. Băran. "Decrease of Energy Consumption in the Case of Water Oxygenation Processes." *Energy Procedia* 50 (2014): 454-459.