ENERGY OPTIMIZATION OF WATER OXYGENATION PROCESSES

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The purpose of the paper is to determine the minimum energy consumed for the introduction of one cubic meter of oxygen in a volume of 0,125 m^3 of water, of the following mixtures: atmospheric air (21% O^2, 79% N_2), a gaseous mixture of atmospheric air and oxygen from a cylinder, a gaseous mixture of 95% O_2 and 5% N_2. In all three versions, the volume of water in which the gaseous mixture is injected, the gas pressure at the entrance of the micro bubbles generator, the water temperature, the initial concentration of the dissolved oxygen in water are maintained constant. The scheme of the experimental installations and the obtained results are presented.

Keywords: water oxygenation, microbubbles air generators.

1. Introduction

The widespread use of water oxygenation is highly dependent on its economic profits.

One of the most important components of the functioning cost is aeration, and according to the study by [1], about 23% and 11% of the operating cost of water oxygenation came from electricity. To obtain a lower operating cost, many researches have been done to optimize water oxygenation [2]. Reducing oxygenation intensity can reduce the investment on water oxygenation. Boyd's research found that moderate oxygenation was more profitable than intensive oxygenation in improving water quality of aquaculture systems. However, the blindfold reducing will have a great influence on dissolved oxygen (DO). In general, it is relatively optimal for fish growth when the DO concentration is greater than 5 mg/dm^3 [3]. Thus, maintaining appropriate DO concentration is

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extremely important for optimal water oxygenation operation. Therefore, an economic investigation on profitable oxygenation installations should be conducted.

The paper deals with the determination of the electricity consumption for the introduction of one cubic meter of oxygen in a given water volume; the paper does not refer to the investments in water oxygenation installations. The nature and composition of the “gas” injected in water to oxygenate it influences the energy consumption of the water treatment plant, swimming pools, fishponds, etc. This “gas” may consist of gas mixtures which in the present work refer to: atmospheric air (21% O_2 +79% N_2), atmospheric air + pure oxygen from a cylinder (in volumes of 25, 50, 75, 100%) and a gaseous mixture of 95% O_2 and 5% N_2.

Increased dissolved oxygen content in water ensures a favorable existence of living beings in water.

2. Materials and methods

2.1. Installations schemes for injecting gas mixtures into water

Fig. 1 shows a general scheme of the water oxygenation research installation. Figures 2, 4, 5 shows the simplified scheme for water oxygenation when into the water the following gases are introduced: in version I: atmospheric air, in version II: a mixture of atmospheric air + pure oxygen taken from a cylinder in certain proportions and in version III: a gaseous mixture of 95% O_2 and 5% N_2supplied by a device called oxygen concentrator [4].

The experimental stand (Fig. 1) comprises an air compressor, airflow meters, air temperature and pressure measuring devices, oxygen sensor probe, water tank, connecting pipes, electricity meter, etc.

In the experimental researches, using the elements of this experimental installation, the increase of the dissolved oxygen concentration in water, depending on the measurement's duration, the electric energy consumption of the plant [5][6] can be measured.

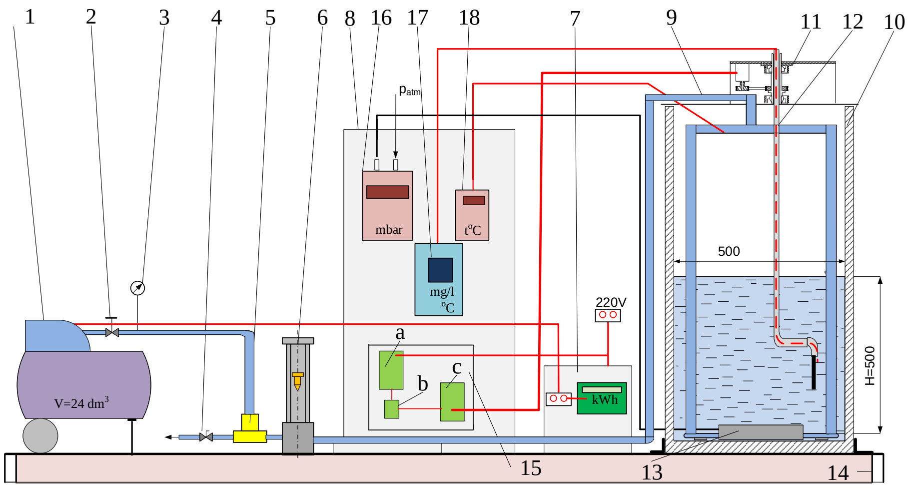

Fig. 1. Sketch of the experimental installation for researches regarding water oxygenation
1-electro compressor with air tank; 2– pressure reducer; 3–manometer; 4– connector for air exhaustion in the atmosphere; 5– T-joint; 6– rotameter; 7–electrical panel; 8- panel with measuring devices;9- pipe for the transport of the compressed air to the micro bubbles generator; 10– water tank; 11- mechanism for the probe actuation; 12– oxygen meter probe; 13– micro bubbles generator; 14- installation holder; 15–electronics control: a– supply unit, b- switch, c- control element; 16–digital manometer; 17– oxygen meter; 18–digital thermometer.

Fig. 2 shows the sketch of the experimental installation for the injection of atmospheric air into water.

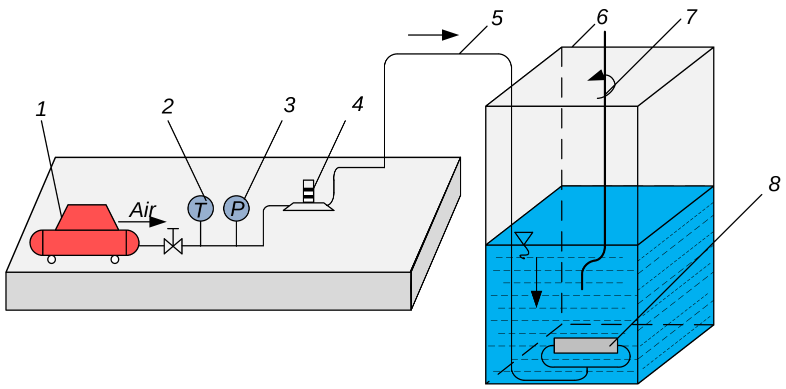

Fig. 2. Sketch of the experimental installation for the injection of atmospheric air into water
1 - air compressor; 2 - thermometer; 3 - manometer; 4 - rotameter; 5 – micro bubbles generator feed pipe; 6 - parallelepiped water tank; 7 – oxygenometer probe; 8 – micro bubbles generator with 152 orifices Ø 0.1 mm

From Fig. 2 one can observe that, after compressing the air, the temperature, the pressure and air flow rate are measured; it is then introduced into the generator with the following parameters: $\dot{V} = 600\ \mathrm{dm^3/h}$; p_m = 573 mm H_2O. The duration of the experiments is two hours, during which the dissolved oxygen concentration in the water increases from the initial concentration (C_0) to the saturation concentration (C_s).

The micro bubbles generator operation of rectangular shape with 152 orifices Ø 0.1 mm is shown in Fig. 3.

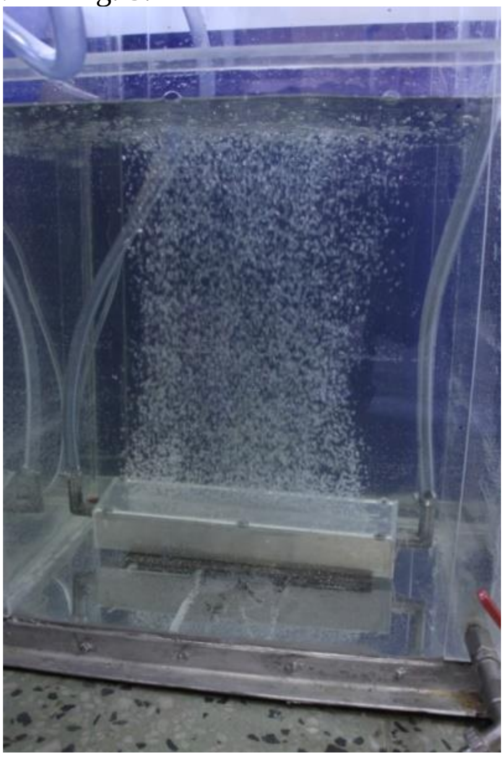

Fig. 3. Microbubbles generator with 152 orifices 0.1 mm Ø in operation

The micro bubbles generator is provided with a perforated plate with Ø 0.1 mm drilled orifices. This type of generator was tested in an experimental installation built in the laboratories of University POLITEHNICA of Bucharest. The orifices were made using a C.N.C. (Numerical Computerized Control) which has a special KERN Micro [7] microprocessor.

Fig. 4 shows a simplified scheme of the experimental installation which works with a mixture of pure air and oxygen taken from a cylinder.

The installation's operating parameters are the same: $\dot{V} = 600\ \text{dm}^3/\text{h}$; p_m = 573 mm H_2O, τ = 2h. Atmospheric air and oxygen supplied from the cylinder are measured separately with the rotameters 4 and 4 '.

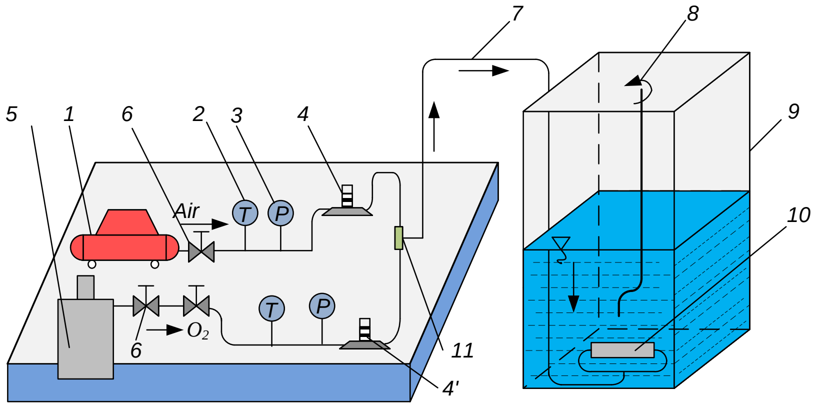

Fig. 4. Sketch of the experimental installation for the injection of a mixture of atmospheric air and oxygen into the microbubbles generator
1 - air compressor; 2 - digital indication gas thermometer; 3 - digital pressure manometer; 4, 4'- rotameter; 5 - oxygen cylinder: p = 120 bar; 6 - pressure reducers; 7 - air / oxygen feed pipe of the micro bubbles generator; 8 - oxygenometer probe; 9 - water tank; 10 – micro bubbles generator; 11 - mixing chamber of the two gas streams

A gas flow rate of $\dot{V} = 600\ \text{dm}^3/\text{h}$ is successively introduced into the water tank, consisting of:

Version II, case 1: $\dot{V}_{O_2} = 150\ \text{dm}^3/\text{h}$ and $\dot{V}_{air} = 450\ \text{dm}^3/\text{h}$;

Version II, case 2: $\dot{V}_{O_2} = 300\ \text{dm}^3/\text{h}$ and $\dot{V}_{air} = 300\ \text{dm}^3/\text{h}$;

Version II, case 3: $\dot{V}_{O_2} = 450\ \text{dm}^3/\text{h}$ and $\dot{V}_{air} = 150\ \text{dm}^3/\text{h}$;

Version II, case 4: $\dot{V}_{O_2} = 600\ \text{dm}^3/\text{h}$ and $\dot{V}_{air} = 0\ \text{dm}^3/\text{h}$.

The oxygenation time is reduced if the oxygen content of the gas mixture is higher, but additionally, electricity consumption occurs [8] [9].

Figure 5 shows the general scheme of the low nitrogen injection system in the water tank. For researches, two oxygen concentrators were purchased with the following characteristics: volumetric flow rate: $\dot{V} = 0.5 \div 5\ \text{dm}^3/\text{min}$, oxygen pressure: p = 38 kPa and the provided oxygen concentration: 93% ± 3.

Each concentrator delivers 5 dm^3/min, i.e. 300 dm^3/h; the two concentrators provide a flow rate of 600 dm^3/h.

Fig. 5 shows the scheme of the installation; the air supplied by each oxygen concentrator passes through a rotameter and then enters the micro bubbles generator.

The safest scheme is the one that uses a gaseous mixture of 95% O_2 and 5% N_2. In this case, the zeolite filters are cleaned by injecting an oxygen stream in the opposite direction to normal operation.

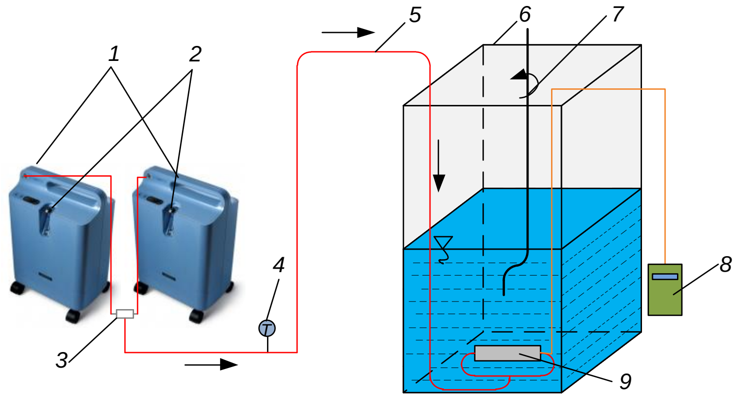

Fig. 5. The installation scheme for the introduction of a gaseous mixture of 95% O_2 and 5% N_2
1 - oxygen concentrators; 2 - rotameters; 3 - mixing chamber of the two gas streams; 4 - digital indication gas temperature meter; 5 - low nitrogen air supply pipe of the micro bubbles generator; 6 - parallelepiped water tank; 7 - oxygenometer probe; 8 - digital pressure manometer; 9 - microbus generator with 152 orifices Ø 0.1 mm

Nitrogen circulation should be avoided through the oxygenation as additional energy consumption appears to transport it [10][11][12].

2.2. Problem statement

The paper analyzes three versions for increasing the dissolved oxygen content in water, namely: introduction of atmospheric air, introduction of a gaseous mixture of air and oxygen from a cylinder and introduction of a gaseous mixture of 95% O_2 and 5% N_2, obtained by using oxygen concentrators.

For the three versions, in the experimental researches, the following parameters were kept constant: the gas volume injected into the water: $\dot{V} = 600 \text{ dm}^3/\text{h}$; the gas pressure into the microbubbles generator: p_m = 573 mm H_2O, the water temperature: t = 20 ºC and the initial concentration of dissolved oxygen in water C_0 = 5.84 mg/dm^3.

As a result, the oxygen flow $\dot{V}_{O_2}$ injected into the water for the three versions is:

I - version I; the introduction of atmospheric air (21% O_2, 79% N_2) into water,

$$\dot{V}_{O_2} = 0.21 \cdot 600 = 126 \text{ dm}^3 O_2/\text{h} \tag{1}$$

II - version II; the introduction of atmospheric air + oxygen from the cylinder,

Here 4 cases are distinguished; the percentage of oxygen taken from the cylinder is changed as follows:

$$\text{Case 1: } \dot{V}_{O_2} = 25\ \%\ (600) = 150 \text{ dm}^3 O_2/\text{h} \tag{2}$$

Case 2: $\dot{V}_{O_2} = 50\ \%\ (600) = 300\ \text{dm}^3\text{O}_2/\text{h}$ (3)

Case 3: $\dot{V}_{O_2} = 75\ \%\ (600) = 450\ \text{dm}^3\text{O}_2/\text{h}$ (4)

Case 4: $\dot{V}_{O_2} = 100\,\%\ (600) = 600\ \text{dm}^3\text{O}_2/\text{h}$ (5)

III - version III; the introduction of a gaseous mixture of 95% O_2 and 5% N_2.

$$\dot{V}_{O_2} = 0.95 \cdot 600 = 570\ \text{dm}^3\text{O}_2/\text{h} \quad (6)$$

One can notice that the gas flows injected into the water are different, which, economically, complicates the solution of the problem: which of the three versions is more economical; where a certain amount of oxygen is injected into the water with the smallest expenses?

To solve this problem, the following are successively determined: the gas volume and the operating time for 1 m^3 of O_2 to be introduced into the water and the required energy to introduce 1 m^3 of O_2 in water.

3. Results and discussion

3.1. The gas volume and the operating time for the introduction of one cubic meter of oxygen into the water

a. Version I

Introducing air into the water; to introduce 1 m^3 of O_2 in water it is necessary to introduce an air volume equal to:

$$\dot{V}_I = \frac{1}{0.21} = 4.76\ \ \text{m}^3\text{air} \quad (7)$$

The installation drives 600 dm^3/h = 0.6 m^3/h, so it's operating time is:

$$\tau_{\text{f, I}} = \frac{4.76}{0.6} = 7.93\ \ \text{h} \quad (8)$$

b. Version II

For version II the four cases with atmospheric air + O_2 from the cylinder are taken into account, the gas mixture having a flow rate of 600 dm^3/h; the following are distinguished:

- case 1. Atmospheric air +25% O_2 = 450 + 0.25·600 = 600 dm^3/h; therefore, the compressor compresses 0.45 m^3/h of air.
- case 2. Atmospheric air +50% O_2 = 300 + 0.5·600 = 300 + 300 = 600 dm^3/h; therefore, the compressor compresses 0.3 m^3/h of air.
- case 3. Atmospheric air + 75% O_2 from the cylinder: 150 + 0.75·600 = 150 + 450 = 600 dm^3/h; therefore, the compressor compresses 0.15 m^3/h of air.
- case 4. Atmospheric air + 100% O_2 = 0 + 600 = 600 dm^3/h of O_2 from the cylinder. No air is compressed in the compressor.

For case 1 one can obtain:

The oxygen flow rate from the air is:

$$\dot{V}_{O_2,air} = \frac{0.21 \cdot 0.45}{3600} = 0.00002625\ \text{m}^3/\text{s} = 0.2625 \cdot 10^{-4}\ \text{m}^3/\text{s} \quad (9)$$

The oxygen flow rate from the cylinder is:

$$\dot{V}_{O_2,\text{cylinder}} = \frac{0.25 \cdot 0.600}{3600} = 0.0000416\ \text{m}^3/\text{s} = 0.416 \cdot 10^{-4}\ \text{m}^3/\text{s} \quad (10)$$

The total O_2 flow rate for case 1 will be:

$$\dot{V}_{II,case\ 1} = \dot{V}_{O_2,air} + \dot{V}_{O_2,\text{cylinder}} = (0.00002625 + 0.0000416) = \\ = 0.00006785\ \ m^3/s = 0.6785 \cdot 10^{-4}\ \ \text{m}^3/\text{s} \quad (11)$$

The operating time of the installation is:

$$\tau_{\text{f,II},case\ 1} = \frac{1}{0,6785 \cdot 10^{-4}} = 14739\,\text{s} = 4.093\ \text{h} \quad (12)$$

Performing the calculations for cases 2, 3, 4 similar to case 1, the data from Table 1 are obtained.

Table 1

Gas flow rates values

Case no.	$\dot{V}_{O_2,air}\ [\text{m}^3/\text{s}]$	$\dot{V}_{O_2,\text{cylinder}}\ [\text{m}^3/\text{s}]$	$\dot{V}_{II}\ [\text{m}^3/\text{s}]$	$\tau_{\text{f,II}}\ [\text{h}]$
1	$0.2625 \cdot 10^{-4}$	$0.416 \cdot 10^{-4}$	$0.6785 \cdot 10^{-4}$	4.093
2	$0.175 \cdot 10^{-4}$	$0.833 \cdot 10^{-4}$	$1.00810 \cdot 10^{-4}$	2.77
3	$0.0875 \cdot 10^{-4}$	$1.25 \cdot 10^{-4}$	$1.337 \cdot 10^{-4}$	2.077
4	$0.000 \cdot 10^{-4}$	$1.66 \cdot 10^{-4}$	$1.66 \cdot 10^{-4}$	1.673

c. Version III

For version III, a gaseous mixture of 95% O_2 and 5% N_2 is introduced into the water. The air consists of volumes: 95% O_2 and 5% N_2.

To introduce 1 m^3 of O_2 into the water, it is necessary to introduce into the water an air volume of:

$$\dot{V} = \frac{1}{0.95} = 1.052\ \ \text{m}^3 \quad (13)$$

Theoretically, the installation must work during:

$$\tau_{\text{f, III}} = \frac{1.052}{0.6} = 1.754\ \ \text{h} \quad (14)$$

3.2. The electrical energy required for the introduction of one cubic meter of oxygen into the water

The three versions will be successively analyzed.

a. Version I

For version I, 0.6 m^3/h of atmospheric air is introduced into the water. The energy E is the product of the power consumption P_I [kW] and the operating time of the installation τ [h].

For version I one can obtain:

$$E_I = P_I \cdot \tau_{f,I} \ [\text{kWh}] \tag{15}$$

The P_I power is the power required to drive the compressor with a one-cylinder step:

$$P_t = \frac{n}{n-1} \cdot p_1 \cdot \dot{V}_a \cdot \left(\varepsilon^{\frac{n-1}{n}} - 1 \right) \cdot \frac{1}{10^3} \ [\text{kW}] \tag{16}$$

where: n - polytropic exponent: n = 1.3; p_1 - suction pressure: p_1 = 1 bar;

$\dot{V}_a$ - aspirated flow rate: $\dot{V}_a = \frac{0.6}{3600}$ m^3/s;

ε - compression ratio: ε = 1.5.

$$P_t = \frac{1.3}{1.3-1} \cdot 1 \cdot 10^5 \cdot \frac{0.6}{3600} \cdot \left(1.5^{\frac{1.3-1}{1.3}} - 1 \right) \cdot \frac{1}{10^3} \ \text{kW} \tag{17}$$

$$P_t = 0.00705 \ W = 7 \cdot 10^{-3} \ \text{kW} \tag{18}$$

By accepting an efficiency of the aggregate η_{agr} (compressor + electric driven motor) of 0.5, the actual driven power is:

$$P_I = \frac{P_t}{\eta_{agr}} = \frac{7 \cdot 10^{-3}}{0.5} = 14 \cdot 10^{-3} \ \text{kW} \tag{19}$$

The operation time of the installation is $\tau_{f,I}$ = 7.93 h, so the mechanical energy consumed for the introduction of 1 m^3 of oxygen in water, in version I, is:

$$E = P_I \cdot \tau_{f,I} = 14 \cdot 10^{-3} \cdot 7.93 = 111 \cdot 10^{-3} \ \text{kWh} \tag{20}$$

It is known that the average efficiency of a coal-fired power plant is about 30%, as a result:

$$E_{I,c} = \frac{E}{\eta_{CTE,c}} = \frac{0.111}{0.3} = 0.37 \ \text{kWh} \tag{21}$$

b. Version II

For version II there are 4 cases:

Case 1. Compressed air and 0.15 m^3/h O_2 from the cylinder; in total 600 dm^3/h, which remains constant for all cases 1, 2, 3, 4.

The one-stage compressor consumes a theoretical power:

$$P_{t,case\ 1} = \frac{n}{n-1} \cdot p_1 \cdot \dot{V}_a \left(\varepsilon^{\frac{n-1}{n}} - 1 \right) \frac{1}{10^3} \ [\text{kW}] \tag{22}$$

$$P_{t,case\ 1} = \frac{1.3}{1.3-1} \cdot 1 \cdot 10^5 \cdot \frac{0.45}{3600} \left(1.5^{\frac{1.3-1}{1.3}} - 1 \right) \frac{1}{10^3} = 5.25 \cdot 10^{-3} \ \text{kW}$$

The real mechanical power is:

$$P_{II,case\ 1} = \frac{P_{t,case\ 1}}{\eta_{agr}} = \frac{5.25 \cdot 10^{-3}}{0.5} = 10.50 \cdot 10^{-3} \ \text{kW} \tag{23}$$

The mechanical energy consumed by the compressor:

$$E_{II,case\ 1} = P_{II,case\ 1} \cdot \tau_{f_{II},case\ 1} = 0.0105 \cdot 4.093 = 0.0429 \text{ kWh} \quad (24)$$

The energy to separate the air from the oxygen has values [4] between 0.392 ÷ 0.55kWh/m^3 of pure oxygen [13]. If for 1 m^3 of pure oxygen consumes 0.4 kWh then, for 0.15 m^3 /h of pure oxygen it consumes:

$$E_{II,\text{cylinder}} = 0.15 \cdot 0.4 = 0.06 \text{ kWh} \quad (25)$$

The total mechanical energy consumed (in version II, case 1) for the introduction of one cubic meter of oxygen in water will be:

$$E_{II} = E_{II,case\,1} + E_{II,cylinder} = 0.0429 + 0.06 = 0.1029 \text{ kWh} \quad (26)$$

The electricity consumed for Version II, case 1, will be in the case of electricity production in a coal-fired thermal plant with a general efficiency of 30% [14]:

$$E^*_{II,case\,1} = \frac{0.1029}{0.3} = 0.343\,\text{kWh} \quad (27)$$

For version II in cases 2, 3, 4, a computation program and the data in Table 2 were obtained.

Table 2

Electricity consumption in version II

	Case	**Gas composition**	**E*$_{II}$ [kWh]**
Version II	1	Air + 25% O_2	0.343
	2	Air + 50% O_2	0.460
	3	Air + 75% O_2	0.624
	4	0 + 100 % O_2	0,800

c. Version III

For version III, energy consumption was measured using an electric counter. The time at which the meter disk performs a rotation was metered: τ = 28 s. The energy consumption resulted of 480 rot/kWh. The number of rotations in one hour is 128.57 rpm, resulting a consumption of 0.2678 kWh. Having two oxygen concentrators, the energy consumption measured by an electric counter resulted E_{III} = 2 · 0.2678 = 0.5356 kWh. This energy is required for the introduction of one cubic meter of oxygen in water, in case of version III.

3.3. Comparative analysis of the studied versions

The data from the previous paragraph are listed in the table below.

Table 3

Electricity consumption in the three versions

Version no.	Gas mixture	Case	O_2 percent	Operation time	Energy consumed [kWh] coal CTE
I	Atmospheric air	-	0	7.93	0.370
II	Air + O_2 from the cylinder	1	25 %	3.19	0.343
		2	50 %	4.093	0.460
		3	75 %	2.77	0.624
		4	100 %	2.077	0.800
III	A gaseous mixture of 95% O_2 and 5% N_2	-	95 %	1.673	0.535

Table 3 shows the following:

For the introduction of one cubic meter of oxygen into the water tank, the electricity consumed in ascending order is evaluated as follows:

Version II, case 1 $\rightarrow E^*_{II,case\,1} = 0.343$ kWh;

Version I $\rightarrow E^*_I = 0.37$ kWh;

Version II, case 2 $\rightarrow E^*_{II,case\,2} = 0.460$ kWh;

Version III $\rightarrow E^*_{III} = 0.535$ kWh;

Version II, Case 3 $\rightarrow E^*_{II,case\,3} = 0.624$ kWh;

Version II, Case 4 $\rightarrow E^*_{II,case\,4} = 0.800$ kWh.

So, the most advantageous version is II, case 1, in which, a mixture of atmospheric air + 25% O_2 gas is injected into the water.

4. Conclusions

1. Installing water oxygenation systems using microbubbles generators leads to savings in the cost of energy consumed for oxygenation [14] [15] [16], [17].

2. For the separation of oxygen from the air, 0.392 ÷ 0.550 kWh/m^3 of pure oxygen is consumed [13].

3. The energy consumption for producing and ensuring the transfer of a mixture of air and pure oxygen to a volume of water is lower than that required for the introduction of air taken from the atmosphere.

4. Table 3 shows the following:

The most economical version is II, case 1, $E^*_{II,case\,1} = 0.343$ kWh.

There are economic advantages in the following order:

Version I $\rightarrow E^*_I = 0.37$ kWh;

Version II, case 2 $\rightarrow E^{*}_{II,case\ 2} = 0.460$ kWh ;

Version III $\rightarrow E^{*}_{III} = 0.535$ kWh ;

Version II, case 1 $\rightarrow E^{*}_{II,case\ 1} = 0.343$ kWh ;

Version II, Case 3 $\rightarrow E^{*}_{II,case\ 3} = 0.624$ kWh ;

Version II, Case 4 $\rightarrow E^{*}_{II,case\ 4} = 0.800$ kWh .

From an energy point of view, a large amount of energy is saved by using pure oxygen in the mixture in certain proportions with air taken from the atmosphere; this energy refers to the compression of nitrogen from the air and its unnecessary introduction into the water mass.

R E F E R E N C E S

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