POLITEHNICA UNIVERSITY OF BUCHAREST

FACULTY OF MECHANICAL ENGINEERING AND MECATRONICS

Department of Thermotechnics, Engines, Thermic and Refrigeration Plants

PhD thesis summary

Theoretical and experimental research on reducing water aeration time

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Content

Introduction

This paper presents the theoretical and experimental results on the influence of geometric and functional parameters of fine bubble generators on the concentration of dissolved oxygen in water. A solution to reduce the aeration time of stagnant water is presented.

Unconventional technologies have been used in the construction of fine bubble generators, namely electro erosion (EDM) processing. Thus, holes were made in the perforated plate of the fine bubble generator with a diameter of 0,1 [mm]. In the case of the research in this paper, fine bubble generators will be used in which the plate has holes with a diameter of 0,3 [mm].

In the paper we have a clearer aeration process:

- Atmospheric air is introduced into the water 21% O_2 and 79 % N_2
- When we refer to “oxygenation of water” it means that a gas (O_2) from:
  a) oxygen cylinders
  b) oxygen concentrators
  c) atmospheric air + ozone delivered by ozone generators.

In case a) to the air taken from the atmosphere is added oxygen from a cylinder to which the volume flow is measured, in relation to the air, the percentage being 25%, 50%, 75%, 100%.

In case b) air with low nitrogen content is blown into the water, the volume participations of the gas mixture being 95% O_2 + 5% N_2.

This mixture is delivered by devices called oxygen concentrators that contain substances called "zeolites" that absorb nitrogen from the air introduced into the device.

In case c) based on the CORONA effect, ozone (O_3) is obtained from the atmospheric air which in mixture with the atmospheric air is blown into the water tank.

Chapter 1. Current state of research on aeration and oxygenation of waters

This chapter presents the main constructive solutions of water aeration installations, namely: mechanical, pneumatic and mixed; separately are presented the oxygenation installations of the water in which the air blown into the water is enriched with oxygen delivered by an oxygen cylinder, oxygen concentrators or ozone generators.

Given the multitude of types and shapes of gas bubble generators that are introduced into the water, there is a need for theoretical and experimental research to treat the entire water aeration system as a unit. In the literature [1] [2] [3] the term aeration or oxygenation is used; it is proposed to make the following distinctions:

- By aerating the waters is meant the introduction of atmospheric air into the water (21% O_2 + 79% N_2);
- Oxygenation of water means the introduction of a gaseous mixture formed in this way:

– atmospheric air + oxygen from a cylinder taken in certain volume participations (25%, 50%, 75%, 100%);

– air with low nitrogen content (Oxygen - 95%, Nitrogen - 5%) delivered by oxygen concentrators;

– atmospheric air + ozone delivered by ozone generators.

Fine bubble aeration is more efficient than coarse bubble aeration because the specific area between the two fluid systems (air - water) is larger. In order to intensify the phenomenon of mass transfer of oxygen from air to water, it is necessary to achieve a maximum interphase contact surface, therefore a small diameter of the gas bubble.

The following objectives are pursued in this paper:

a) Performance of an extensive analysis of the current state of theoretical, numerical and experimental research on the influence of geometric and functional parameters on the concentration of dissolved oxygen in water, based on extensive documentation, a rigorous selection of literature.

b) Identification and presentation in a scientifically coherent manner problems related to the analysis of hydro-dynamic and geometric parameters involved in the process of water aeration and numerical integration of the differential equation of the rate of oxygen transfer to water; presentation of an original solution for increasing the concentration of dissolved O_2 in water.

c) Creation of a program for calculating the function $C_{O_2} = f(\tau)$.

d) Research on the variation of the air flow depending on the diameter of the holes:

I. The speed is kept constant (n_r) and the FBG (fine bubble generator) with Ø 0.1 [mm]; Ø 0.3 [mm]; Ø 0.5 [mm].

As a result, the curve is built $C_{O_2} = f(\Phi)$.

II. The speed is changed and observe $C_{O_2} = f(n_r)$

e) Presentation of an original solution in which FBG is mobile: it is rotating in the water tank.

Comparing the results on:

- The operation of the FBG in fixed position (n = 17 holes Ø 0.3 [mm]);
- The operation of the FBG in rotational motion position (n = 17 holes Ø 0.3 [mm]).

f) Suggestive presentation of the experimental results obtained, tabular and graphical, for all the investigated cases and comparison of the experimentally determined results with the theoretically obtained results in order to establish the most favorable variant regarding the speed of increase of the dissolved oxygen concentration in water.

Chapter 2. Air-water interphase mass transfer

This chapter presents fundamental notions on gas - liquid mass transfer, more specifically air - water; the equation of the rate of oxygen to water transfer is numerically integrated and a calculation program is developed to determine the concentration of dissolved oxygen in the water. At the end of the chapter, the performances of the aeration installations are analyzed, namely: oxygenation yield and oxygenation efficiency.

Gas - liquid mass transfer in stagnant water

The mass transfer which is called diffusion [4] is determined by the migration of particles from the area of upper intensive parameter (pressure, temperature, concentration) to the area where the same parameter is lower.

The development of mass transfer processes is influenced by differences in intensive parameters such as the temperature, the pressure and the concentration of a component.

In biphasic systems the transport of a component can be done between areas in different phases; for example, from a gas to a liquid (air to water). In this case the mass transfer is interphase.

The transport phenomenon is described by means of physical quantities that characterize the amount of substance, energy, etc., that cross a certain imaginary surface, and the transport equation has the form:

$$\frac{\partial \Phi}{\partial t} + \nabla f(t, x, \nabla \Phi) = g(t, x, \Phi), \tag{2.1}$$

Where: Φ – represents the physical quantity that describes the transport phenomenon;

f – represents the flow;

g – is the source that generates the transport process.

If Φ is the concentration and $t = \tau$, we obtain:

$$\frac{\partial \mathrm{C}}{\partial t} + \nabla f(t, x, C, \nabla \mathrm{C}) = \mathrm{g}(\mathrm{t}, \mathrm{x}, \mathrm{C}), \tag{2.2}$$

The transport phenomenon manifested by a transfer of atoms or molecules under the influence of non-uniformity of concentration or density represents the molecular diffusion.

Diffusion consists in the migration of molecules from a region with a higher concentration to one with a lower concentration. The diffusion process is performed by the thermal stirring mechanism. The intensity with which the diffusion phenomenon occurs depends on the state of aggregation of the system, this being the higher the higher the concentration gradient (figure 2.1.).

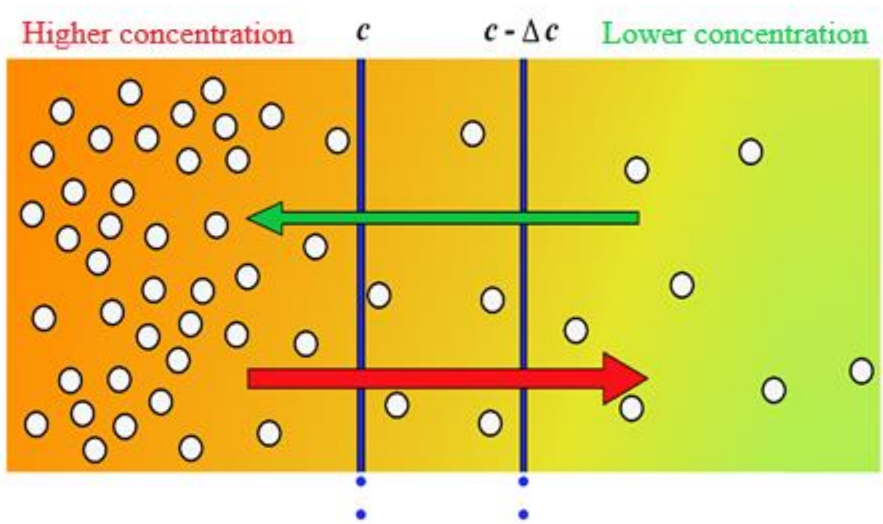

Fig. 2.1. The phenomenon of diffusion in a system with a varied, non-uniform concentration

Concentration gradient

Substance flow

Classification of diffusion processes for gas - liquid mass transfer

Table 2.1. Classification of diffusion processes for gas – liquid systems

The environment in which the process is running	The nature of movement	Flow regime	The nature of the diffusion phenomenon
A – Stagnant fluid	-	-	Molecular diffusion
B – Fluid in motion	B1 – Free movement	-	Natural convective diffusion (natural mass convection)
	B2 – Forced movement	Laminar regime	Forced convective diffusion (forced mass convection)
		Turbulent regime	Forced convective diffusion (forced mass convection)

The equation of the rate of oxygen transfer to water

The expression for the rate of oxygen transfer to water is given by the relation [1]:

$$\frac{dC}{d\tau} = ak_L(C_s - C) \tag{2.3}$$

where:

– ak_L represents the volumetric mass transfer coefficient [s^{-1}];

– C_S – saturation concentration [m^2/m^3];

– C – concentration at the moment τ [kg/m^3];

– $C = f(x,\tau)$.

The relation (2.3) is an ordinary differential equation that is solved using one of the numerical integration methods [5] [6].

Numerical integration of the oxygen to water transfer rate equation

The relation (2.3) is resumed, which represents the equation of the rate of oxygen transfer in water:

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

The relation in which:

– C is the concentration of dissolved oxygen at the moment τ; at the moment τ = 0. C becomes C_0;

– $a \cdot k_L$ – volumetric mass transfer coefficient;

– C_s – oxygen concentration in water, at saturation.

The values $a \cdot k_L$ and C_s are constant over time.

If boundary conditions $C = C_0$ are imposed for $\tau = 0$. the equation (2.3) can be integrated:

$$\frac{\mathrm{d}C}{C_s - C} = a \cdot k_L \, \mathrm{d}\tau \tag{2.4}$$

In the hypothesis $C < C_s$, then, after integration,

$$-\ln(C_s - C) = a \cdot k_L \cdot \tau + ct \tag{2.5}$$

The constant is obtained from the boundary condition:

$$C = C_0 \quad \text{for } \tau = 0 \tag{2.6}$$

and it has the value

$$ct = -\ln(C_s - C_0) \tag{2.7}$$

After introduction of (2.7) into (2.5) we have:

$$C = C_s - (C_s - C_0) \cdot e^{-a \cdot k_L \cdot \tau} \tag{2.8}$$

$$\tau = 0 .$$

In the studied case, air is continuously introduced into the tank for 120 minutes, so the regime is non-stationary and C_{O_2} increases over time.

In non-stationary regime, the measured quantity is the oxygen concentration in the water as a function of time. The following are measured: water and air temperature, gas flow at the inlet to the tank and gas pressure in the body FBG.

Calculation program for determining the concentration of dissolved oxygen in water

The Euler method is used to develop a calculation program for the numerical integration of the oxygen to water transfer rate equation.

In order to establish theoretically the increase of the concentration of dissolved oxygen in water as a function of the oxygenation time of water, the following quantities must be known:

– initial oxygen concentration for a given water temperature (t = 25 [°C]), C_0=5.12 [mg/dm^3];

– saturation concentration C_s = 9.2 [mg/dm^3] for the same water temperature;

– the integration step: a research duration of about two hours is estimated; chosen step: h=1 [min] (n=121); $\Delta\tau$ = 120 [min].

From the literature [7] for a blown air flow of 540 [dm^3/h], kept constant, a value for ak_L of 0.09 [s^{-1}] is adopted.

Schematic of the numerical integration of the differential equation of the oxygen transfer rate to water is presented in *figure 2.2*.

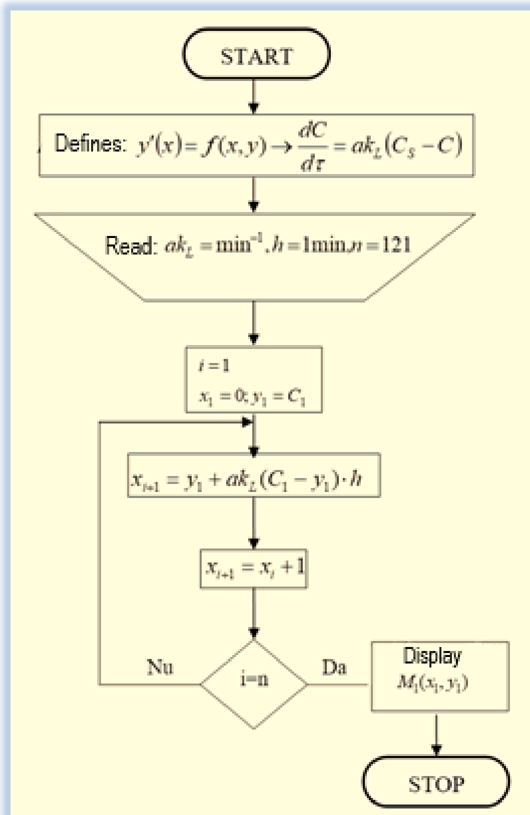

Fig. 2.2. Schematic calculation for the numerical integration of the differential equation of the oxygen transfer rate to water

Performances of the aeration installations

These performances are oxygenation yield and oxygenation efficiency.

a) Oxygenation yield indicates the percentage of oxygen transferred to water from the total amount of oxygen (approximately 21% by volume of the amount of atmospheric air) introduced into the water.

b) Aeration efficiency indicates the amount of oxygen transferred to the water, for an electricity consumption of 1 [kWh].

Chapter 3. Presentation of bubble generators

This chapter addresses both fixed and mobile bubble generator types; the constructive solution for the bubble generator, mobile, rotating in stagnant water, generator which will be used in the experimental research performed in this paper, is detailed.

Fine bubble generators - Fixed

In order to follow the subject of the thesis, a fine bubble generator is presented in two situations:

a) The fine bubble generator, in a fixed state, in the water tank;
b) Fine bubble generator, in moving state (it rotates in the water tank).

In both situations a) and b) the generator has 17 holes with a diameter of 0.3 [mm].

In this paragraph is presented the fixed F.B.G. mounted inside a water tank.

Thus, the following types of F.B.G were performed:

a) F.B.G with holes of 0.1 [mm], the hole plate is made of transparent plexiglass.
b) F.B.G with holes of 0.3 [mm], the hole plate is made of transparent plexiglass.
c) F.B.G with holes of 0.5 [mm], the plate with holes being made of aluminum.

Presentation of fine bubble generators with a rectangular shape

Figure 3.1. shows the plate with holes for F.B.G with 152 holes, Ø 0.1 [mm].

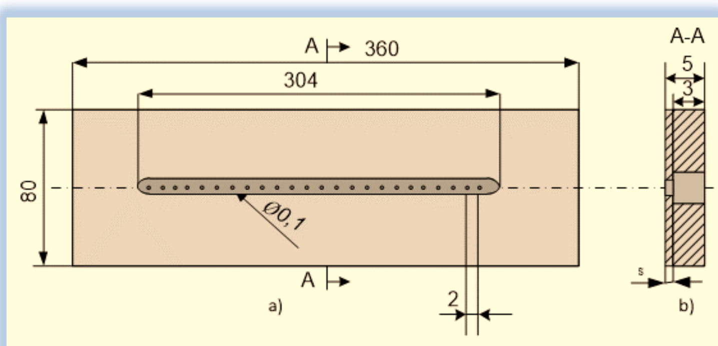

Fig.3.1. Plate with holes of F.B.G

a) top view; b) cross section

To make the holes in the plate, a channel deep of 3 [mm], and a length of 304 [mm] was created; the hole where the air comes out has a thickness of 2 [mm]. Later, with the help of a

C.N.C (Computer Numerical Control), which has a special machine for micro-processing type KERN Micro, 152 holes with a diameter of Ø 0.1 [mm] were made in the channel.

The CNC equipment has a precision of ± 0.5 [µm], which assures the creation of an original F.B.G solution.

Figure 3.2 shows the constructive solution of F.B.G.

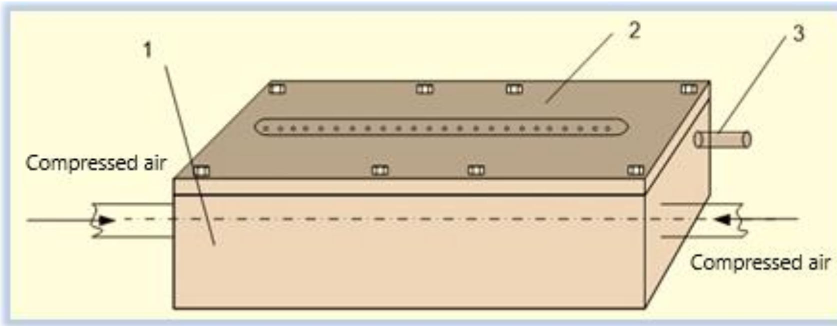

Fig. 3.2. Fine bubble generator

1 – tank filled with compressed air; 2 – plate with holes;

3 – coupling for the measurement of the air pressure

Through the connection 3 is measured the static gas pressure using a digitally indicated pressure gauge.

A rectangular plate was chosen as the construction form. In the figure 3.3. the sketch of this plate is presented.

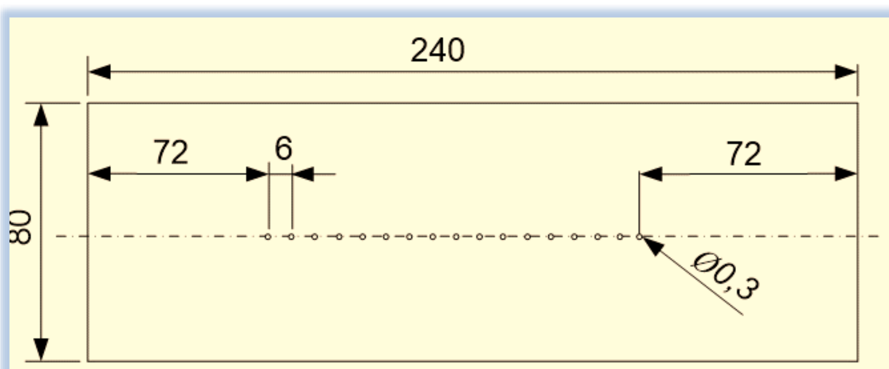

Fig. 3.3. Plate with 17 holes of Ø 0.3 [mm]

Fine bubble generators – Mobile

These generators are equipped with an electromechanical displacement mechanism for:

I) a rotational movement in water tank;

II) a translational movement in the water tank

For both generators the speed of movement is constant.

In this paper only the option I was analyzed.

The sketch of this new type of F.B.G. is shown in *figure 3.4.* In this case the compressed air duct enters through the upper part of the water tank (1)

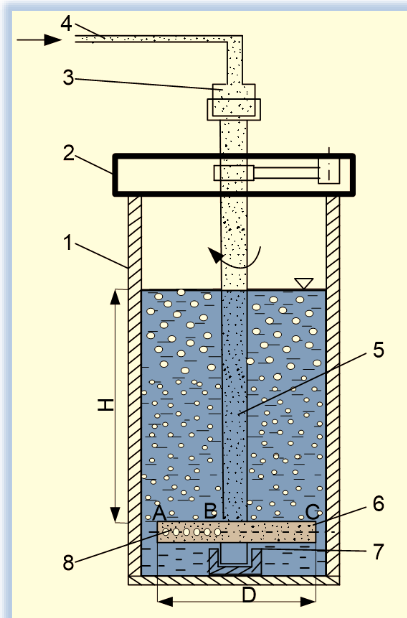

Fig. 3.4. The sketch F.B.G. immersed in water

1-water tank; 2-platform for the F.B.G. rod drive mechanism; 3-mobile seal; 4-compressed air pipe; 5-F.B.G rod; 6-constructive element of F.B.G.; 7-axial bearing; 8-holes with a diameter of 0.3 [mm]

This type of F.B.G. is provided with a mobile seal (3) which allows driving in rotational motion of the plate with holes.

Solutions to increase the concentration of dissolved oxygen in water

Figure 3.5. shows a sketch in which are observed:

I) Current solutions used to increase the concentration of dissolved oxygen in water;

II) An original solution related to a F.B.G., namely the rotation of the F.B.G. in water tanks; by this process under the same initial conditions (V, p, t_{H2O}, H), the time for which C_0 tends to C_s is reduced by half.

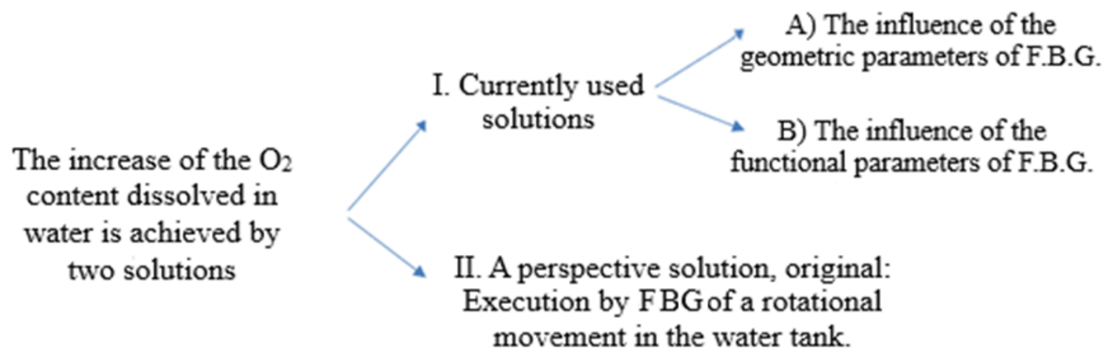

Fig. 3.5. Current and forward-looking solutions for achieving value: $C_0 \rightarrow C_s$

Chapter 4. The influence of geometric parameters of fine bubble generators on the concentration of dissolved oxygen in water

In this chapter is analyzed the equation of oxygen transfer to water. Constructive variants of the fine bubble generators are presented and their location in water tanks.

Analysis of the oxygen to water transfer equation

The equation of the rate of transfer of dissolved oxygen in water is given by the relation

$$\frac{dC}{d\tau} = ak_L(C_s - C) \quad \left[\frac{kg}{m^3 \cdot s}\right] \tag{4.1}$$

where: $\dfrac{dC}{d\tau}$ – speed of the variation of the concentration of dissolved oxygen in water (speed of oxygen transfer to water) $\left[\frac{kg}{m^3} \cdot \frac{1}{s}\right]$;

ak_L – volumetric mass transfer coefficient [s^{-1}];

C_s – mass concentration of oxygen at saturation in the liquid phase [kg/m^3];

C_0 – the initial mass concentration of oxygen in the liquid phase [kg/m^3].

In the field of water oxygenation, it is known that the smaller the diameter of the gas bubble (air), the higher the rate of oxygen transfer to water. In this sense, the results of theoretical research on the performance of fine bubble generators built by special technologies will be presented [8] [9] [10]. By micro-drilling, three variants of perforated plates were made with holes of: $Ø_1 = 0.1$ [mm], $Ø_2 = 0.3$ [mm], $Ø_3 = 0.5$ [mm].

With the notations in *figure 4.1*, in the design and construction of F.B.G. the following two conditions must be meet:

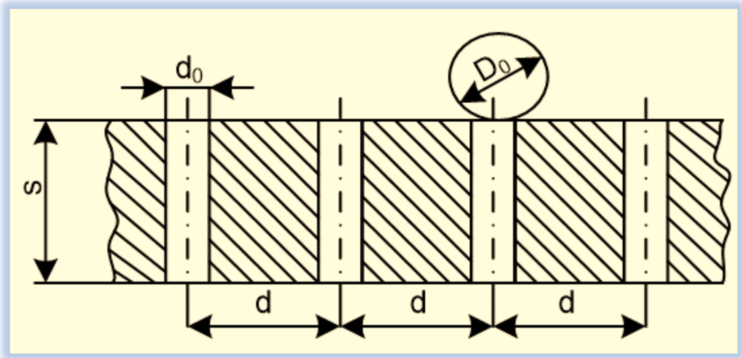

Fig. 4.1. Plate with holes for air dispersion in water

d_0 – hole diameter, $d_0 = 2r_0$; s – the thickness of the perforated plate

D_0 – The diameter of the gas bubble at the outlet of the hole (at the time of its detachment)

$$\text{I} \rightarrow \frac{s}{d_0} > 3 \tag{4.2}$$

$$\text{II} \rightarrow \frac{d}{d_0} > 8 \tag{4.3}$$

In experimental research for the three variants, are obtained:

$$\text{I. } d_0=0.1\ mm;\ \frac{s}{d_0} = \frac{2}{0,1} = 20;\ \frac{d}{d_0} = \frac{2}{0,1} = 20 \tag{4.4}$$

$$\text{II. } d_0=0.3\ mm;\ \frac{s}{d_0} = \frac{2}{0,3} = 6,66;\ \frac{d}{d_0} = \frac{6}{0,3} = 20 \tag{4.5}$$

$$\text{III. } d_0=0.5\ mm;\ \frac{s}{d_0} = \frac{2}{0,5} = 4;\ \frac{d}{d_0} = \frac{10}{0,5} = 20 \tag{4.6}$$

We noticed that for the three variants the ratio $\frac{s}{d_0} > 3$, and the ratio $\frac{d}{d_0} = 20$, thus $\frac{d}{d_0} > 8$.

Based on previous research [11] [12] and considering the architecture of the experimental research facility, the number of holes for the three variants is obtained.

The author proposes a new generation of F.B.G. in which the air dispersion holes in water are processed by micro-drilling ($Ø_1$ =0.1 [mm], $Ø_2$ =0.3 [mm], $Ø_3$ =0.5 [mm]).

Constructive variants of fine bubble generators and theoretical results for calculating the reduction of aeration time.

The following are the three constructive variants of the F.B.G.

Based on the calculation program built to solve the equation of the rate of oxygen transfer from air to water, the curve of variation of the concentration of dissolved O_2 in water was determined as a function of time for the three constructive variants of F.B.G.

A) Theoretical research for the fine bubble generator, with perforated plate having 152 holes Ø 0.1 [mm].

Figure 4.2. shows the plate with holes.

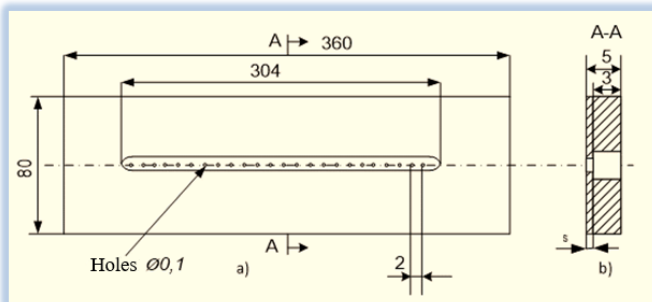

Fig. 4.2. Plate with 152 holes of F.B.G.

a) Top view; b) cross section

To make the holes in the plate (*figure 4.3*), a channel deep of 3 [mm], and a length of 304 [mm] was created; a hole where the air comes out has a thickness of 2 [mm]. Later, with the help of a C.N.C (Computer Numerical Control), which has a special machine for micro-processing type KERN Micro, 152 holes with a diameter of Ø 0.1 [mm] were made in the channel. The CNC has a precision of ± 0.5 [µm], which assures the creation of an original F.B.G solution.

Figure 4.3 shows the constructive solution of F.B.G for the variant I

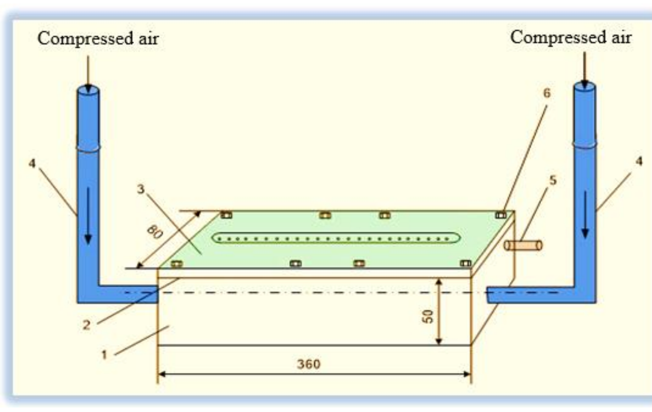

Fig. 4.3. Fine air bubble generator

1- compressed air tank; 2- sealing gasket; 3- plate with holes; 4- compressed air supply pipe of F.B.G Ø 18mm; 5- connection for measuring compressed air pressure; 6- screws for fixing of the plate with holes to the compressed air tank

After running the calculation program [13] [14], for F.B.G in variant I, the curve was built C=f(τ), having as initial data: $\dot{V} = 600\left[dm^3/h\right]$; C_0 = 5.48 [mg/dm^3], τ = 120 [min]; t_{H_2O} = 24 [^0C] C_s = 8.4 [mg/dm^3].

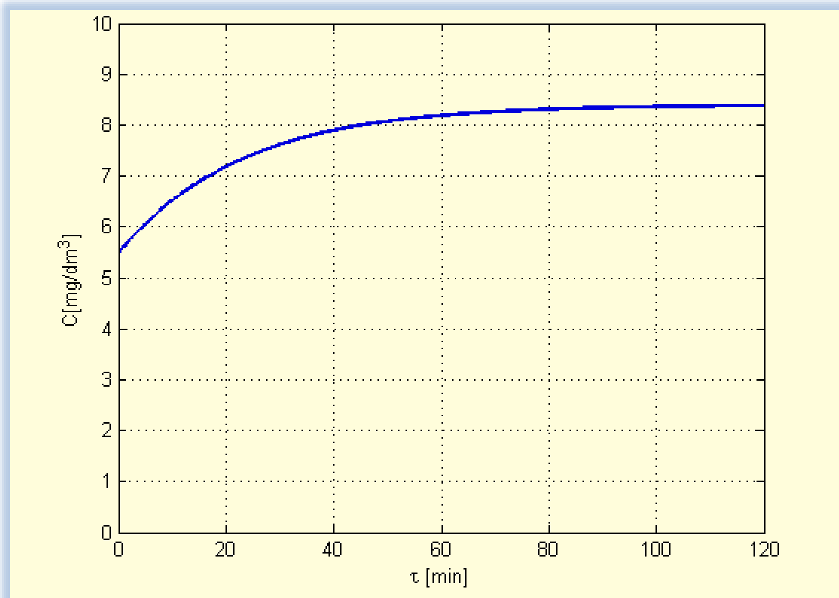

Fig. 4.4. Change of dissolved oxygen's concentration in the water, as a function of time for F.B.G with 152 holes Ø 0.1 [mm]

B) Theoretical research for the fine bubble generator, with perforated plate having 17 holes Ø 0.3 [mm]

A rectangular plate was chosen as the construction form. A sketch of this plate is shown in *Figure 4.5*.

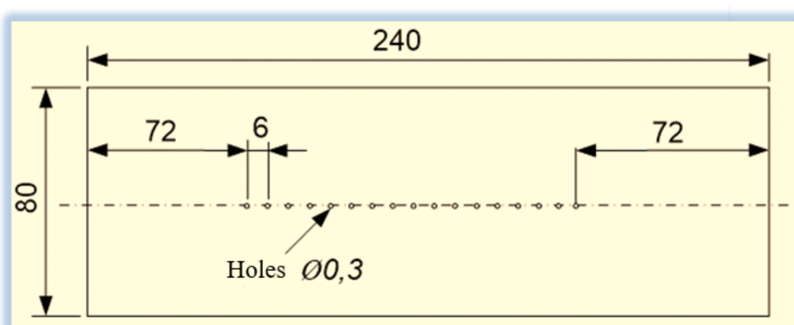

Fig. 4.5. Plate with 17 holes Ø 0.3 [mm]

The distance between the holes is 6 [mm] and the thickness of the aluminum plate is 2 [mm].

Figure 4.6. shows the variation of the dissolved O_2 concentration over time for the above F.B.G.

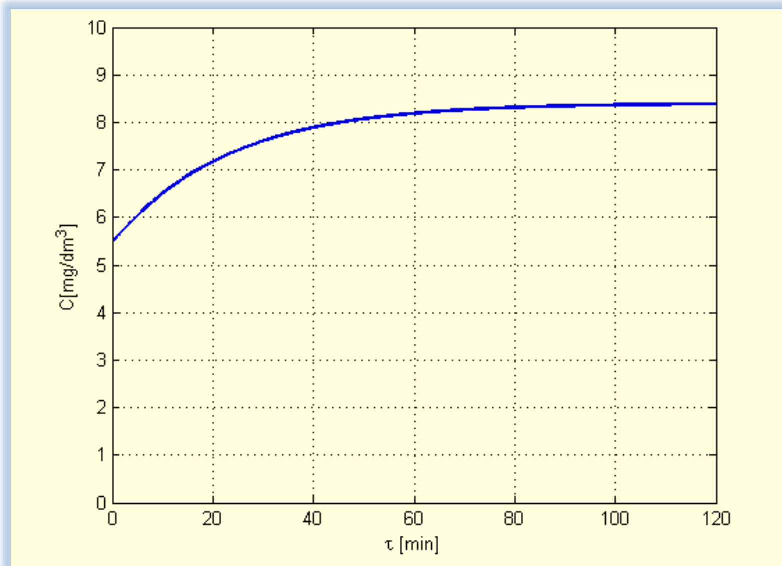

Fig. 4.6. Change of dissolved oxygen's concentration in the water, as a function of time for F.B.G with 17 holes Ø 0.3 [mm]

C) Theoretical research for the fine bubble generator, with perforated plate having 6 holes Ø 0.5 [mm]

A rectangular plate was chosen as the construction form. A sketch of this plate is shown in *Figure 4.7*.

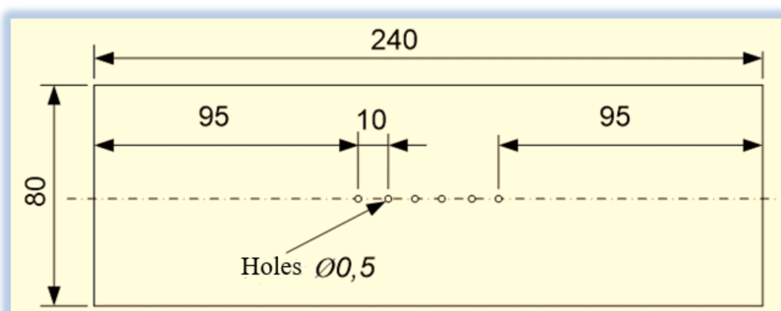

Fig. 4.7. Plate with 6 holes Ø 0.5 [mm]

The distance between the holes is 10 [mm] and the thickness of the aluminum plate is 2 [mm].

Figure 4.8. shows the variation of the dissolved O_2 concentration over time for the above F.B.G.

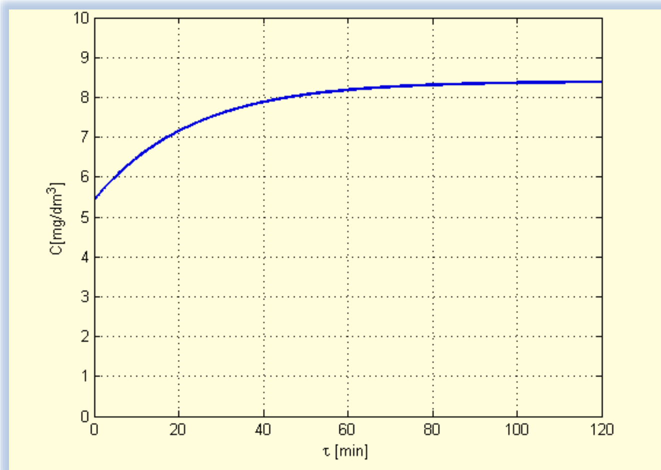

Fig. 4.8. Change of dissolved oxygen's concentration in the water, as a function of time for F.B.G with 6 holes Ø 0.5 [mm]

To highlight the influence of the diameter of the air blowing hole on the water on the concentration of dissolved oxygen in the water, a comparison can be made of theoretical research conducted for the three types of fine bubble generators [15] [16].

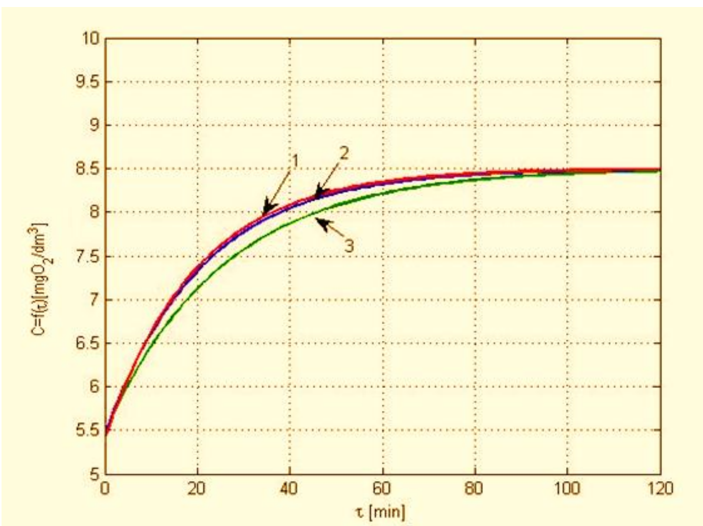

Fig. 4.9. Change of dissolved oxygen's concentration in the water, as a function of time

1- F.B.G with 152 holes Ø 0.1 [mm], 2- F.B.G with 17 holes Ø 0.3 [mm], 3- F.B.G with 6 holes Ø 0.5 [mm]

By analyzing *figure 4.9*, the following conclusions can be drawn:

- the increase in the concentration of dissolved O_2 in water is faster in the case of the fine bubble generator with holes Ø 0.1 [mm] compared to the generations of fine bubbles with holes Ø 0.3 [mm] and Ø 0.5 [mm];

- it is confirmed that a smaller diameter of the air blowing holes in the water leads to a more efficient oxygenation of the water volume.

Location of generators on the water tank screed

Obviously, the increase in the number of F.B.G. placed in water will shorten the time in which $C_0 \rightarrow C_s$ [17].

In *figure 4.10.* we have 4 F.B.G. mounted in parallel.

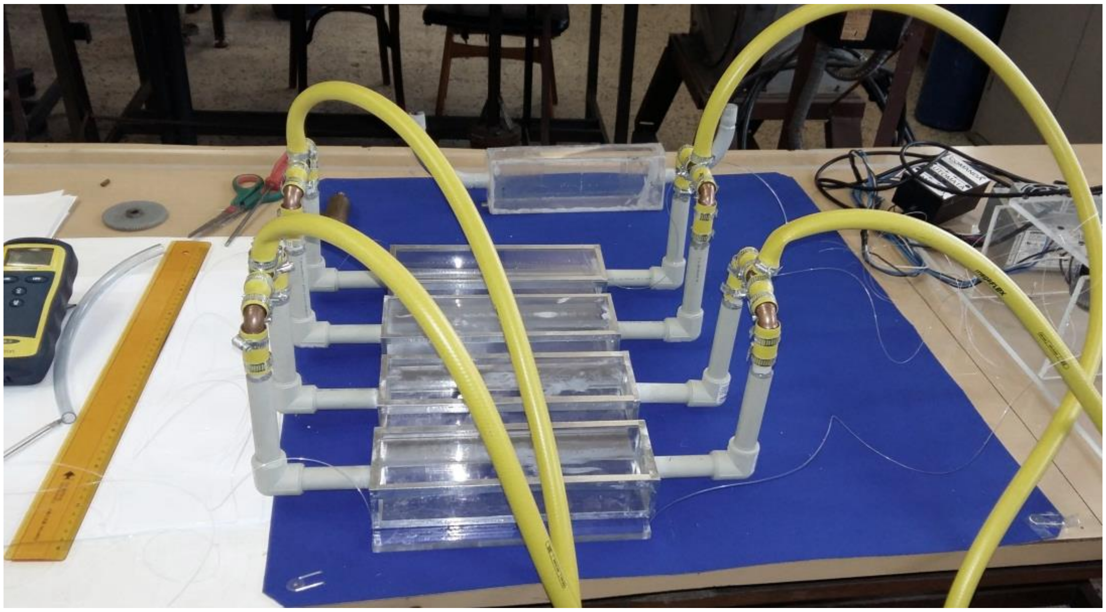

Fig. 4.10. Four F.B.G. before being placed in the water tank [18]

In this case, the aeration time is reduced by four times: it becomes 30 min (*figure 4.11.*).

In order to highlight as clearly as possible the benefits of using a larger number of fine bubble generators, the variation curves of the dissolved oxygen concentration in water for $n_{F.B.G} = 1, 2, 3, 4$ will be compared.

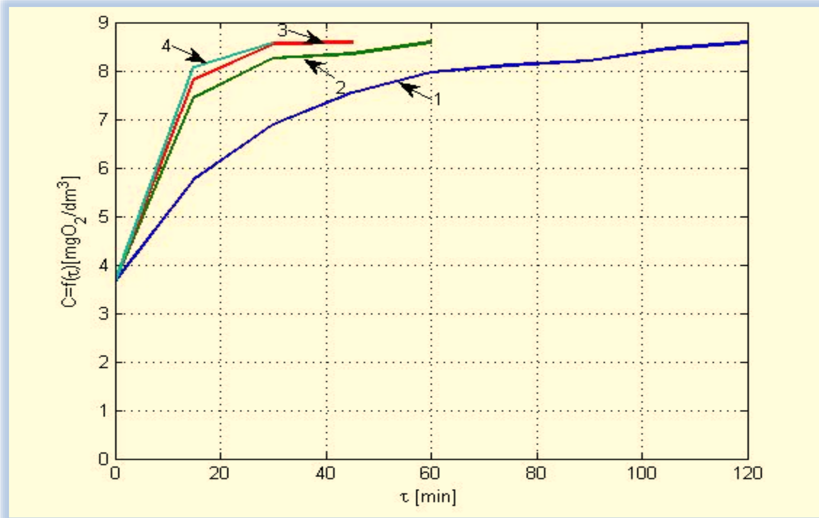

Fig. 4.11. Change of dissolved oxygen's concentration in the water, as a function of time

1- $n_{F.B.G}$ = 1 F.B.G.; 2- $n_{F.B.G}$ = 2 F.B.G.; 3- $n_{F.B.G}$ = 3 F.B.G.; 4- $n_{F.B.G}$ = 4 F.B.G.

From *figure 4.12.* is possible to observe the variation of the concentration of dissolved oxygen in the water in time depending on the number of used fine bubble generators, as well as the shortening of the duration of the oxygenation time.

Chapter 5. The influence of functional parameters of fine bubble generators on the concentration of dissolved oxygen in water

In this chapter the following analyzes were made: the influence of the initial concentration (C_0) on the aeration process, the influence of the air pressure introduced into the water on the aeration process, the influence of temperature and atmospheric pressure on the oxygen concentration at saturation. The influence of hydrostatic load and the degree of water turbulence on the aeration process is revealed.

The influence of C_s on the aeration process

The concentration of oxygen at saturation (Cs) or the maximum dissolved oxygen is the maximum amount of substance (oxygen) that is dissolved in the mass of water (clean, wastewater, etc.). This can be measured with electronic devices that use electrochemical or optical sensors. In aquatic environments, oxygen saturation is a relative measure of the maximum oxygen dissolved in water. Supersaturation is often a problem in aquatic environments because the presence of oxygen in very large quantities leads to decompression and disease of organisms in the aquatic environment.

The influence of C_0 on the aeration process

The initial dissolved oxygen concentration (C_0) is considered to be the minimum dissolved oxygen concentration required for aquatic life to survive or consume certain compounds in the case of wastewater [19] [20].

For different values of the initial concentration the theoretical curves from *figure 5.1* were obtained (using the Runge-Kutta method in Mathlab), in which the influence of the initial concentration on the rate of oxygen transfer from air to water is observed.

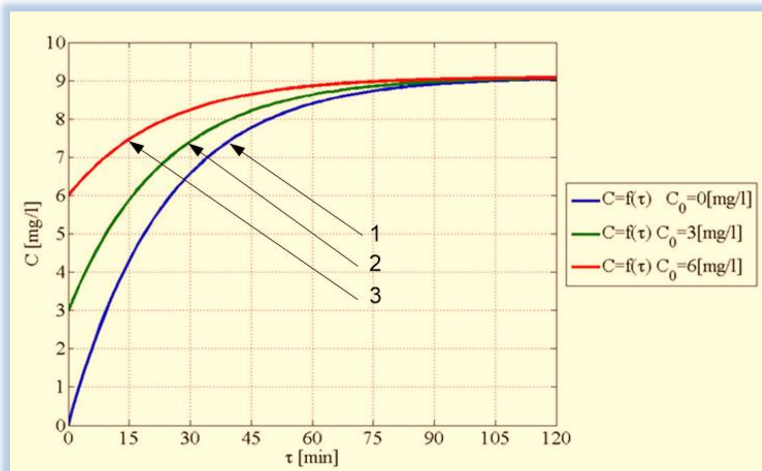

Fig. 5.1. Dissolved oxygen concentration $C=f(\tau)$ at different values of the initial concentration 1- $C=f(\tau)$ at $C_0=0$ [mg/dm^3]; 2- $C=f(\tau)$ at $C_0=3$ [mg/dm^3]; 3- $C=f(\tau)$ at $C_0=6$ [mg/dm^3].

From *figure 5.1.* we observed that for higher values of C_0. the value of C increases faster.

The influence of the air pressure introduced into the water on the aeration process

The air pressure at the inlet to the fine bubble generator is a very important parameter in the selection, evaluation and monitoring of fine bubble generators, regardless of the shape or material from which they are constructed.

The energy consumption required for aeration from the total consumption of a treatment plant is about *67%*, which justifies scientific research on obtaining F.B.G. with lower pressure drop or higher oxygenation capacity, at a reduced compressed air consumption [21] [22].

The energy consumed is calculated using the relation [23]:

$$E_c = \Delta p \cdot \dot{V} \cdot \tau \quad [\mathrm{J}] \tag{5.1}$$

where:

Δp [N/m^2] – pressure drop;

$$\Delta p = \Delta p_{supply\ network} + \Delta p_{aeration\ system} [\text{N/m}^2] \quad (5.2)$$

$\dot{V} [m^3/s]$ – aeration system flow;

τ [s] – operating time.

In order to be efficient, a F.B.G. must have a pressure drop as small as possible and emit fine bubbles evenly over its entire work surface. A lower pressure drop on the equipment leads directly to a low energy consumption used to compress the air and thus to a better efficiency of the aeration system [21].

The influence of the air flow introduced into the water on the aeration process

The air flow with which the fine bubble generator is fed has a significant role in the transfer of dissolved oxygen in the standing water. It influences the mass transfer coefficient ak_L and therefore the mass transfer rate [24] [25].

Depending on the flow of air chosen for each piece of equipment, the speed of oxygen transfer in water is also determined, each regime having its own characteristics.

A dynamic regime was chosen for the experimental research. The air flow significantly influences $ak_{L(20)}$,$\partial C/\partial \tau$, η_{OX} *and* E in all experiments performed. As the airflow increases, so do $ak_{L(20)}$ and $\partial C/\partial \tau$, but η_{OX} and E decrease. At a higher air flow, the turbulence at the liquid interface and the speed of renewal of the liquid film increase.

The influence of water temperature on the oxygen concentration at saturation

The temperature influences most of the physical, chemical and biological processes involved in the aeration process. So, in the aeration process, the temperature influences the oxygen regime in the water, the intensity of the bacterial decomposition processes, the degree of toxicity of some substances.

The influence of temperature on saturation concentration at *695* [*mmHg*], *760* [*mmHg*] and *795* [*mmHg*] are shown in *figure 5.2*. The values on the basis of which the chart was drawn up were taken from the specialized publications.

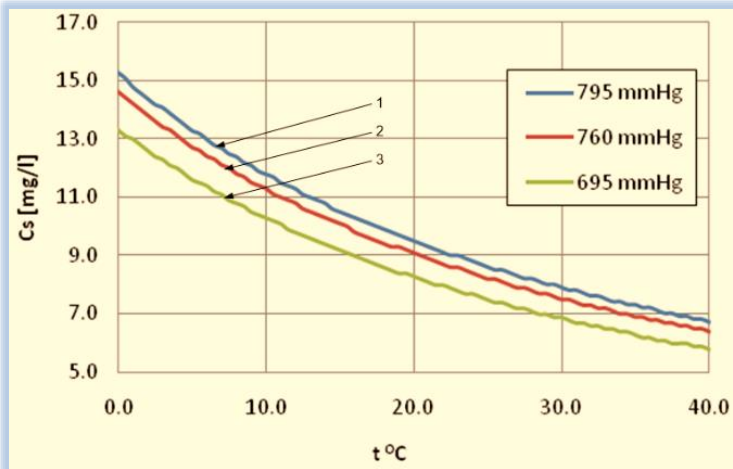

Fig. 5.2. Variation of saturation concentration with temperature at different values of atmospheric pressure.

1- C_s depending on the temperature at 795 [mmHg]; 2- C_s depending on the temperature at 760 [mmHg]; 3- C_s depending on the temperature at 695 [mmHg];

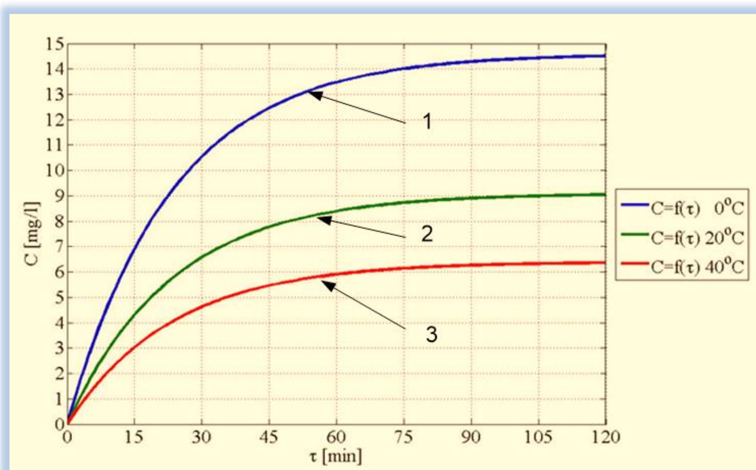

Fig. 5.3. Dissolved oxygen concentration *C=f(τ)* at different temperatures [26].

1- *C=f(τ)* la *0* [°C]; 2- *C=f(τ)* la *20* [°C]; 3- *C=f(τ)* la *40* [°C].

As can be seen, the concentration of dissolved oxygen in water over time is inversely proportional to temperature in the sense that if the temperature of aerated water increases, the concentration of oxygen saturation decreases and implicitly we have a lower transfer rate.

The atmospheric pressure is another factor that directly influences the saturation concentration of dissolved oxygen in water. A correlation of this factor can be seen in *Table 5.1*, at a water temperature of *20 [°C]* [1].

Table 5.1. Variation of saturation concentration depending of atmospheric pressure at 20 [°C]

p_{at}	**795**	**790**	**785**	**780**	**775**	**770**	**765**	**760**	**755**	**750**
C_s	*12.40*	*12.30*	*12.20*	*12.10*	*12.10*	*12.00*	*11.90*	*11.80*	*11.70*	*11.70*
p_{at}	745	740	735	730	725	720	715	710	705	700
C_s	*11.60*	*11.50*	*11.40*	*11.30*	*11.30*	*11.20*	*11.10*	*11.00*	*11.00*	*10.90*
p_{at}	695	690	685	680	675	670	665	660	655	650
C_s	*10.80*	*10.70*	*10.60*	*10.60*	*10.50*	*10.40*	*10.30*	*10.20*	*10.20*	*10.10*
p_{at}	645	640	635	630	625	620	615	610	605	600
C_s	*10.00*	*9.90*	*9.90*	*9.80*	*9.70*	*9.60*	*9.50*	*9.50*	*9.40*	*9.30*

According to Henry's law, the saturation concentration is proportional to the partial presence of oxygen. The calculations use a corrected pressure of the average atmospheric pressure at altitude H using the subunit factor:

$$f = \frac{p_{atH}}{p_{ato}} \tag{5.13}$$

where, p_{at0} - represents the value of atmospheric pressure at sea level.

Table 5.2. The values of the correction coefficient on the O_2 depending on altitude

Altitude *H[m]*	**0**	**500**	**1000**	**1500**	**2000**	**2500**
f	1	0.924	0.887	0.834	0.784	0.737

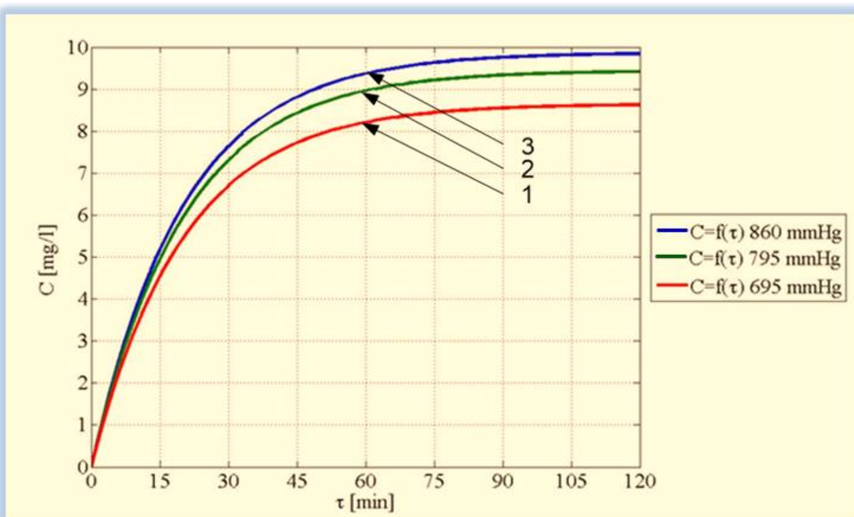

Fig. 5.4. Dissolved oxygen concentration *C=f(τ)* at different atmospheric pressure values

1- *C=f(τ)* at *695 [mmHg]*; 2- *C=f(τ)* at *795 [mmHg]*; 3- *C=f(τ)* at *860 [mmHg]*

As can be seen from *Figure 5.4*, the concentration of dissolved oxygen is directly proportional to the atmospheric pressure, in the sense that if the atmospheric pressure increases, the saturation concentration also increases.

The influence of water salinity on oxygen concentration at saturation

The salinity is another factor that influences the saturation concentration of dissolved oxygen. The values of saturation concentration as a function of salinity are corrected by the subunit coefficient β, using the relation [26]:

$$\beta = \left(C_{s_{uz}} - C_s\right) \tag{5.18}$$

where: $C_{s_{uz}}$ - concentration at saturation in wastewater

The values of dissolved oxygen concentration in water as a function of salinity can be expressed as a function of the chloride concentration in water or as a function of conductivity in [*µs/cm*] at *25 [*°C*]* of water, using the correction factor. For example, to correct a saturation concentration of 9.1[mg/*dm*^{3}] (at a temperature of *20 [*°C*]* and a normal atmospheric pressure of *760* [*mmHg*]), the following formula is used:

$$9.1\ mg/dm^3 \times 0.956 = 8.70\ [mg/dm^3] \tag{5.19}$$

where, *9.1* [mg/dm^3] represents the saturation concentration in clean water; *0.956* [mg/dm^3] represents the correction coefficient from *table 5.2*; *8.70* [mg/dm^3] represents the corrected saturation concentration.

The specific electrical conductivity indicates the level of water salinity and is a convenient overall measure of salts.

In *figure 5.5.* can be seen the variation of the correction coefficient with salinity at *0 [*°C*]*, *20 [*°C*] and 35 [*°C*]*.

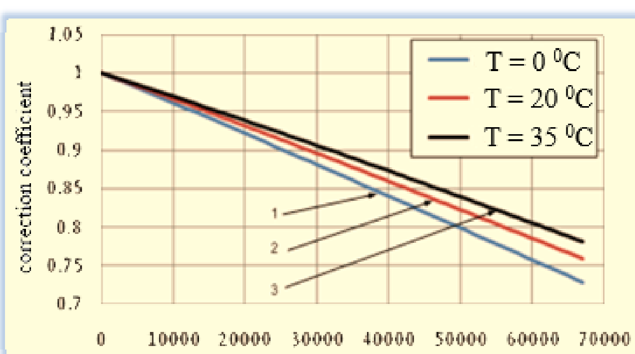

Fig. 5.5. Variation of the correction coefficient with salinity depending on the conductivity [µs/cm] [27]

1- C_s depending on conductivity at 0 *[*°C*]*; 2- C_s depending on conductivity at 20 *[*°C*]*;

3- C_s depending on conductivity at 35 *[*°C*]*.

So, in order to be able to express the rate of oxygen transfer over time, this correction factor is introduced in the equation of the rate of oxygen transfer - *relation (2.3)*, obtaining a relation in the form:

$$\frac{dC}{d\tau} = ak_L(C_s \cdot s - C) \quad \left[\frac{kg}{m^3 \cdot s}\right] \tag{5.20}$$

where:

s – represents the correction factor with salinity based on conductivity.

Thus, the concentration of dissolved oxygen in water is obtained over time at different conductivity values for a water temperature of *20 [°C]*. The same data for the temperature and pressure calculation are used as data necessary for the calculation of the curves.

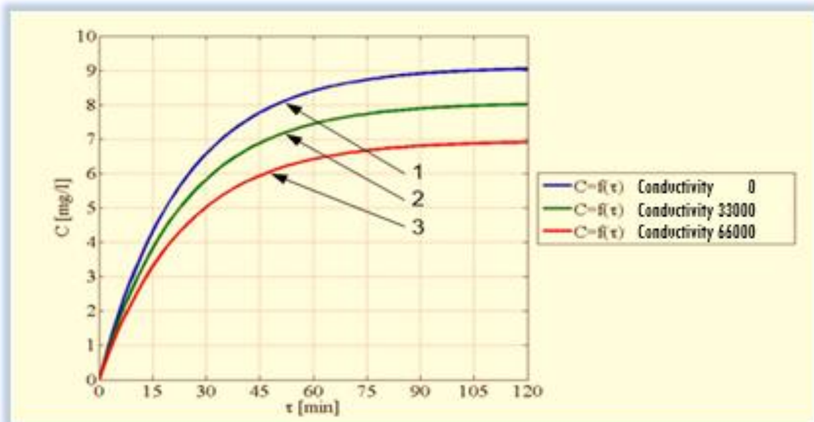

Fig. 5.6. Dissolved oxygen concentration C=f(τ) at different values of the correction coefficient with salinity 1- C=f(τ) at conductivity 0 [μs/cm]; 2- C=f(τ) at conductivity 33000 [μs/cm]; 3- C=f(τ) at conductivity 66000 [μs/cm] [28];

The influence of hydrostatic load on the aeration process

The hydrostatic load in an aeration process represents the load exerted by the existing water mass above the F.B.G., i.e. by the height of the existing water layer above the fine bubble generator.

If we consider the relation of the transfer rate in the case of the correction with the atmospheric pressure, we can intervene on the water state, so we can obtain values of the oxygen transfer rate according to it.

Chapter 6. Analysis of the operation of a bubble generator, fixed or rotating, in a volume of stagnant water

In this chapter is presented the constructive solution of the bubble generator that will be studied in two situations: a) the fixed bubble generator; b) the bubble generator, mobile, which is in rotational motion.

The two bubble generators, fixed and mobile, are included in a scheme of operation of an experimental installation.

Framing the fine bubble generator, fixed, in an operating scheme

The fine bubble generator presented in Chapter 3 is included in the diagram in *Figure 6.1*.

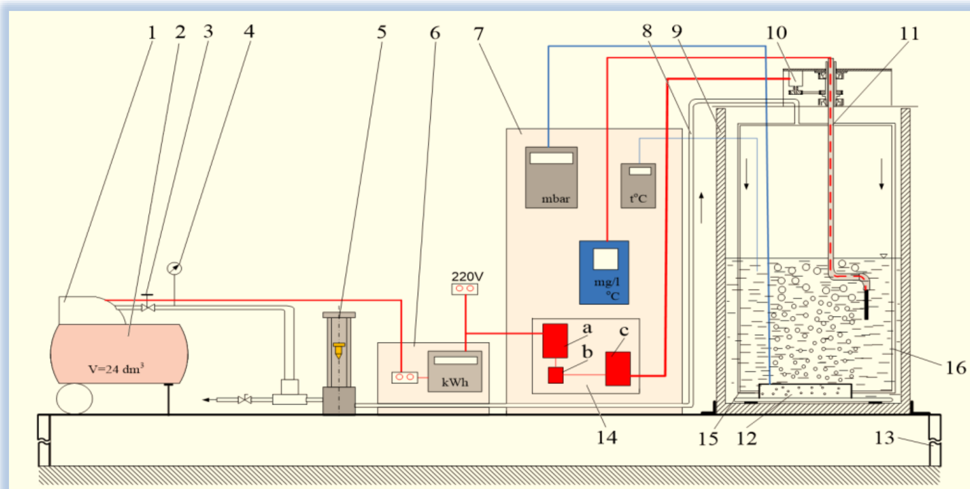

Fig. 6.1. Drawing of the experimental equipment regarding the water oxygenation

1 – compressor with air tank; 2 – tank with compressed air, V = 24 [m^3]; 3 – pressure reducer; 4 – pressure gauge; 5 – flowmeter; 6 – electrical cabinet; 7 – panel with measuring devices; 8 – pipe for compressed air transportation to F.B.G.; 9 – water tank; 10 – probe drive mechanism; 11– Oxygen meter probe; 12 – F.B.G. with rectangular shape;13 – equipment's stand; 14 – electronic command device: a – power supply, b – switch, c – command device; 15,16 – compressed air pipes

Determining the equation of the trajectory of a gas bubble leaving FBG in rotating motion; determination of the concentration of dissolved oxygen in water

Using the calculation program, the variation of the dissolved oxygen concentration in water was determined for a fixed generator with 17 holes 0.3 [mm].

Following the running of the calculation program, we obtained the data for plotting the variation of the concentration of O_2 dissolved in water depending on time: C = f(τ).

It was observed that after two hours of operation, the C_0 value tends to C_s.

Figure 6.2 shows the F.B.G. in rotating motion, immersed in the water tank. The compressed air is introduced inside the rod 6. The rod is driven in rotational motion by a mechanism. In detail, the rod drive mechanism is shown in *Figure 6.3.*

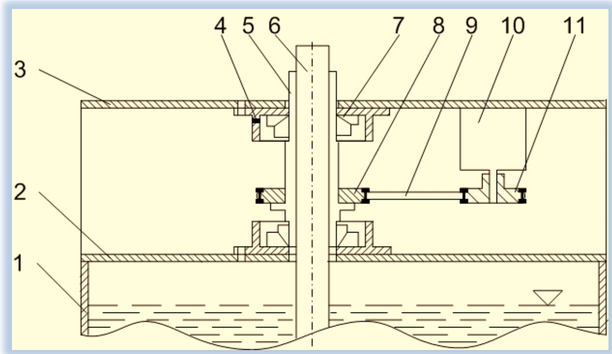

Fig. 6.2. Device used to involve the FBG rod in a circular motion:
1 – water tank; 2- base plate; 3- upper plate; 4- casing for bearing cone;
5- central nut; 6- rod; 7 – bearing cones; 8 – gear wheel; 9- gear belt;
10 - stepping motor; 11 – gear wheel coupled with the motor axle.

Framing the fine bubble generator in an operating scheme

The fine bubble generator was included in the installation in *figure 6.3.*

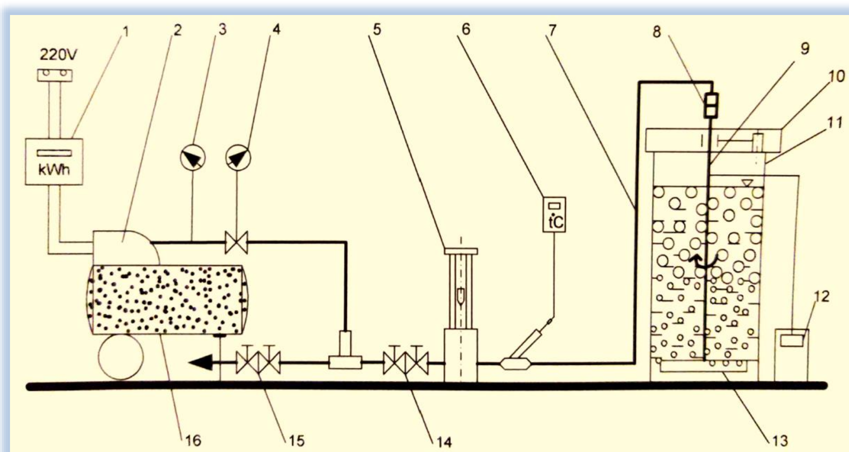

Fig. 6.3. The general sketch of the experimental plant
1-electricity meter; 2-compressor; 3-pressure gauge; 4-pressure reducer; 5-flowmeter (rotameter); 6-digital thermometer; 7- compressed air pipe; 8- mobile sealing; 9- driving rod of the FBG; 10- platform for the driving mechanism of the FBG rod; 11- water tank; 12-digital manometer; 13- nozzle box; 14- control valves for the air flow towards the FBG; 15- valves for the evacuation of the additional air; 16- compressed air tank

The mobile seal (8) ensures the supply of compressed air to the F.B.G. in rotating motion.

Theoretical determination of the dissolved oxygen concentration in water for F.B.G. in rotating motion

The equation of the trajectory of an air bubble coming out of the F.B.G. in rotating motion and enters the water in the tank is established from the beginning.

A fine bubble generator that rotates at an angular velocity $\omega = ct$ in a water tank is used. This F.B.G. creates air bubbles through holes Ø *0.3* [*mm*] located in the *xOy* plane.

Neglecting the centrifugal force of an air bubble, the bubble will move in a curvilinear trajectory (*figure 6.4.*).

The tensile strength *(F_r)* and the inertial force *(F_i)* have components on the *Oy* and *Oz* axes.

The forces acting on the bubble at a point on the bubble's trajectory are in a plane parallel to the *yOz* plane; the equilibrium conditions are specified in relations *(6.4)* and *(6.5)* [29]:

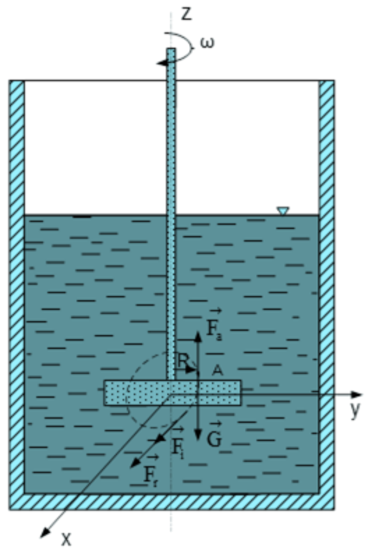

Fig. 6.4. Forces acting on the gas bubble

On the axis Oy: $$\vec{F}_{i,oy} + \vec{F}_{r,oy} = 0 \qquad (6.4)$$

On the axis Oz: $$\vec{F}_a - \vec{G} - \vec{F}_{r,oz} - \vec{F}_{i,oz} = 0 \qquad (6.5)$$

where:

F_a – the Archimedean force acting on the gas bubble;

G – the weight of the gas bubble.

Calculation results obtained

To solve the equations that define the trajectory of the air bubble in ascending motion, when the fine bubble generator is in rotational motion, a simulation program in **MatLab** was used.

Following the running of the program, the curve in *figure 6.5* resulted.

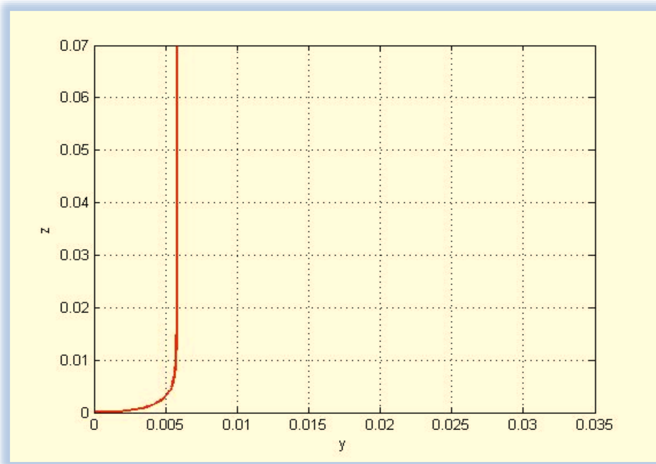

Fig. 6.5. The trajectory of the air bubble for the fine bubble generator in rotating motion

The trajectory of the air bubble, for the fine bubble generator in rotating motion, was determined for a speed of F.B.G. of 0.392 [m/s]. At higher rotational speeds of the F.B.G. bubble coalescence occurs [30][31].

The variation of the dissolved oxygen concentration in water, determined theoretically is presented in *figure 6.6*.

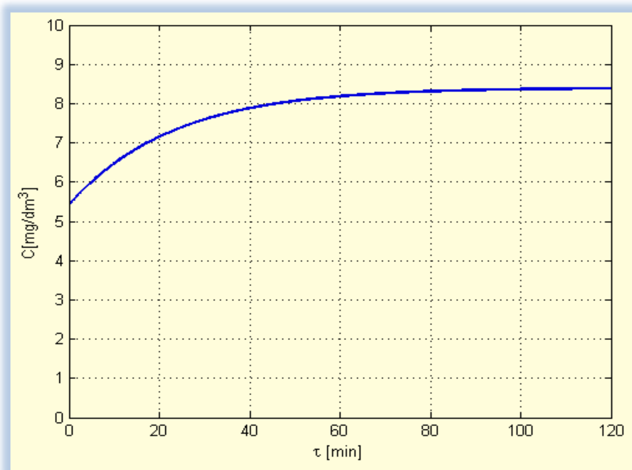

Fig. 6.6. Function $C_0 = f(\tau)$ for F.B.G. in rotation motion: n = 17 holes; Ø 0.3 [mm]

From *figure 6.6.* it is observed that $C_0 \rightarrow C_s$ after 60 [min], so the aeration time is reduced by half. This process is an original solution that can be useful in various chemical processes, energy, environmental protection, etc., i.e. where aeration is required in a very short time.

Chapter 7. Conception, design and construction of the experimental installation

This chapter presents the scheme of the experimental installation, the purpose of the research, the research methodology and the measuring devices used.

Compressed air was introduced into the F.B.G at pressure (p_1) [32][33].

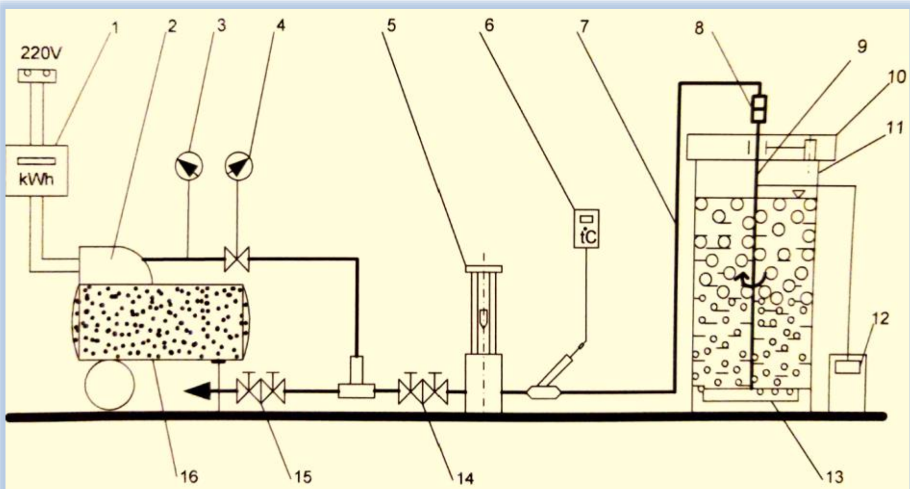

Fig. 7.1. The general sketch of the experimental plant

1-electricity meter; 2-compressor; 3-pressure gauge; 4-pressure reducer; 5-flowmeter (rotameter); 6-digital thermometer; 7- compressed air pipe; 8- mobile sealing; 9- driving rod of the FBG; 10- platform for the driving mechanism of the FBG rod; 11- water tank; 12-digital manometer; 13- nozzle box; 14- control valves for the air flow towards the FBG; 15- valves for the evacuation of the additional air; 16- compressed air tank

The air delivered by the electro-compressor (2) passes through the flowmeter - rotameter (5) and through the mobile sealing (8) enters in F.B.G.(13).

The aim of the experimental research is to demonstrate that the oxygenation installations with fine bubble generators in rotating motion are more efficient than the classic ones with fine, fixed bubble generators.

One of the aims of the paper is to present a new type of fine bubble generator that halves the oxygenation time of water.

Initially a fine bubble generator is introduced in a water tank, immobile, having 17 holes with Ø 0.3 [mm]: The air flow introduced into the water and the hydrostatic load are kept constant; the saturation concentration of O_2 dissolved in water is reached in two hours. Subsequently, under the same conditions, the fine bubble generator with the rotating orifice plate is tested and the water aeration time is reduced by one hour.

Chapter 8. Experimental research on the influence of geometric and functional parameters on water aeration time

This chapter presents the results of experimental research on the analysis of aeration time in the case of the fixed fine bubble generator and the fine bubble generator in rotating motion.

Figure 8.1. shows a fixed F.B.G. in a water tank.

Fig. 8.1. Fine bubble generator with 17 holes (Ø 0.3mm) in operation in water tank

For the geometric parameters, two aspects were analyzed:

– Influence of the diameter of the air inlet on C_{O_2}(*figure 8.2.*);
– Influence of the location of F.B.G. in the water tank (*figure 8.3.*).

Figure 8.2. shows the theoretical and experimental results comparatively.

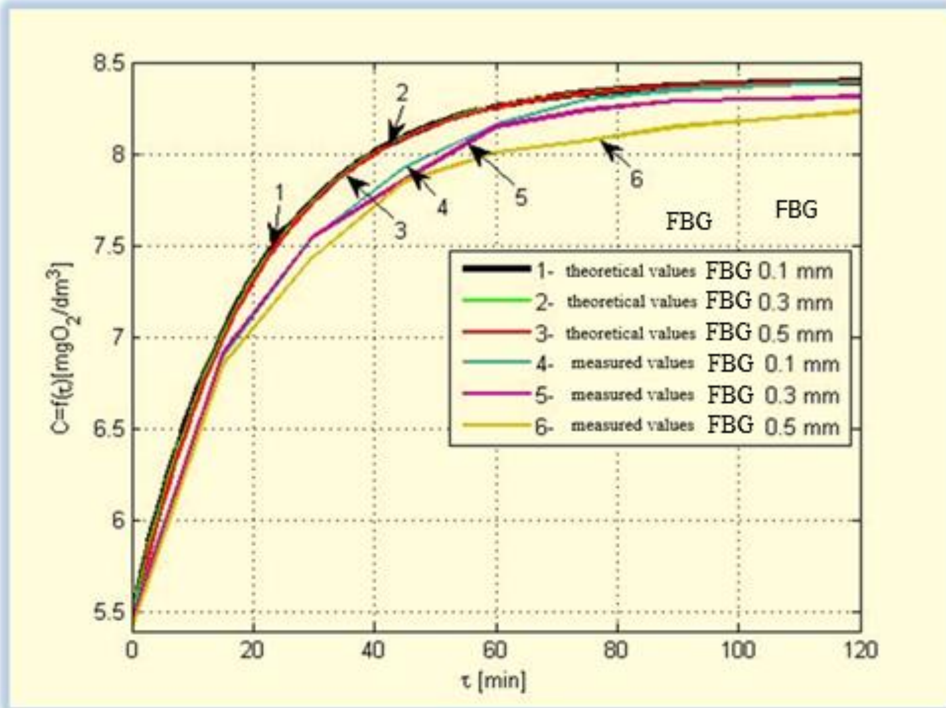

Fig. 8.2. The evolution in time of the concentration of O_2 dissolved in water: C=f(τ)

From *figure 8.2.* it is observed that the value of dissolved oxygen concentration in water reaches from C_0 to C_s the fastest when F.B.G. has the smallest hole (Ø 0.1 mm), a result which is confirmed by other specialized papers [34][35][36].

In *figure 8.3.* it is observed the change of the dissolved oxygen concentration in the water depending on time, for a certain number (id) of F.B.G.

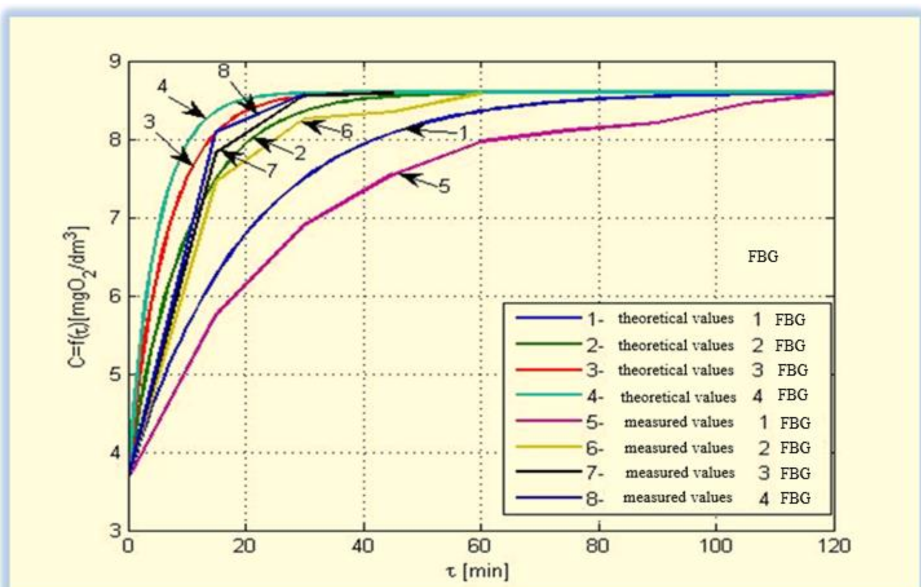

Fig. 8.3. The evolution in time of the concentration of O_2 dissolved in water: C=f(τ)

In *figure 8.3.* it can be seen that the use of a large number of fine bubble generators ($n_{F.B.G.}$ =4), greatly shortens the time required for the oxygenation process of the water from the water tank.

From *figure 8.3.* it follows that C_0 tend to C_s fastest when the number of F.B.G. is the largest (n = 4) [37][38].

Influence of functional parameters

a) The influence of the initial concentration and the saturation concentration of dissolved oxygen in water.

When t_{H2O} = *24 [°C]*, from [1] is obtained: C_0 = 5.46 [mg/dm^3]; C_s = 8.4 [mg/dm^3].

When t_{H2O} = *21 [°C]*, from [1] is obtained: C_0 = 7.72 [mg/dm^3]; C_s = 8.9 [mg/dm^3].

Figure 8.4. shows the variation in time of the concentration of dissolved oxygen in the water.

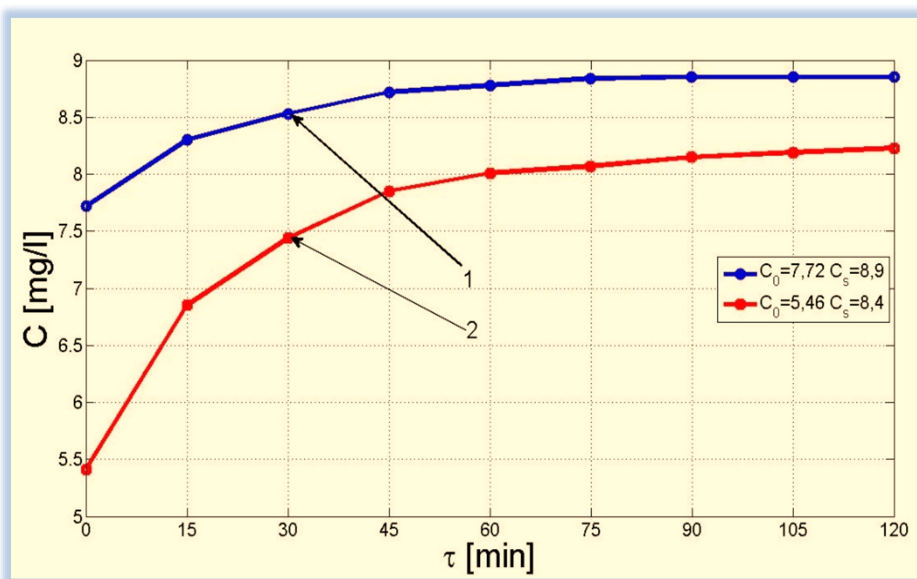

Fig. 8.4. The evolution in time of the concentration of O_2 dissolved in water
1- C_0=7.72 [mg/dm^3] C_s=8.9 [mg/dm^3]; 2- C_0=5.46 [mg/dm^3] C_s=8.4 [mg/dm^3];

Fine bubble generator (F.B.G.) used in the experimental research had the plate with 17 holes Ø 0.3 [mm].

b) The influence of air flow and pressure introduced in the F.B.G. on the concentration of dissolved oxygen in the water.

In figure 8.5. it is observed that when the air flow increases from 400 to 600 [dm^3/h], the increase of the dissolved oxygen concentration in the water is faster.

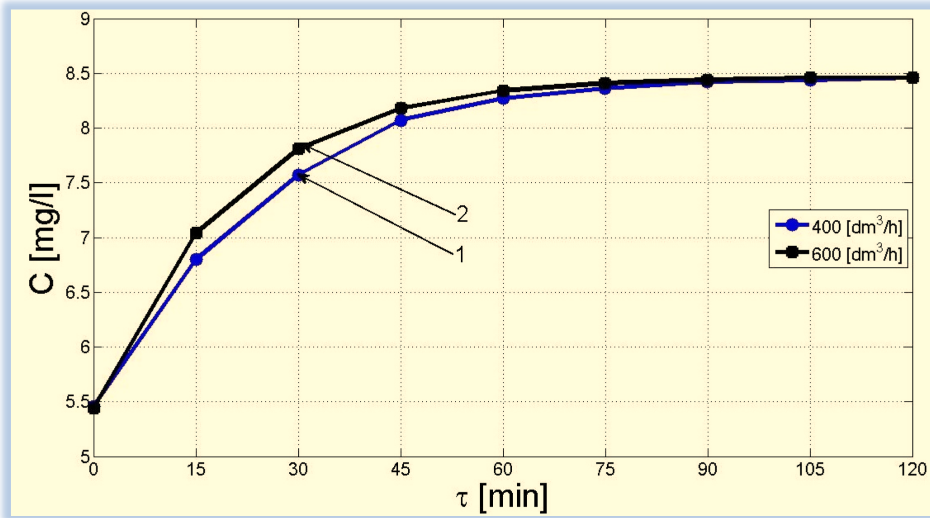

Fig. 8.5. The variation in time of the dissolved oxygen concentration in water depending on the air flow into water. 1- flow 400 [dm^3/h]; 2- flow 600 [dm^3/h];

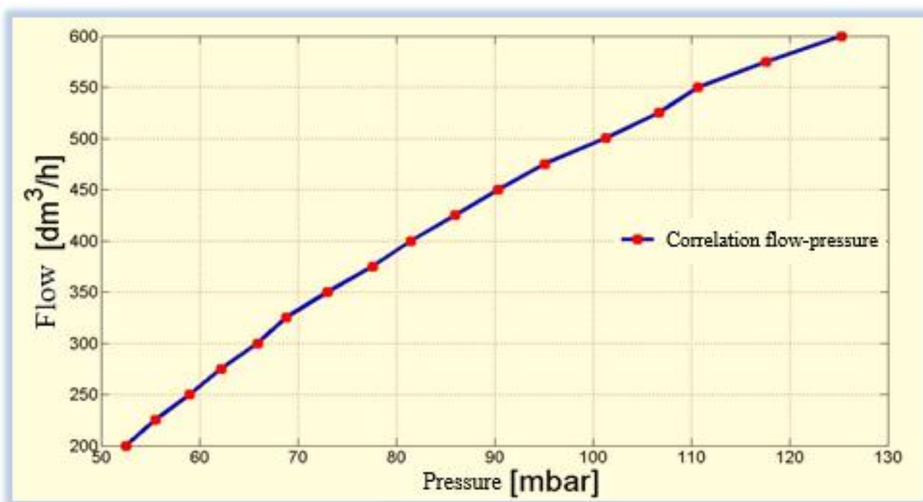

Fig. 8.6. The correlation between flow and pressure for F.B.G. with *6 holes Ø 0.5* [*mm*]

Obviously, as the flow rate increases, the air pressure will increase from 82 [mbar] to 123 [mbar] (*figure 8.6.*)

c) The influence of hydrostatic charge on the concentration of dissolved oxygen in water.

Because in the laboratory of the department of Thermodynamics, Engines, Thermal and Refrigeration Equipments we had a 1 [m] high water tank, the hydrostatic load values were modest: h = 0.5 [m], respectively 0.75 [m].

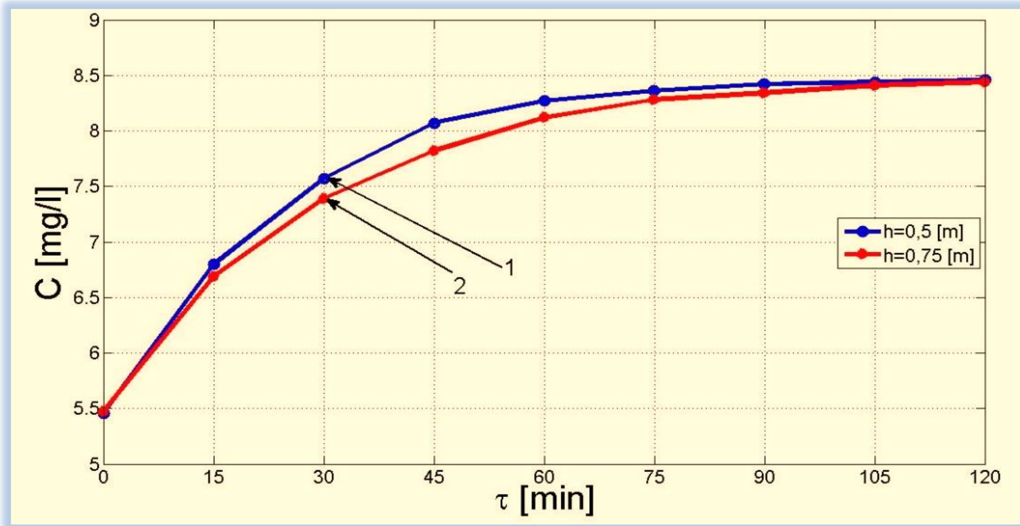

Fig. 8.7. The evolution in time of the concentration of O_2 dissolved in water
1- h=0.5[m]; 2- h=0.75[m];

From *figure 8.7.*, a difference is observed in the graphs C = f (τ), depending on the hydrostatic load.

The experimental research performed is similar to those presented in other specialized papers [39].

The results of experimental research on the analysis of aeration time in the case of F.B.G. fixed and F.B.G. in rotating motion

The experimental researches were carried out in two variants:

- Variant I, F.B.G. is fixed
- Variant II, the hole plate of the F.B.G. is driven by an electric motor in rotating motion.

⌘ In the variant I, the water temperature was t=24 [°C], the initial concentration of dissolved oxygen in water: C_0 = 3,12 [mg/dm^3]; for the same temperature, the saturation concentration is C_s = 8,3 [mg/dm^3]. The flow of the introduced air was 600 [dm^3/h]; after two hours the concentration of dissolved oxygen in the water increased, according to the curve shown in *figure 8.8.*, reaching the C_s value.

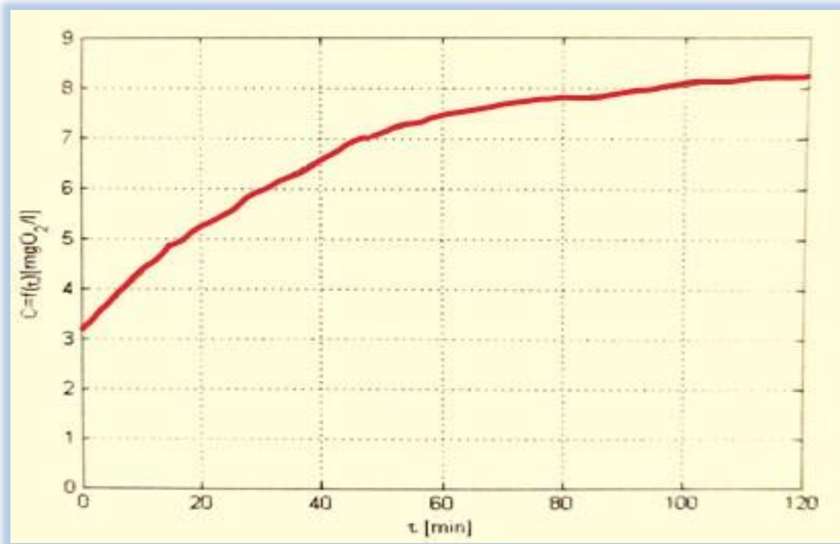

Fig. 8.8. The evolution in time of the concentration of O_2, for variant I

This graph was drawn based on experimental data.

From *figure 8.8.* we observed that C_s value tends to be reached after two hours.

⌘ After that, a F.B.G. was introduced into the same water tank, for which the orifice plate was rotated at a speed of 0.392 [m/s]. Air flow and air pressure were kept constant and equal to those of previous experiments. The air bubbles have the direction of exit contrary to the direction of movement of the F.B.G in its rotational motion.

The increase of the dissolved oxygen concentration in the water is observed in *figure 8.9.*

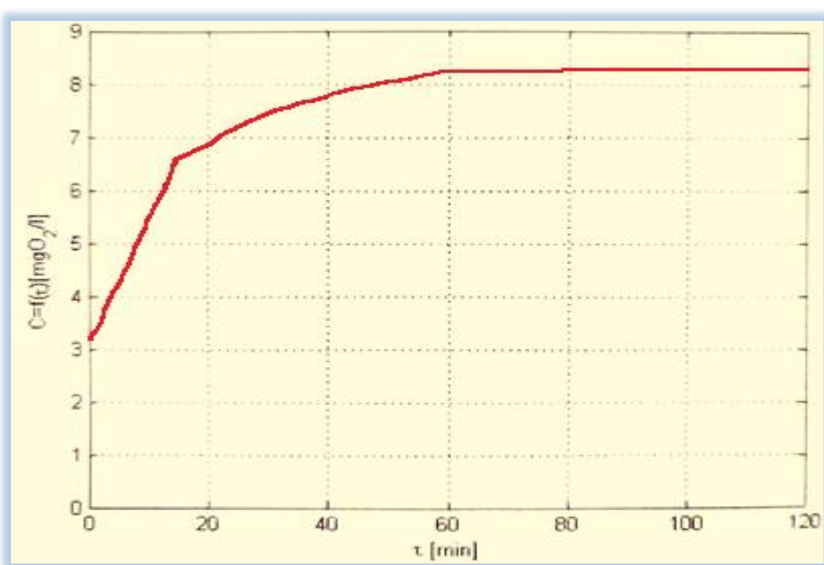

Fig. 8.9. The evolution in time of the concentration of O_2, for variant II

If the graphs in *figure 8.8.* and *8.9.* overlap on the same drawing, the *figure 8.10* is obtained.

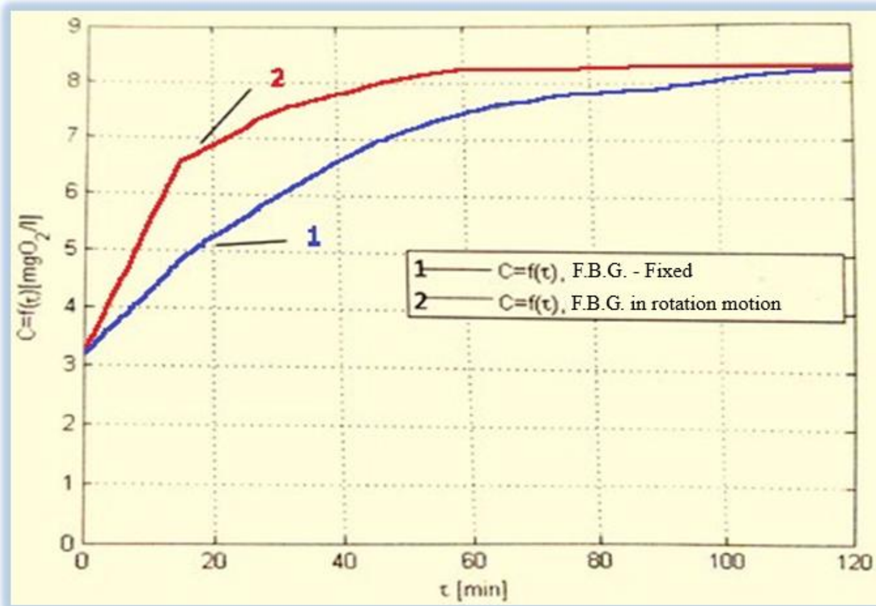

Fig. 8.10. The evolution in time of the concentration of O_2, for both studied variants

From *figure 8.10.* for variant II it is found that the saturation concentration C_s=8,3 [mg/dm^3] is reached after about 60 minutes, so **the oxygenation time is reduced by half**. This is due to the fact that the cylinder filled with water of diameter D and height H is permanently swept away by a loss of moving bubbles (*figure 3.6.*).

CONCLUSIONS AND PERSONAL CONTRIBUTIONS

The last chapter "Conclusions" contains general conclusions, original contributions and perspectives for further research. Following is a rich list of bibliographic references. The research results were finalized by publishing a number of 9 articles in specialized journals and at national and international conferences.

C1 General conclusions

- The use of F.B.G. provided with plates with holes performed using electro-erosion ensure a uniform distribution of air bubbles entering the water body.
- Because the holes have the same diameter, the air bubbles have the same diameter at the entrance to the water body.
- There is no danger of clogging of the holes.

- For F.B.G. with the perforated plate in rotating motion the oxygenation time of the water is reduced by two times compared to F.B.G. which have a fixed perforated plate.
- Following the experiments it was found that the pressure losses at F.B.G. made with plates machined by electro-erosion are smaller than those with porous diffusers.

In water treatment and purification processes, oxygenation, called in some specialized works and aeration, is the basic operation in ensuring a proper water quality.

Aeration is used [40][41]:

- In water treatment processes, when removing dissolved inorganic substances or chemical elements such as iron, manganese, etc., by oxidation and formation of sedimentable compounds or which can be retained by boiling.
- For the biological treatment of wastewater, either by the process with activated sludge or with biofilters;
- In disinfection processes, by ozonation of raw water captured from a source in order to make it drinkable.
- In the separation and collection of emulsified fats from wastewater.
- Water oxygenation is a mass transfer process with wide applications in the technique of water treatment and purification. Oxygenation equipment is based on the dispersion of one phase in the other, for example gas in liquid, energy consuming process.

C2 Original contributions

The following contributions will be briefly presented:

- The solution to achieve F.B.G. by electro-erosion is original. F.B.G. made using electro-erosion ensures a controlled and uniform dispersion of air in water.
- The use of F.B.G. with rotating perforated plate is an original solution to increase the transfer of oxygen to the water, which leads to an increase in the concentration of dissolved oxygen in the water.

A. Theoretical contributions

1. Elaboration of a bibliographic study on aeration and oxygenation of waters.
2. Determining the mass transfer of oxygen to water by analyzing the equation of the rate of oxygen transfer to water. Elaboration of a method of numerical integration of this equation and subsequently realization of a calculation program for determining the change of the dissolved oxygen concentration in water.

3. The conception, design and construction of F.B.G. of original design, useful for aerating waters.
4. Specification of solutions to increase the concentration of O_2 dissolved in water.
5. Analysis of the parameters that modify the concentration of O_2 dissolved in water with the highlighting of the operation of an F.B.G. in rotating motion.
6. Establishing the equation of the trajectory of air bubbles emitted by F.B.G. in rotating motion.
7. By performing this movement, the aeration time of the water is reduced by half, from 120 min to 60 min.

B. Numerical contributions

1. Determination of the change in the concentration of dissolved oxygen in water using a calculation program (Matlab).
2. Development of calculation programs for different input data such as: $C_{0.}$ C_s, for F.B.G. fixed or F.B.G. in rotation motion in a water tank.

C. Experimental contributions

1. The conception, design and construction of experimental installations for F.B.G. fixed and F.B.G. mobile, rotating at a speed of 0.392 [m/s].
2. The construction of three types of F.B.G. with perforated plate having holes with Ø 0.1 [mm], Ø 0.3 [mm] and Ø 0.5 [mm].
3. A methodology of experimental research was developed based on which original results were obtained.
4. The results of theoretical and experimental research were the basis for the elaboration of the 9 papers presented in Annex 1.

C3 Prospects for further research

Research on water aeration will continue in the following directions:

- The conception and construction of some F.B.G. in which the perforated plate has holes with a diameter of 0.005 [mm] or of the order of [µm].
- Use of nanotechnologies in water aeration; use of air jets to aerate water [42].
- Aeration of water to be done directly by blowing compressed air into the wastewater transport pipeline [43]; this avoids the construction of wastewater water tanks on the radier of

which there are perforated pipes through which compressed air is blown. This reduces investment in wastewater treatment plants.

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