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Theoretical and Experimental Researches on the Determination of Pressure Losses on Bubble Generators Used for Water Aeration

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Abstract: *The paper presents a theoretical and experimental analysis of pressure losses in the case of pneumatic aeration, which can be performed by:*
A. A network of pipes with orifices arranged on the tank foundation plate
B. A system of porous diffusers
C. A network of fine bubble generators
Theoretically, the pressure loss is determined when the air passes through the three constructive solutions (A, B, C); subsequently, the theoretical results are compared with the data obtained from the experimental researches carried out in the laboratory of the department of Thermotechnics, Engines, Thermal and Refrigeration Equipment.

Keywords: *Fine air bubble generator, water aeration, porous diffusers.*

1. Introduction

The process of water aeration is based on a transfer between two environments: air - water, i.e., it is an interphase process.
The air bubbles provided by the aeration equipment are introduced into a volume of water; the smaller the diameter of the air bubble, the more efficient the water aeration.
The performance of a water aeration system is specified by two parameters:
- the efficacy of the water oxygenation process;
- the efficiency of the water oxygenation process.
The water aeration process can be performed as follows [1] [2]:
1. By mechanical aeration;
2. By pneumatic aeration;
3. By mixed aeration.
In the case of mechanical aeration, the air is introduced into the water through aerators, thus realizing the surface aeration.
In the case of pneumatic aeration, the air is introduced into the water through dispersion systems, which can be:
A. A network of pipes with orifices arranged on the tank foundation plate,
B. A porous diffuser system in which the dispersion element is a rubber member with orifices,
C. A network of fine bubble generators.
Aeration systems must meet the following conditions:
- ensuring the air supply, for the existence of water fauna;
- maintaining a mixture between air and water;
- elimination of CO_2 excess resulting from the oxidation of organic matter.
In the literature [3] [4], there are several criteria for classifying aeration equipment, as follows:
a. According to the way of obtaining the interphase contact surface:
- water spray equipment and cascade equipment;
- equipment that disperses the gas in water (deep mechanical aerators, etc.);
- mixed equipment - sprays water in the form of drops and entrains the air through the jet effect at the re-entry in the water mass from the tank (mechanical surface aerators).
b. According to the mode of the aeration equipment active organ movement:
- static equipment (static aerators, ejectors, etc.);
- dynamic equipment (mechanical surface or deep aerators).

c. *By the gas type used for aeration*:
- equipment that disperses air in water (deep mechanical aerators, pneumatic aerators, ejectors, etc.);
- equipment that disperses pure oxygen in water (pneumatic type);
- equipment with the introduction of ozone or ozone-enriched air in water (such as fluid jet pumps).

2. Theoretical determination of the pressure loss in case of pneumatic aeration

For the three cases A, B, C, presented in the paper abstract, the initial data are the same, namely:
- The introduced air flow rate $\dot{V} = 600 \ \mathrm{dm}^3/\mathrm{h}$:
- Compressed air pressure: p = 583 mmCA;
- Hydrostatic load: H = 500 mmCA;
- Water temperature: t = 24ºC;
- Air temperature: t = 24ºC;
- Water density: ρ = 1000 kg / m^3;
- The air density --- will be calculated in the next paragraph.

Further in the paper, the pressure losses that occur in pneumatic aeration systems are theoretically calculated.

2.1 Pneumatic aeration systems, made with orifices pipes

INKA aeration systems (figure 1) are systems based on the bubble aeration process in which the perforated pipes, located at approximately 0.8 m below the water level, represent the element of air dispersion.

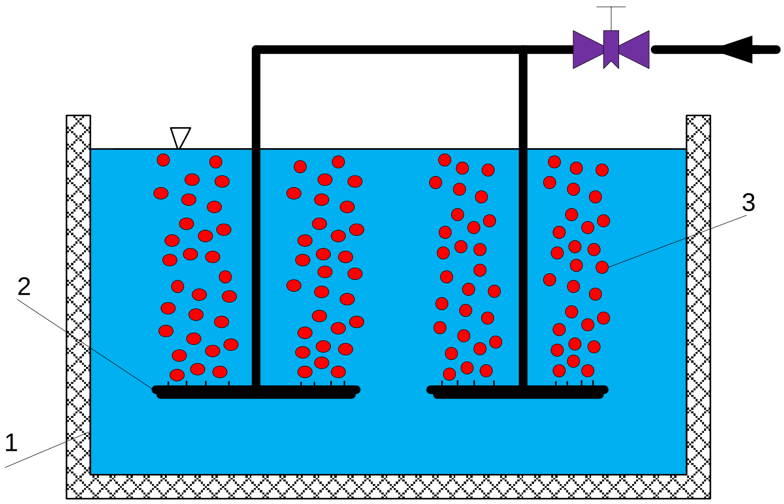


Fig. 1. INKA aeration system
1 – water tank; 2 - perforated pipes; 3 - air bubbles

Fine bubble water aeration systems (Ø <1 mm) include pneumatic generators, air transport and distribution pipes, control fittings.
Pressure loss when air passes from the piping system into the water through the orifices with Ø = 0.05 mm, is calculated with the relation [5]:

$$\Delta p = \zeta_{aer} \rho_{aer} \frac{w^2}{2} [N/m^2] \tag{1}$$

From [6], ζ = 0.6 and the air density is obtained from the relation:

$$\rho = \frac{p}{RT} \left[kg/m^3 \right] \tag{2}$$

$$p = p_{atm} + p_H \left[N/m^2 \right] \tag{3}$$

Where:
p_{atm} = 101325 N / m^2;
p_H = hydrostatic load: p_H = 0.5 mH_2O;
R = air constant: R = 287 J / kgK;
T = air temperature: T = 297.15 K;
Substituting in relation (2) one can obtain: ρ = 1.25 kg / m^3
The theoretical velocity of air flow is obtained by dividing the volumetric flow rate ($\dot{V}$) by the air outlet section in water: A = 1.2·10-6 m^2

$$w = \frac{\dot{V}}{A} = \frac{600 \cdot 10^{-3}}{3600} \cdot \frac{1}{1,2 \cdot 10^{-6}} = 138\ [m/s] \tag{4}$$

$$\Delta p = 0.6 \cdot 1.25 \cdot \frac{138^2}{2} = 7187.4 N/m^2 = 0.71 mH_2O \tag{5}$$

$$\Delta h = 0.71 mH_2O = 710\, mmH_2O \tag{6}$$

2.2 Calculation of the pressure drop when air passes through a porous diffuser

The orifices of the porous diffuser are not circular in shape, but approximately rectangular. A single orifice was measured using a modern OLYMPUS BX51M microscope, the overview of which can be seen in Figure 2.

Fig. 2. OLYMPUS BX51M microscope overview

The elastic membrane contains over 100 rectangular orifices, a single orifice was measured with a modern OLYMPUS BX51M microscope, shown in Figure 2.
The materials of which the elastic membranes are made are rubber, latex, E.P.D.M. membranes (Ethylene-Propylene-Dien-Monomer).
Figures 3 and 4 show a porous diffuser with elastic E.P.D.M membrane.

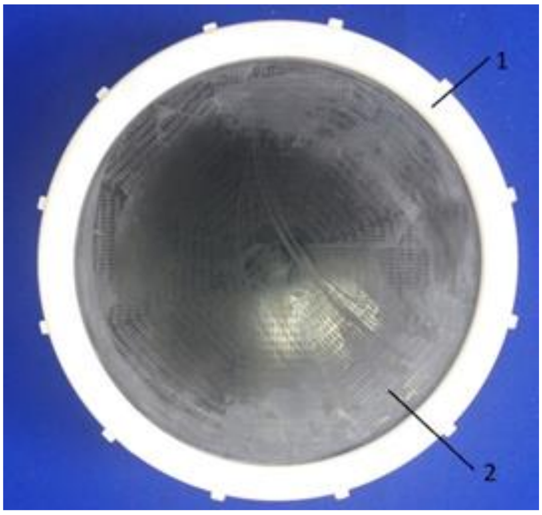


Fig. 3. Overview of the porous diffuser
1 - elastic membrane fixing ring; 2 - elastic membrane

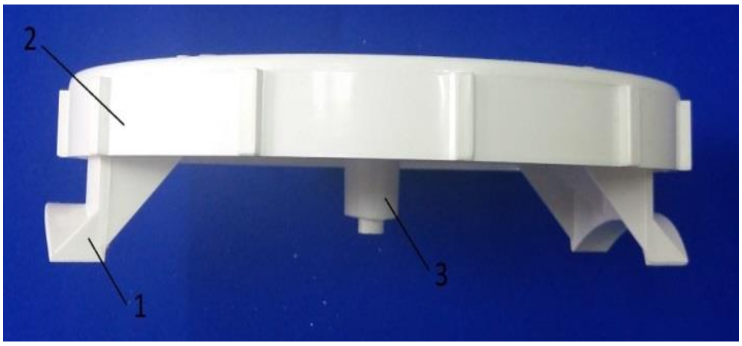


Fig. 4. Side view of the porous diffuser

The shape of the orifice in the porous diffuser is shown in figure 5.

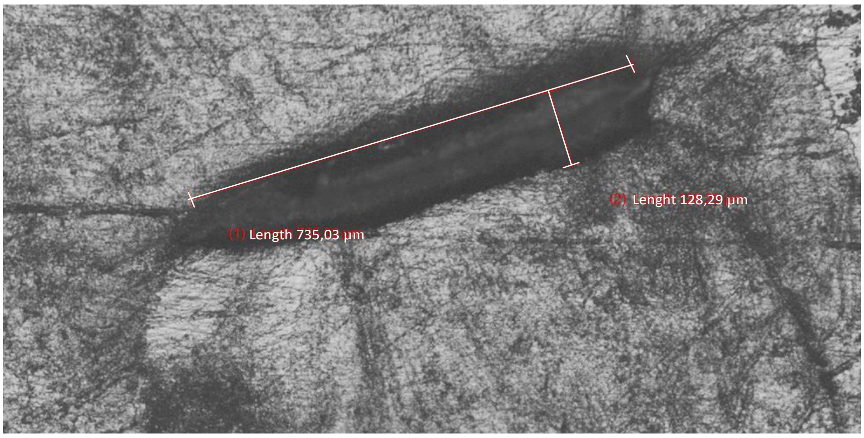


Fig. 5. View of the orifice in the porous diffuser

The orifice (figure 5) has a length of 735.03 µm and a width of 128.29 µm.
The dimensions of the orifice, approximately as a rectangle, are:

$$L \; x \; l \; = \; 735.03 \cdot 128.29 \; = \; 94296.998 \; \mu m^2 \tag{7}$$

The equivalent diameter of the orifice will be [7]:

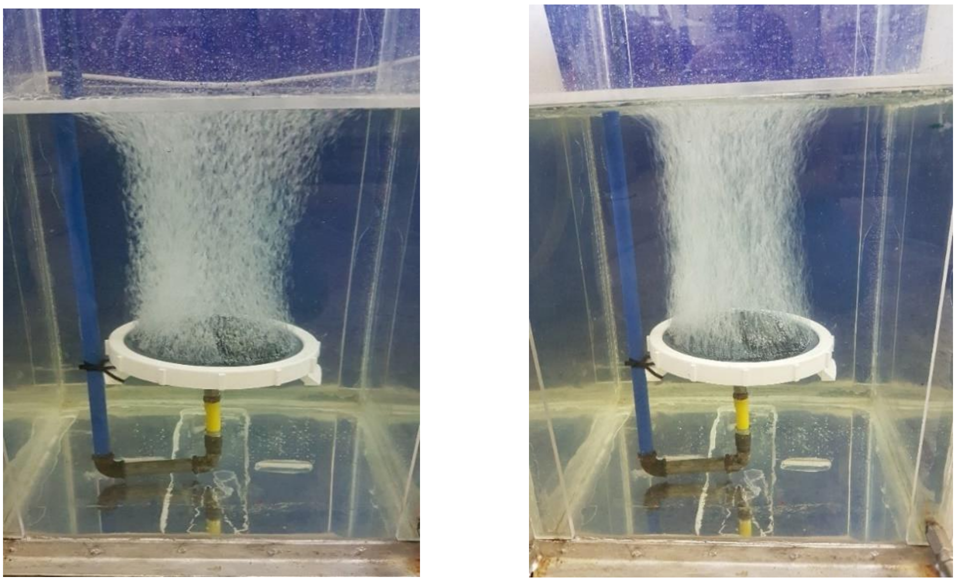
$$d_e = \frac{4A}{P} = \frac{4 \cdot 94296.998}{2 \cdot \left(735.03 + 128.29\right)} = 218.45\ \mu m \tag{8}$$

$$d_e = 0.21845\ mm \tag{9}$$

The value of this diameter falls within the operating range of bubble generators, which emit fine bubbles [8].
The air speed when passing through the orifice will be:

$$w = \frac{\dot{V}}{A} = \frac{600 \cdot 10^{-3}}{3600} \cdot \frac{1}{100 \cdot \frac{\pi}{4} 0.21 \cdot 10^{-3}} = 48.1 m/s \tag{10}$$

Figure 6 shows the operation of the porous diffuser; the elastic membrane has Ø229 mm.



a) b)

Fig. 6. Column of air bubbles generated by the porous diffuser
a) $\dot{V} = 1400\, dm^3/h$;b) $\dot{V} = 1600\, dm^3/h$

The pressure drop will be:

$$\Delta p = \zeta \cdot \rho \cdot \frac{w^2}{2} = 2.4 \cdot 1.25 \cdot \frac{48.1^2}{2} = 34.102 [N/m^2] \tag{11}$$

$$\Delta p = \rho_{H_2O} \cdot g \cdot \Delta h \tag{12}$$

$$\Delta h = \frac{\Delta p}{\rho_{H_2O} \cdot g} = \frac{34 \cdot 10^2}{10^3 \cdot 9.81} = 0.351 mH_2O = 35.1 mmH_2O \tag{13}$$

2.3 Calculation of the pressure drop at a fine bubble generator

Figure 7 shows a fine bubble generator which has the orifices plate of rectangular shape. Taking into account the size of the water tank and the height of the water layer, a water outlet section of $1.2 \cdot 10^{-6}$ m^2 [6] [7] was chosen, for which a number of orifices of Ø 0.1 mm equal to:

$$n = \frac{A}{\frac{\pi d_O^2}{4}} = \frac{1.2 \cdot 10^{-6}}{\frac{\pi \cdot (0.1 \cdot 10^{-3})^2}{4}} = 152\ orifices \tag{14}$$

result.

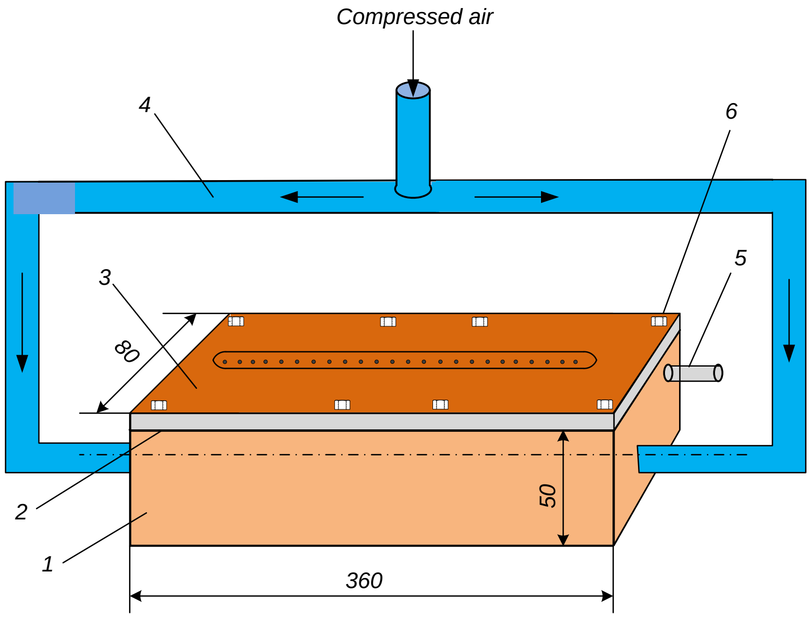


Fig. 7. Fine bubble generator with rectangular orifice plate
1 - compressed air tank; 2 - sealing system; 3 - orifices plate; 4 - compressed air pipe; 5 - connection to manometer; 6 - screws for fixing the orifices plate

The plate (3) contains 152 orifices (Ø 0.1 mm) made with the help of the KERN Micro machine; the constructive solution of this fine bubble generator is original and a very efficient constructive solution. The framing of this fine bubble generator in the experimental installation is presented in figure 8.

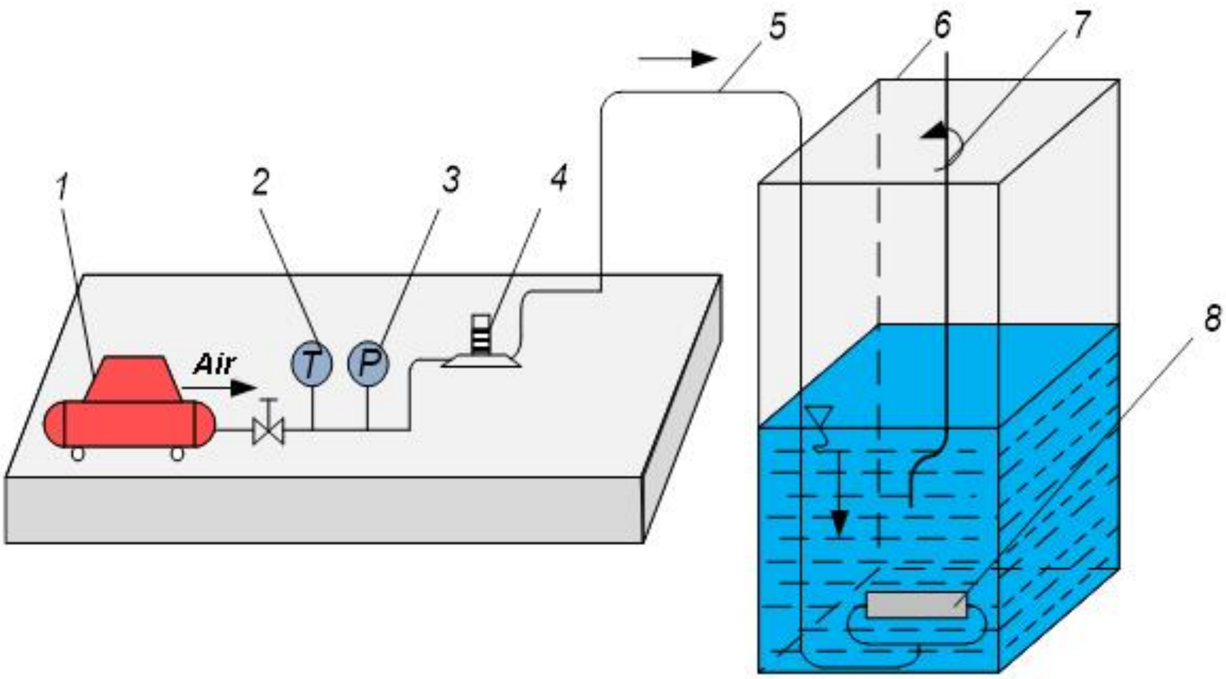


Fig. 8. Installation scheme for the introduction of atmospheric air into water
1 - electro compressor; 2 - digital thermometer; 3 - digital manometer; 4 - rotameter; 5 - air transport pipe; 6 - parallelepiped water tank; 7 - oxygenometer probe; 8 - fine bubble generator.

During the measurements, the following parameters were kept constant:
- Flow of air blown into water: $\dot{V} = 0.6\ m^3/h$;
- Air pressure at the end of the fine bubble generator: p = 573 mmH_2O;

- Hydrostatic load: H = 500 mmCA;
- Water temperature: 24º C;
- Air temperature: 24º C.

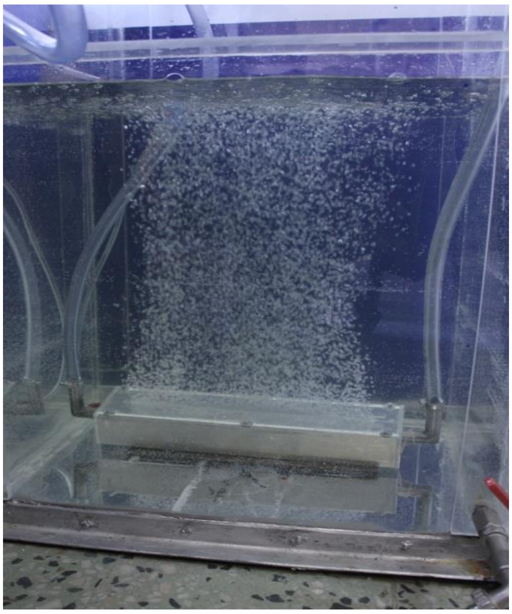


Fig. 9. Fine bubble generator in operation

To calculate the pressure drop that occurs when air passes through the fine bubble generator, the following formula is used:

$$\Delta p = \zeta \cdot \rho \cdot \frac{w^2}{2} \tag{15}$$

where:
ζ - local pressure loss coefficient; from [6] ξ = 0.82 is chosen;
ρ - air density; was previously calculated: ρ = 1.25 kg / m^3
Air passage speed through the orifices:

$$w = \frac{\dot{V}}{A} = \frac{600 \cdot 10^{-3}}{3600} \cdot \frac{1}{1.2 \cdot 10^{-6}} = 138.8\, m/s \tag{16}$$

$$\Delta p = 0.63 \cdot 1.25 \cdot \frac{138.8^2}{2} = 7498.5 \left[N / m^2 \right] \tag{17}$$

$$\Delta h \; = \; 0.749 \; mH_2O \; = \; 74.9 \; mmH_2O \tag{18}$$

In cases A, B, C, both the local pressure loss coefficient (ζ) and the exit speed of the compressed air in the water influence the pressure loss when the air passes through fine bubble generator.

3. Experimental researches

Next, a calculation relation of the pressure drop that occurs when air passes through an orifice in Figure 1 is established.
In capsule 1 there is compressed air with the pressure p_1 [N / m^2]; in operation, this pressure will have to overcome:

- the hydrostatic load: $\rho_{H2O} \cdot g \cdot H$;
- the surface tension: $2\sigma / r_0$
- the air pressure loss when passing through the orifice (Δp).

An equilibrium equation can be written [6]:

$$p_1 = \rho_{H_2O} g H + \frac{2\sigma}{r_0} + \Delta p \left[N / m^2 \right] \tag{19}$$

$$\Delta p = p_1 - \rho_{H_2O} g H - \frac{2\sigma}{r_0} \left[N / m^2 \right] \tag{20}$$

$\rho_{H2O} = 10^3$ kg / m^3; g = 9.81 m / s^2; σ = 7.3·10^{-2} [N / m] are known.
From relation (20) one can observe that, if p_1 is known, the air pressure drop can be calculated when passing through the orifice.
For different flow rates $\dot{V}$, pressure losses Δp are presented in table 1. Subsequently, water was introduced into the tank (H = 500 mmH_2O) and the pressure drops for the case of the "wet" membrane were measured; the air flow rates remained the same and the experimental results are presented in table 1.

Table 1: Pressure losses when air passes through the porous diffuser with elastic membrane

No.	"Dry" membrane		"Wet" membrane	
	$\dot{V}$ [dm³/h]	Δp [mbar]	$\dot{V}$ [dm³/h]	Δp [mbar]
1	400	1.47	400	57.5
2	600	2.11	600	61.1
3	800	2.70	800	62.40
4	1000	3.79	1000	64.50
5	1200	4.92	1200	66.30
6	1400	5.86	1400	68.20
7	1600	7.58	1600	71.80

For the porous diffuser the experimental values for Δp are close in size to the theoretical ones.
Based on the data in the table 1, the curves Δp = f ($\dot{V}$) were drawn for the two cases.

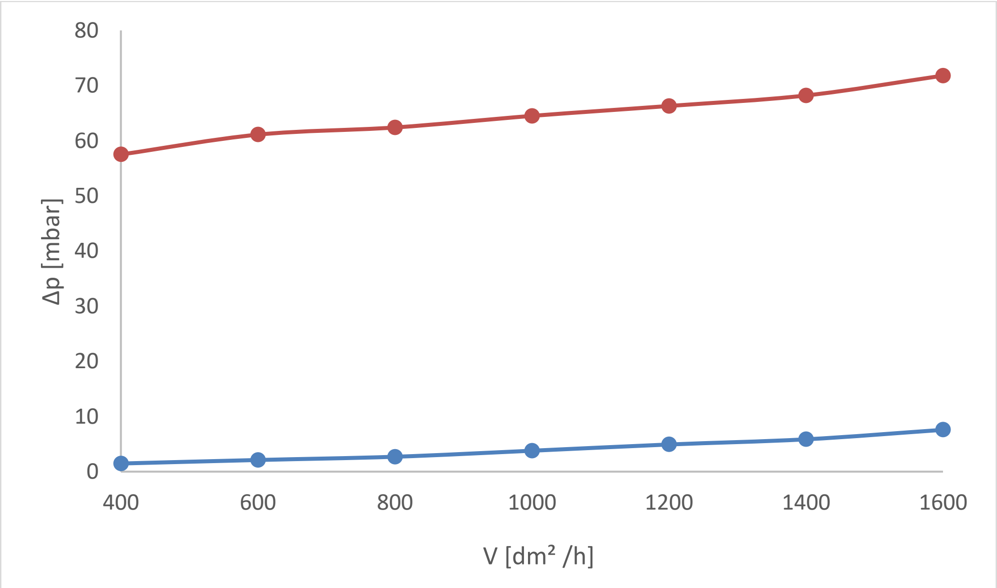


Fig. 10. The curves Δp = f ($\dot{V}$)
Δp = f ($\dot{V}$) for the "dry" membrane; 2 - Δp = f ($\dot{V}$) for the "wet" membrane

4. Conclusions

• In order to achieve a water oxygenation process as efficient as possible, it is necessary to analyse the factors involved in the equation of oxygen transfer to water, namely the speed of oxygen transfer to water increases slightly by:
- increasing the air-water contact surface, by dispersing air bubbles as fine as possible, d <0.5 mm in the water mass;
- increasing the mass transfer coefficient k_L by intensifying the turbulence;
- increase in oxygen deficiency that is increasing the difference (C_S - C)

• From the analysis of the parameters that intervene in the water oxygenation process, the following parameters have a special importance:
- the size of the air bubbles immersed in water (the smaller the diameter, the higher the concentration of dissolved oxygen in the water);
- the architecture of the bubble network - must be established in such a way as to avoid their coalescence;
- choosing an operation regime of the fine bubble generators so that the pressure losses are as small as possible; a lower pressure drop leads to saving of energy consumed for compressing the air to be introduced into the water.

Advantages of using bubble generators:
- ensure good oxygen transfer efficiency;
- ensure good mass transfer / power unit / time unit;
- can satisfy high oxygen demands;
- are easily adaptable to existing tanks.

Disadvantages of using bubble generators:
- are susceptible to chemical or biological degradation, which may lead to a decrease in mass transfer efficiency and an increase in pressure drop;
- do not ensure a uniform dispersion of air in a volume of water.

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