GLOBAL GAS-DYNAMIC STRENGTH FACTORS OF POROUS DIFFUSERS AND THE STUDY OF GAS BUBBLES FORMATION

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Sistemele clasice de aerare din stațiile de epurare a apelor uzate au fost înlocuite în ultimele două decenii cu generatoare de bule fine. Utilizarea acestora poate conduce la economisirea cu până la 50% a energiei consumate în procesul de aerare. S-au determinat căderile de presiune pe mai multe tipuri de generatoare şi raza inițială a bulelor de gaz. Asimilând porii plăcilor poroase cu tuburi capilare care funcționează în paralel, s-au calculat coeficienții de rezistență globală ai generatoarelor; s-a determinat timpul de formare a bulelor de gaz.

Classical aeration systems from waste water treatment plants are replaced in the last two decades with porous diffusers. Their utilization can lead to saving up to 50 percent of aeration energy cost. The pressure drop on different types of porous diffusers and the initial radius of the gas bubbles were determined. Assimilating the pores with capillary tubes which work in parallel, porous diffusers global strength factors were calculated; the time of gas bubbles formation was determined.

Keywords: porous diffuser, bubble, pressure drop, porosity

1. Introduction

In the last two decades, owing to high aeration energy costs, the classical oxygenation systems from waste water treatment plants have been replaced with fine bubble generators – porous diffusers (PD). An Environmental Dynamics Inc. technical bulletin [1] sustains that a PD aeration systems use the operating fluid (compressed air) efficiently and works with 50 ÷ 80 % from the energy spend by the classical aeration systems. Owing to costs reduction and to high efficiency of the oxygenation process [2], the PD aeration systems are permanently studied and have applications in various areas: waste water aeration, lakes and ponds aerations, ozonization, chemical processes [3] etc. In order to obtain high aeration efficiencies when operating in situ, the PDs must accomplish the following

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conditions: have low pressure drops, generate fine gas bubbles (that corresponds to certain porosity), provide a high retention time of the gaseous phase into the aeration tank. However, in operating conditions other problems emerge: fooling, materials deformation, chemical oxidation, PDs disposal in tanks. Thus, the necessity of new studies concerning the improving of material characteristics and PDs performances appears.

The aim of the paper is to determine the global gas-dynamic strength factors of the PDs, the time for an isolated bubble formation, the pressure drops on circular plate diffusers from sintered glass and circular PDs dimensioning for running in quasi-static emission regime.

2. The time of gas bubbles formation

The devices providing gas bubbles with 1÷4 mm diameters are considered fine bubble generators. The size of a bubble emitted by a fine pores device is influenced by the material porosity and air flow rate, becoming bigger when the flow rate increases. If the gas-liquid surface is large and the gas retention time in system is long, then the aeration process is efficient. The more bubbles diameter decreases, the more interfacial area increases. Small bubbles have low rising velocity and high retention time; coarse bubbles have high rising velocity and low retention time.

The pores are assimilated with a capillary tubes network running in parallel [4], [5]. It is considered a porous plate mounted in a capsule and immerged in water, at the depth H, in a basin; the PDs pores have the radius r_0.

With the assumption that the formed bubbles are spherical, one considers the variation dV of the volume inside a gas bubble, in a period of time dt in which the bubble radius grows with dR (fig. 1).

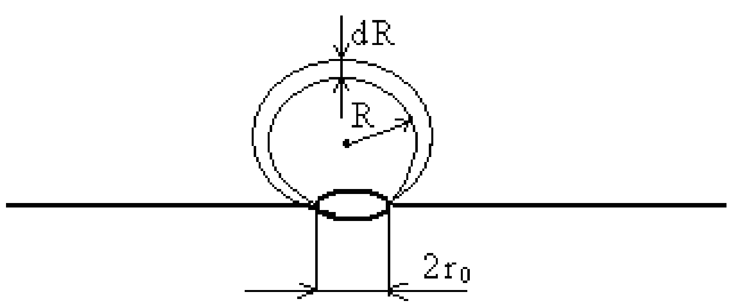

Fig. 1. Bubble formation

$$dV = V_f - V_i = \frac{4\pi\left(R + dR\right)^3}{3} - \frac{4\pi R^3}{3} = \frac{4\pi}{3}\left(R^3 + R^2 dR + R dR^2 + dR^3 - R^3\right), \quad (1)$$

with V_f – bubble final volume, corresponding to the bubble radius in the moment of detachment from the PD pore, R_d; V_i – bubble initial volume, corresponding to a bubble radius R.

Since dR^2 and dR^3 are infinitesimals of superior order, the terms containing them are zero. Relation (1) becomes

$$dV = 4\pi R^2 dR \,. \tag{2}$$

Considering $dV = Qdt$ in relation (2), it results

$$dt = \frac{4\pi}{Q} R^2 dR \,, \tag{3}$$

where $Q = \pi r_0^2 v_0$ is the gas flow rate through the pore, corresponding to bubble formation and v_0 is the gas velocity through the pore.

Integrating the differential equation with separable variables (3) from $t = 0$ to $t = \tau$ – the time for a bubble formation, respectively from $R = 0$ to $R = R_d$ – the radius of the bubble in the moment of detachment from the capillary tube, one obtains

$$\int_0^{\tau} dt = \int_0^{R_d} \frac{4\pi}{\pi r_0^2 v_0} R^2 dR \,, \tag{4}$$

or

$$\tau = \frac{4R_d^3}{3} \cdot \frac{1}{r_0^2 v_0} \,. \tag{5}$$

The pressure drop on the PD can be expressed by the relation

$$\Delta p = \zeta \frac{\rho}{2} \left(\frac{Q}{S_e} \right)^2 = \zeta \frac{\rho}{2} v_0^2 \,, \tag{6}$$

where ζ is a global gas-dynamic strength factor, ρ – the air density, Q − the air flow rate, S_e − the PD emission surface, formed from n capillary tubes; these tubes work in parallel while the r_0 radius of the pore is considered constant.

Replacing the relation of v_0

$$v_0 = \sqrt{\frac{2\Delta p}{\zeta \rho}} \tag{7}$$

in expression (5) there results

$$\tau = \frac{4}{3} \cdot \frac{\sqrt{\zeta}}{\sqrt{\frac{2\Delta p}{\rho}}} \cdot \left(\frac{R_d}{r_0} \right)^2 \cdot R_d \,. \tag{8}$$

The duration for an isolated bubble formation, τ, is given by relation (8). The pressure drop on the porous plate, Δp it calculated with

$$\Delta p = p_1 - \rho_\ell g H - \frac{2\sigma}{R_d}, \tag{9}$$

where p_1 – the pressure inside PD capsule, read on manometer; $\rho g H$ – the hydrostatic head with $\rho_\ell = 10^3$ kg/m^3 (the water density); $2\sigma / R_d$ – the additional pressure necessary for bubble formation, with the superficial tension air/water at 20^{o}C, $\sigma = 73 \cdot 10^{-3}$ N/m.

3. Global strength coefficients

The measurements were accomplished with PD from sintered glass, with 50 mm diameter and different porosities: 100÷250 µm and 250÷315 µm. The pressure drops on the tested porous plates are shown in table 1.

Table 1

Pressure drop by function of air flow rate

PD 100÷250 µm	Q [m^3/h]	0.06	0.09	0.12	0.14	0.18	0.21	0.25	0.28
	Δp [mbar]	20.47	25.81	29.81	31.14	33.14	34.48	36.48	37.15
PD 250÷315 µm	Q [m^3/h]	0.06	0.10	0.13	0.13	0.16	0.16	0.18	0.20
	Δp [mbar]	18.93	22.94	25.60	25.60	27.61	28.27	28.27	28.94

The pressure drop on PDs is calculated subtracting the hydrostatic head and the additional pressure necessary for bubble formation from the pressure measured at manometer. The values Δp obtained are comparable with those offered in the catalogues of PDs manufacturers [1], [6], [7], [8]. The variation of the pressure drop versus air flow rate is a straight line, as specified in literature (e.g. the operation guides of Stamford Scientific International Inc., Clearly Water [9]).

The values of air flow rate – pressure drop can be considered as a pair (x_i, y_i), with x_i the flow rate – on Ox axis and y_i the pressure drop – on Oy axis. The points (x_i, y_i) will be graphically disposed after a straight line $y = a + bx$. The variation of the pressure drop versus the air flow rate is given by $y = 0.2242 + 0.0006x$ with a correlation coefficient 0.9247 for PD 100÷250 µm and by $y = 0.1719 + 0.0007x$ with a correlation coefficient 0.9222 for PD 250÷315 µm.

Considering S = $1.963 \cdot 10^{-3}$ m^2 the porous plate surface and S_e the PD emission surface, S_e = 10%S, one calculates the global strength factor, ζ with the relation

$$\Delta p = \zeta \frac{\rho}{2}\left(\frac{Q}{S_e}\right)^2 . \tag{10}$$

Neglecting the weight of the air inside the bubble, from the equality between the superficial tension force and the uplift force acting on bubble in the forming process

$$2\pi r_0 \sigma = \rho_\ell g \frac{4}{3}\pi R_d^3 \tag{11}$$

there results the radius of the bubble in the moment of detachment from the PD pore

$$R_d = \sqrt[3]{\frac{3}{2}\frac{r_0 \sigma}{\rho_\ell g}} . \tag{12}$$

The measurements were accomplished with PD Ø50 having the porosity 100÷250 µm, respective by 250÷315 µm. The diameter of a capillary tube is considered equal with the PD mean porosity – 175 µm, respective by 282.5 µm. Replacing the values of the terms in equation (12), there results R_d = 1.024 mm for the first plate tested and R_d = 1.201 mm for the second.

4. The dimensioning of circular PDs for running in quasi-static emission regime

The bubbles emission regimes through an immerged orifice are classified after some authors [10], [11] in quasi-static and dynamic, being separated by the critical flow rate Q_{cr} [12]; in 1993, the critical flow rate separating those two regimes was determined and published in [10]. For air/water and a capillary tube radius $r_0 = 0.1 \div 2$ mm we have:

$$Q_{cr} = \pi\left(\frac{16}{3g}\right)^{1/6}\left(\frac{\sigma r_0}{\rho_\ell}\right)^{5/6} . \tag{13}$$

For $Q > Q_{cr}$, the bubbles emission regime is dynamic. For air/water with $\rho_\ell = 1000$ kg/m^3, $\sigma = 73 \cdot 10^{-3}$ N/m, and r_0 in mm one obtains: $Q_{cr} = 0.2365 \cdot 10^{-5}\, r_0^{5/6}$ m^3/s, i.e. $Q_{cr} = 8.5\, r_0^{5/6}$ dm^3/h. If $r_0 = 1$ mm, then $Q_{cr} = 8.5$ dm^3/h; if $r_0 = 0.1$ mm, $Q_{cr} = 1.25$ dm^3/h. The Reynolds number of the flow inside the capillary tubes with $r_0 = 1$ mm, for air ($\nu = 15 \cdot 10^{-6}$ m^2/s) at the Q_{cr}, is Re $\cong 0.1$, indicating a slow laminar flow.

Beside the already mentioned emission regimes, other authors [13] define the turbulent regime, which is obtained at $Q >> Q_{cr}$. For capillary tubes with $r_0 = 0.1 \div 2$ mm, the turbulent regime is obtained when $Q > 720$ dm^3/h.

The first conclusion of the presented analyse is that for $Q > Q_{cr}$, the emission regime does not depend on PDs porosity. The second conclusion refers to PD dimensioning for running in quasi-static regime.

A porous diffuser with mean porosity 0.1 mm, for which $Q_{cr} = 1.25$ dm^3/h is considered; the operating flow rate is set at 1 dm^3/h. If the air flow rate to accomplish aeration is 1 m^3/h, then 1000 capillary tubes (pores) result, each having a surface of $(\pi/4)10^{-8}$ m^2; the emission surface will be $10^3(\pi/4)10^{-8}$ $=10^{-5}(\pi/4)$ m^2 while the effective surface 5 times bigger; if the surface is circular, then its diameter is about 63 mm.

Thus, knowing the materials porosity of fine bubbles generators devices and the air required for water oxygenation (in function of the tank volume), PD can be dimensioned for different shapes (circular plates, square plates, tube etc.).

5. Results and interpretations

Considering $S = 1.963 \cdot 10^{-3}$ m^2 the surface of circular fine bubble generators Ø 50, $S_e = 10\%S$, the emission surface, replacing in relation (8) the flow rates and the pressure losses from table 1, the global gas-dynamic strength factors ζ are calculated, (fig. 2).

Knowing all the terms from relation (8), the time needed for an isolated bubble formation is calculated; the bubbles emission frequency is $f = \tau/60$, in bubbles/min (table 2).

Table 2

The time for an isolated bubble formation as function of porosity and flow rate

PD 100÷250 μm	Q [m^3/h]	0.06	0.09	0.12	0.14	0.18	0.21	0.25	0.28
	τ [s]	1.99	1.47	1.10	0.92	0.71	0.61	0.52	0.46
PD 250÷315 μm	Q [m^3/h]	0.06	0.10	0.13	0.13	0.16	0.16	0.18	0.20
	τ [s]	1.24	0.78	0.62	0.59	0.50	0.49	0.45	0.40

Figure 2 shows that, once the air flow rate increases, the global gas-dynamic strength factor values decreases, as confirmed in literature [4].

The time for an isolated air bubble formation decreases with the increasing of the air flow rate, as shown in table 2; corresponding to this, the bubbles emission frequency increases when the flow rate increases (fig. 3).

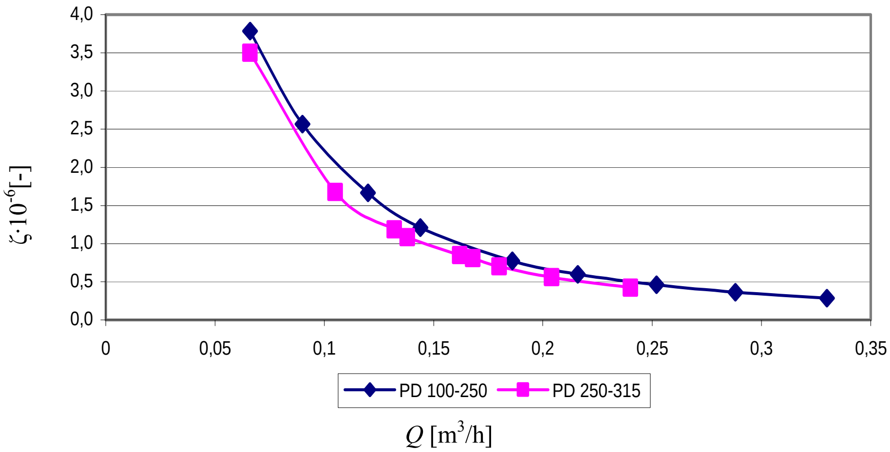

Fig. 2. The variation of global gas-dynamic strength factor versus flow rate

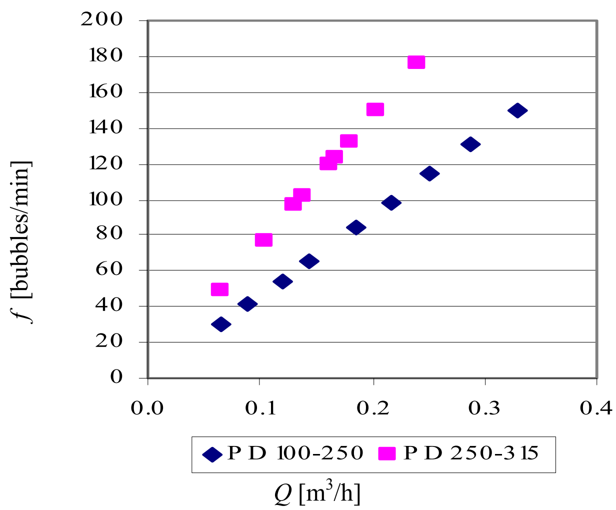

Fig. 3. The variation of bubbles emission frequency versus flow rate

The results obtained by assimilating the PDs pores with capillary tubes are comparable with the values from literature; in [10], for example, the emission frequency is 1 ÷ 125 bubbles/min for capillary tubes with radius 0.11 ÷ 1.94 mm at flow rates $0.144 \cdot 10^{-6} \div 0.736 \cdot 10^{-3}$ m³/h or $f = 0 \div 60$ bubbles/min for capillary tubes with $r_0 < 1$ mm and an air flow rate inferior to the critical flow rate.

6. Conclusions

The theoretical relation for the time for an isolated bubble formation calculus, assimilating the PDs pores with the capillary tubes, is shown in this paper. To evaluate this relation, the results of the measurements accomplished with circular PDs Ø 50 and porosities 100÷250 μm, respective by 250÷315 μm were used. The obtained results are comparable with the values from literature [10]. The global gas-dynamic strength factors of sintered glass PDs were calculated. The obtained values are comparable with authors' anterior results (ζ of order 10^5 in [5], for hemispherical PDs Ø 75 and $Q < 2$ m^3/h).

The following remarks have been done:

- the pressure drops on PDs are comparable with the values offered by manufacturers [6],
- the global gas-dynamic strength factor ζ, decreases when the flow rate increases; comparing the values from literature with the values obtained by authors (in anterior papers and in the present paper), there results that ζ increases when the emission surface decreases,
- the time for an isolated bubble formation decreases with the increasing of the air flow rate and of the pores diameter.

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