Theoretical and Experimental Study of Gas Bubbles Behavior

Lucian Mândrea, Gabriela Oprina, Rareș-Andrei Chihaia, Lucia-Andreea El-Leathey, and Radu Mirea

Abstract—**The paper presents theoretical considerations on gas bubbles behavior - analytic calculation of bubble time formation, extra pressure needed for the bubble formation and detachment, bubble size and correlation between the extra pressure and the liquid superficial tension.**

In order to evaluate the theoretical relation for extra pressure calculation, the results of the tests performed on different metallic perforated plates Ø 60, with a specific number of orifices of different diameters, were used. The extra pressure needed for bubble formation varies from approximately 171 Pa for the MPP with 0.9 mm orifices to 245 Pa for the MPP with 0.2 mm orifices.

Index Terms—**Bubble size, bubble detachment, extra pressure, orifice.**

I. Introduction

Due to various applications in chemical units and waste water treatment, bubbles and bubble columns have been largely investigated during the last decades. Thus, various studies have been performed regarding the bubble formation, both in still and flowing liquid. Some research focused on the formation and evolution of single bubbles [1], while others investigated bubble columns. Most of the studies found in literature were performed in clear (tap) water, and envisaged bubble formation and detachment, bubble velocity, bubble size and bubble size distribution, bubbles flow regime, gas-liquid interfacial area, gas-liquid hydrodynamics, gas hold-up, volumetric mass transfer coefficient etc. Also, other studies were performed in water with surfactants [2].

Since the bubble behavior depends on the generation type, the media in which bubbles are generated, gas flow rate, etc. the previously developed studies achieved on dispersed aeration systems and mentioned in literature were focused on the investigation of different parameters influence on bubbly flows. Thus, some studies have mainly investigated the bubble size, bubble size distribution and flow regime transitions in bubble columns [3]-[7]. For example, in [7], an experimental study regarding the local gas hold up of five types of perforated membranes was carried out. The membranes have been investigated in two rectangular experimental setups by varying the following parameters: air flow rate through the orifices, the diameter of the orifices and their density on the membrane surface. In the case of the membranes provided with low density of orifices, it was found that the bubble size increases with the air flow rate; in the case of the membrane with the highest orifice density, an intense interaction among bubbles was found, leading to a significant increase in the bubbles size in their rising motion to the surface. It was also noticed that the influence of the orifices density on bubbles size is lower at higher air flow rates.

The bubbly (homogeneous) flow is characterized by small bubbles and a narrow distribution of the equivalent diameters; the shifting from homogeneous to heterogeneous flow regime is achieved through the transition regime, when the diameters variation domain becomes larger; when reaching heterogeneous regime, the flow is characterized by coalescence and by the coexistence of small and big deformed bubbles. The transition between homogeneous to heterogeneous flow determines radical modifications of the air-water dispersed system, reflecting simultaneously in the bubble size distribution, global gas hold up and the rising velocity of the bubbles [8].

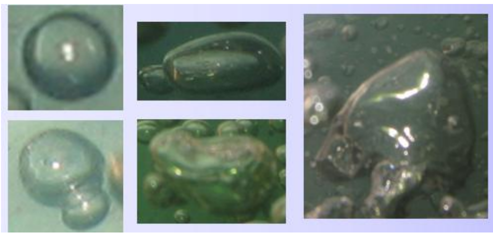

Fig. 1. Variation of bubbles shape from homogeneous (left) to heterogeneous regime (right) [8].

Several other numerical and experimental studies focused on the investigation of the bubble column hydrodynamics [9-12] and bubble oscillations. On a range of air flow rates, the bubble columns present an oscillating movement. The time interval of this oscillation depends on the air flow rate and on the tank geometry. Experiments on a narrow rectangular experimental setup have been performed in [9] in order to determine the oscillation period of the bubble column. Also, in [10], some experimental results are reported, obtained by varying different parameters such as air flow rate, liquid properties, and porous diffuser; the study revealed that the bubble column oscillating period decreases with the increase of the air flow rate. Some similar results provided by numerical simulations, using the data from a rectangular experimental setup of 0.45 m height and a square cross section 0.2 m x 0.2 m were reported in [11]. The simulations developed for an air flow rate of 240 l/h revealed a bubble column oscillation period varying from 10.7 to 16 s. In order to correlate the bubbles shape oscillation to their trajectories,

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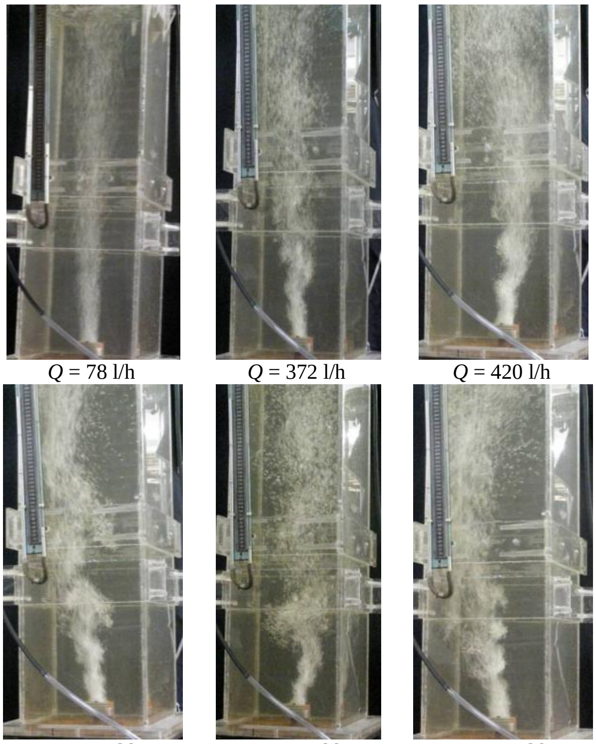
3.4 mm diameter isolated bubbles (generated by capillary tubes) were experimentally studied in [12]. Along with the oscillations and trajectories, the bubbles shape and liquid velocity field were investigated. It was found that the bubbles present a rectilinear rising motion up to a height of 25 mm out of the 420 mm height of the column; beyond this distance, complex shape oscillations appear, along with the transition of the trajectory to a spiral. Investigations on the bubble column stability were also performed in [8], by experimentally studying the operation of 50 mm diameter ceramic porous diffusers in a rectangular column; the behavior of the bubble plume was studied for different air flow rates and the period of the different identified oscillations were determined, ranging from 11 to a maximum of 31 seconds.



Q = 78 l/h | *Q* = 372 l/h | *Q* = 420 l/h

Q = 480 l/h | *Q* = 582 l/h | *Q* = 624 l/h

Fig. 2. Bubble column instability [8].

Different studies were performed on bubble formation, growth and detachment [2], [13]-[19] in different conditions. In [2] experimental studies were performed on bubble growth and detachment, bubble diameter and bubbles frequency in different aqueous solutions for the case of one rigid orifice of 0.7 mm diameter and several flexible orifices with diameters ranging from 0.35 to 0.45 mm, depending on the air flow rate. For both rigid and flexible orifices, the study revealed that the bubble diameter is smaller in water with surfactants than in tap water; also, for the rigid orifice case, higher frequencies were registered in aqueous solutions.

Some studies carried out in flowing water [13], [14] investigate the effect of several parameters on bubble formation: nozzle diameter, liquid velocity and direction, gas chamber volume, gas flow rate etc. In [13], the study is focused on the mechanism of bubble formation in concurrently upward flowing liquid. The results following the study on a non-spherical bubble formation model when considering that the bubble surface is formed by n elements, are compared to the experimental results regarding volumes, shapes and growth curves of the bubbles released by nozzles with inner diameter of 1.19 mm, 2.09 mm and 3.00 mm and a length of 150 mm. For the pressure drop on the nozzle, three coefficients were defined: F, from the Hagen-Poiseuille equation when the flow inside the nozzle is laminar, F' from the Blasius's equation when the flow inside the nozzle is turbulent and K for contraction and enlargement losses. Thus, for laminar flow, the pressure inside the bubble, P_i, was evaluated by:

$$P_i = P_c - FQ_0 - K|Q_0|Q_0 \tag{1}$$

And for turbulent flow by

$$P_i = P_c - F'|Q_0|^{3/4}Q_0 - K|Q_0|Q_0. \tag{2}$$

In equations (1) and (2), Pc is the pressure in the nozzle's chamber and Q_0 is the flow rate at the outlet of the gas chamber.

For gas flow rates varying between $0.13 \cdot 10^{-6}$ and $5.11 \cdot 10^{-6}$ m^3/s and for liquid velocities varying between 0 and $17.3 \cdot 10^{-2}$ m/s, as well as for a gas chamber volume from $33.3 \cdot 10^{-6}$ to $89.9 \cdot 10^{-6}$ m^3 it was noticed that: the bubble volume decreases with the increase of the liquid velocity and increases with the gas flow rate when the liquid velocity is kept constant; also, since the liquid flow influences the detachment of the bubbles from the nozzle, the bubble growth time decreases with the liquid velocity increase. Regarding the bubbles shapes, a significant change with the modification of the liquid flow was not noticed.

Having in mind the development in space technology applications, some studies investigated the bubble formation under various gravity conditions. In [15], the bubble detachment and formation of new bubbles under microgravity conditions was numerically investigated. By using a Lagrangian smoothed particle hydrodynamics, the bubble detachment from an orifice of 1.5 mm diameter, at a gas flow rate of $3.75 \cdot 10^{-7}$ m^3/s, was studied for different gravity conditions. For lower gravity, it was noticed that the bubbles have a larger size than in normal gravity conditions; they were rather elongated and, after detachment, combined to the next bubble that was in the process of formation. The bubble detachment from a submerged orifice in quiescent liquid under normal and reduced gravity, as well as the bubble volume and frequency, were numerically investigated in [16]. For a gas flow rate of $3.33 \cdot 10^{-6}$ m^3/s through an orifice of 3 mm diameter and three different gravity conditions, the study found that the size of the detached bubbles is getting larger with the decrease of the gravity and the bubble's contact area with the orifice increases, leading to a higher surface tension that delays the bubble detachment; also, along with the gravity decrease, the bubble formation frequency decreases and the bubble volume increases. Moreover, for very low gravity ($g \cdot 10^{-2}$), the bubbles do not detach from the orifice.

In [17], the formation and nature of the bubbles detached from rigid and flexible orifices was experimentally studied. The diameter of the rigid orifice of the diffuser used in experiments was equal to 0.7 mm, whereas for the flexible case a rubber membrane was used, with a single puncture in its center. A 4.5 mm diameter of the bubbles detached from the rigid orifice was determined; a discontinuity in the bubbles formation and a low bubbles frequency respectively were found, most probably due to the decrease of the pressure in the gas chamber below the hydrostatic pressure during the bubble's detachment, followed by liquid entrance into the orifice. A diameter below 2.5 mm was determined for the flexible membrane case; the pressure inside the gas chamber remains constant, preventing the liquid to penetrate the orifice. Overall, the experimental study revealed that the bubbles diameter at detachment and their growth rate do not depend on the gas flow rate in the rigid orifice case, while they increase with the gas flow rate in the flexible orifice case.

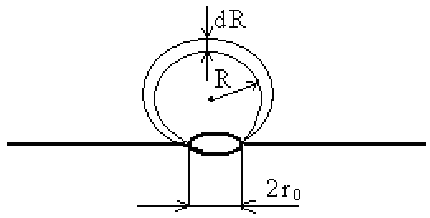


Fig. 3. Gas bubble evolution.

The bubble formation from a single orifice in aqueous solutions was investigated in [18]; the experiments performed in different operating conditions and for different single orifices showed that the shape of the orifice influences the bubble formation and that the volume of the bubble increases with the gas flow rate, viscosity of the aqueous solution, surface tension and orifice diameter.

There are also numerous studies investigating bubble parameters and related phenomena aiming either to evaluate the correlation between the bubble shape and pressure field during growth and detachment [19] or the bubbles frequency [20], as well as the changes in bubble diameter and frequency for different gas properties such as surface tension and gas density [21] and the influence of continuous (liquid) phase properties (density, viscosity, surface tension) and geometrical properties on bubble behavior (bubble formation, diameter, detachment and motion) [22].

The present study aims to provide an insight in the bubbles behavior by theoretically investigating the bubble formation time, the extra pressure needed to create the bubble and its correlation to the liquid superficial tension. In order to evaluate the theoretical results, tests were performed on different metallic perforated plates (MPP) Ø 60 with different orifice sizes ranging from 0.2 mm to 0.9 mm and different number of orifices, varying from 21 to 918.

II. Theoretical Study of Bubbles Behavior

A. Analytic Calculation of Bubble Time Formation

The theoretical study presented in this paper takes into account the results reported in [23], namely that, for an orifice number higher than 15, the size of the bubbles is not influenced by the gas chamber volume. For rigid orifices, the study [23] suggests that the bubble interaction during the bubbles formation process can be neglected for a ratio of pitch to orifice diameter below 8. The study reported in [7] on several membranes, with different pitch to diameter ratios revealed that the finding/conclusion of the study [23] is not valid in the flexible materials case.

The current study is performed assuming that the compressed air is provided by a compressor and the bubbles exit through a disk (perforate plate) with the constructive radius r_0. In an ideal case, the bubbles are characterized by the interior radius R at a certain moment of time. During a small variation of time dt, the bubble radius increases with dR and, as a consequence, the bubble volume increases with dV as in Fig. 3.

The infinitesimal variation of the bubble volume can be expressed as a difference between the final bubble volume and the initial bubble volume:

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

Since dR^2 and dR^3 have low values, they can be neglected and the previous relation becomes

$$dV = 4\pi R^2 dR \quad (4)$$

If the compressor volumetric flow rate is Q, then during the same small variation of time dt, the bubble volume increases with dV:

$$dV = Q \cdot dt \quad (5)$$

Thus, from (4) and (5), it results:

$$dt = (4\pi / Q) R^2 \cdot dR \quad (6)$$

The air volumetric flow rate provided by the compressor may be expressed using the constructive orifice area and the air normal mean velocity through the orifice, v_0:

$$Q = \pi r_0^2 \cdot v_0 \quad (7)$$

By substituting the flow rate from (7) to (6), the following differential equation is obtained:

$$dt = \frac{4}{r_0^2 \cdot v_0} R^2 \cdot dR \quad (8)$$

If τ is the bubble detachment time and R_0 the corresponding bubble radius, then the previous equation can be integrated:

$$\int_0^{\tau} dt = \int_{r_0}^{R_0} \frac{4}{r_0^2 \cdot v_0} R^2 \cdot dR \quad (9)$$

Thus, the bubble detachment time is obtained:

$$\tau = \frac{4}{3v_0} \frac{R_0^3 - r_0^3}{r_0^2} \quad (10)$$

B. Pressure Loss on the Perforated Plate

A diffuser with a considerable number of orifices is considered, with the global local hydraulic loss coefficient on the orifices ς and the air density ρ. If S_e is the emission (active) surface of the diffuser, formed by *n* parallel capillary tubes, each having the inner radius r_0, the pressure loss becomes:

$$\Delta p = \varsigma \frac{\rho}{2}\left(\frac{Q}{S_e}\right)^2 = \varsigma \frac{\rho}{2} v_0^2 \Rightarrow v_0 = \frac{1}{\sqrt{\varsigma}}\sqrt{\frac{2\Delta p}{\rho}} \quad (11)$$

By substituting the mean air velocity v_0 from (11) in (10), a new expression of the bubble detachment time is obtained

$$\tau = \frac{4}{3}\frac{R_0^3 - r_0^3}{r_0^2}\sqrt{\varsigma}\sqrt{\frac{\rho}{2\Delta p}} \quad (12)$$

This expression also represents the duration needed for an isolated bubble formation, the bubbles emission frequency being $f = 1/\tau$ bubbles/min.

The pressure loss on the porous plate, Δp, may be computed with the difference between the pressure inside the diffuser's capsule, p_1 (read at the manometer), the hydrostatic pressure determined with the water density, ρ_l and the extra pressure needed to create the bubble:

$$\Delta p = p_1 - \rho_\ell g H - 2\sigma / R_0 \quad (13)$$

C. Correlation between the Bubble Extra Pressure and the Liquid Superficial Tension

The mechanical work necessary in order for the bubble to grow from r_0 to R_0 can be computed by the following relation:

$$L = p_s\left(V_f - V_i\right) = p_s\left(4\pi R_0^3/3 - 4\pi r_0^3/3\right) \quad (14)$$

It can be also seen like the energy used to increase the bubble volume:

$$E = \frac{4\pi}{3} p_s\left(R_0^3 - r_0^3\right) \quad (15)$$

The infinitesimal variation of the necessary energy used to increase the bubble may be expressed as:

$$dE = \sigma \cdot dA = \sigma\left[4\pi(R + dR)^2 - 4\pi R^2\right] = 4\pi\sigma\left(2R \cdot dR + dR^2\right) \quad (16)$$

with σ – the air-water surface tension.

Because dR^2 has a reduced value, it can be neglected and the variation of the energy becomes $dE = 8\pi\sigma R \cdot dR$. Thus, the total energy used to increase the bubble volume is

$$E = \int_{r_0}^{R_0} dE = 4\pi\sigma\left(R_0^2 - r_0^2\right) \quad (17)$$

Consequently, from relations (15) and (17) the correlation between the bubble extra pressure and the liquid superficial tension is obtained as:

$$p_s = 3\sigma \frac{R_0 + r_0}{R_0^2 + R_0 r_0 + r_0^2} \quad (18)$$

III. Experimental Study of Bubbles Behavior

In order to evaluate equation (18), the results of the tests performed on different metallic perforated plates (MPP) Ø 60 developed within a research contract [24] were used. These plates aim to improve the mass transfer in aeration processes and therefore are characterized by a high number of orifices and low pressure loss. The number of orifices and their arrangement/layout on the surface of the plates were sized and controlled by using the manufacturing technology discussed in [25]. The number of orifices was determined by keeping a constant distance between them, big enough to prevent bubble coalescence, complying with the conditions reported in literature [23]. In order to neglect the contraction coefficient of the orifice, thickness *t* of 5 orifice diameters (5*d*) was chosen for the plates; thus, a different thickness for each plate resulted, ranging from 1 mm to 4.5 mm. Table 1 shows the main characteristics of the perforated plates: orifice diameter *d*, orifices number *n*, and distance among orifices *l*.

TABLE I: Perforated Plates Characteristics

Perforated plate	*d* [mm]	*n* [–]	*l* [mm]
MPP with orifices placed at a distance of 10*d*			
MPP0.2	0.2	377	2
MPP0.3	0.3	177	3
MPP0.5	0.5	61	5
MPP0.9	0.9	21	9
MPP with orifices placed at a distance of 7*d*			
MPP0.2	0.2	918	1.4
MPP0.3	0.3	406	2.1
MPP0.5	0.5	151	3.5
MPP0.9	0.9	43	6.3

Using the technology described in [25], MPPs with *l*=10d and *t*=5d were firstly manufactured, the orifices being disposed in a square layout on the plate surface; therefore, the MPP characteristics presented in the authors previous work correspond to the first type of perforated plates developed under the research contract [24]. In order to improve the mass transfer, for the second series of MPPs, a distance *l*=7*d* between orifices was used and a triangular layout was considered, thus obtaining an increased number of orifices (Table I) that provides a higher interfacial area.

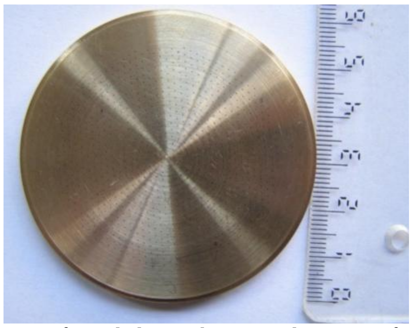


Fig. 4. Perforated plate with 0.2 mm diameter orifices.

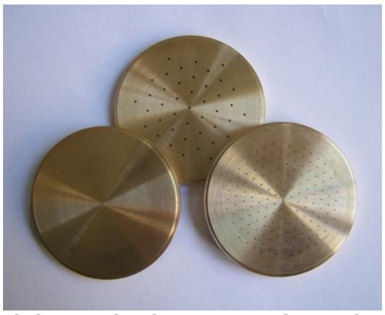


Fig. 5. Perforated plates used in the experimental research – orifices of 0.3, 0.5 and 0.9 diameter in triangular layout.

For the calculation of the extra pressure provided by equation (18), the bubble radius in the moment of detachment, R_0 for each MPP, was firstly determined. In the assumption that the bubbles are emitted in cvasi-static regime (air flow rate Q is lower than the critical flow rate Q_{cr} defined in [26], R_0 was calculated using the following equation

$$R_0 = \left(\frac{3}{2} \cdot \frac{r_0 \sigma}{\rho_\ell g} \right)^{1/3} \tag{19}$$

The extra pressure needed by the bubbles to detach from the surface of the four types of perforated plates with orifice in triangular layout, as well as the detachment radius of the bubbles are shown in Table 2.

TABLE II: EXTRA PRESSURES AND DETACHMENT RADII OF THE BUBBLES

Perforated plate	r_0 [mm]	R_0 [mm]	p_s [Pa]
MPP0.2	0.1	1.0695	245.392
MPP0.3	0.15	1.2242	220.059
MPP0.5	0.25	1.4515	193.824
MPP0.9	0.45	1.7657	170.568

Secondly, in order to evaluate equation (18), the pressure loss on the plates was experimentally determined in laboratory, by immersing each perforated plate in a rectangular tank with the cross section of 0.3 m x 0.3 m and the height of 1.1 m. The compressed air necessary for the operation of the perforated plates was provided by a compressor; in order to deliver a constant pressure into the air chamber of the plates, a pressure regulator was attached to the compressor outlet. A manometer with a measuring scale of up to 10 L/min was used for the plates' operation testing at lower air flow rates, whereas a manometer with 10 to 20 L/min scale was used for the tests performed at higher air flow rates. Fig. 6 shows the variation of the pressure loss with the air flow rate and orifice diameter for a (tap) water column of 0.8 m.

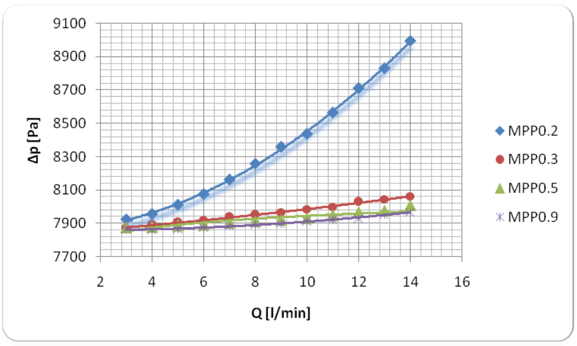


Fig. 6. Pressure loss variation with the air flow rate and orifice diameter.

The analysis of Fig. 6 shows that the pressure loss on the perforated plates increase with the air flow rate and a higher pressure loss on the MPP with orifices of 0.2 mm diameter can be noticed. This high may be given by the number of orifices, which is considerably higher than in the other MPPs cases.

The tests performed on the perforated plates revealed the necessity of a minimum air flow rate in order to achieve a continuous bubbles formation and detachment.

For example, there was identified that: in the case of the MPP with 61 orifices of 0.5 mm diameter an air flow rate of minimum 100 L/h is necessary for a full operation, whereas for the MPP with 21 orifices of 0.9 mm diameter an air flow rate of at least 160 L/h is required.

The modification of the flow regime has been experimentally noticed but further investigations in order to determine the precise flow rates, bubble size distribution and gas hold up have to be carried out. For air flow rates superior to 600 L/h changes in bubble shape can be noticed (Fig. 7), as well as the bubbles coalescence (Fig. 8).

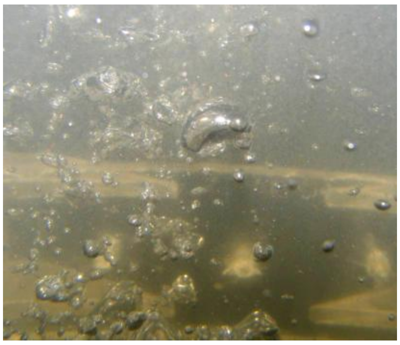


Fig. 7. Coexistence of small and big bubbles specific to transition regime.

Fig. 8. Coalescence of bubbles.

IV. CONCLUSION

The paper presents theoretical considerations on gas bubbles behavior - analytic calculation of bubble time formation, extra pressure needed for the bubble formation and detachment, bubble size and correlation between the extra pressure and the liquid superficial tension.

The theoretical aspects have been evaluated by experimental results on different plates with rigid orifices.

During the testing of the perforated plates a discontinuity in the bubbles formation was noticed at lower air flow rates, as well as a minimum flow rate necessary for the MPPs to entirely operate (i.e. to release bubbles from all orifices). This may be due to a low pressure in the gas chamber and its further decrease when bubbles detach from the MPP's surface, as suggested by other results provided by the literature; also, the gas chamber (MPP's capsule) should be better designed (a height of the chamber at least 5 times higher than its diameter) in order to achieve an uniform pressure distribution inside the capsule.

In order to have a better insight in the bubble formation mechanism and behavior during their rising to the free surface, further research must be conducted on bubble size distribution and gas hold up.

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