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JANUSZ A. SZYMCZYK[1], JANUSZ T. CIEŚLIŃSKI[2]

Measurements of gas and vapour bubble detachment frequency, diameter and rise velocity[3]

For single gas and vapour bubbles, the equivalent diameter, the rise velocity, and the frequency were measured on single artificial sites in distilled water. The air bubbles were emitted from glass nozzles with internal diameters of 0.3 mm, 0.6 mm, 0.9 mm and metallic orifice plates 2 mm and 4 mm in diameter. Electrically heated needles have been employed to produce vapour bubbles. The needles made of brass and stainless steel were placed in glass tubes so a kind of pin fin were produced. The diameter of the pin fin at the base ranged from 0.27 mm to 0.78 mm and height from 0.48 mm to 4.8 mm. The experiments were conducted at atmospheric pressure. A technique based on Particle Image Velocimetry for measurement of bubble size and rise velocity has been developed and frequency of bubble departure was measured using a variable frequency stroboscope.

1. Background

In a number of technical processes, gas is bubbled up through a layer of fluid. This situation is found in such applications as metallurgical processing, e.g. the continuous casting of steel, chemical engineering involving interaction between liquid and gaseous systems such as aeration, fermentation, saturation and absorption processes.

A variety of systems for where gas-liquid local phenomena can be found. The injection devices used vary from simple orifices, nozzles, capillaries, holes (sonic holes) and slots to multiple orifice plates or even porous (sintered) disks. The complexity of the process is enormous. There are numerous system and physical parameters including physical properties of the two phases, gas flow rate, pressure

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above nozzle or orifice plate, height of the liquid, gravity conditions which exert varying levels of influence on the formation of bubbles. Hence, most of the efforts have been devoted to the formation of bubbles from single nozzles or orifice plates. The parameters of central interest are the size of the bubble produced (volume or diameter) and bubbling frequency.

Two limiting modes of bubble formation are distinguished: constant flow rate regime (CFRR) and constant pressure regime (CPR). The CFRR can be obtained by imposing a strong restriction between the settling chamber and the injection point, in such a way that the incoming flow of the bubble should be controlled and therefore constant. To achieve constant flow rate conditions Kumada et al. [1] applied a small diameter connection pipe between the gas bomb and the settling chamber, Manasseh [2] used an additional valve and Dias et al. [3] constructed the sonic hole of very small diameter (50μm). The CPR occurs whenever the chamber volume is sufficiently large (in practice > 1000 cc – [4]) and the pressure in the gas chamber is maintained constant. With progression of time and the extent of bubble formation, pressure drop across the orifice (nozzle) varies and thereby results in a non-constant flow rate. Costes and Alran [5] suggested that the bubbles are formed under CFRR provided that the orifice Reynolds number is larger than 1000, and CPR prevails for orifice Reynolds number smaller than 1000. The experimental data by Davidson and Amick [6] and Hayes et al. [7], presented in [8], display the influence of the chamber volume on the frequency of bubble emission. For smaller chamber volume the bubble emission frequency was higher. Lately, Dias et al. [3] have shown, both experimentally and theoretically, that it is impossible to obtain a CFRR, even using a sonic hole.

Although dynamics of gas bubbles emitted from the most simple injection devices, i.e. single orifice plate or nozzle has been experimentally investigated by many researchers, contradictory results have been obtained. Additionally, a general model encompassing the formation and motion of gas bubbles under all conditions of interest is yet to emerge.

For the isolated bubble region, bubble frequencies, diameters at detachment and rising velocities are of major importance to understand nucleate pool boiling heat transfer. Theoretically, if one knows the length of the waiting period and the growth period, the bubble frequency is known too. However, because of the difficulty involved in determining both periods, it is more convenient to tie the frequency to some other parameter, such as the departure diameter. Various parameters affecting the bubble departure volume (diameter) and frequency can be distinguished and amongst them most commonly found are: liquid (wall) superheat, cavity size, surface tension, density of the liquid and the rate of bubble expansion [9-11]. Bankoff [12] studied the theoretical thermodynamic aspects of the nucleation process. He found that the free energy difference required for nucleation on a solid phase can be smaller, equal to, or larger than that for the homogeneous phase, depending on whether the solid geometry is a cavity, a perfect flat plane, or a protruding point. The free energy required was predicted to be a minimum for cavity.

It was first observed by Jakob [13] that the product of bubble diameter and bubble frequency appeared to be inversely proportional to the departure diameter, that is,

$$fD = C\,. \tag{1}$$

Many other attempts have been made to generalise the relation between f and D. Zuber [14] has proposed an equation based on the assumption that the product fD is proportional to the bubble rise velocity

$$fD = 0.59[\sigma g(\rho_l - \rho_b)/\rho_l^2]^{0.25}\,. \tag{2}$$

From the dimensional analysis coupled with their experimental results McFadden and Grassmann [15] have developed the expression

$$fD^{0.5} \approx 0.56[g(\rho_1 - \rho_b)/\rho_l]^{0.5} \approx 0.56g^{0.5} \tag{3}$$

Cole [16] has proposed a correlation for the region near the critical point

$$fD = [(4/3)g(\rho_l - \rho_b)/\rho_l]^{0.5} \tag{4}$$

Frederking and Daniels [17] have derived a similar relation as McFadden and Grassmann using a different method and for the film boiling regime it yields:

$$fD^{0.5} \sim [g(\rho_l - \rho_b)/\rho_l]^{0.5} \tag{5}$$

Siegel and Keshock [18] found experimentally that

$$fD = g^{0.5} \tag{6}$$

Ivey [19] proposed three separate regions for all nucleate boiling bubble diameters, which correlate f with D better than a single relationship:

- hydrodynamic region (0.13 cm< D <10 cm; coalesced bubbles – [1])

$$fD^{0.5} = 0.9g^{0.5} \tag{7}$$

- transition region

$$fD^{0.75} = 0.14g^{0.5} \tag{8}$$

- thermodynamic region (isolated bubbles – [1])

$$fD^2 = 23\pi a \tag{9}$$

where a – thermal diffusivity of the boiling liquid.

Bergez [20] accounted the wall temperature variations of a thin heating plate and proposed a correlation

$$fD^2 \approx 8a_w \tag{10}$$

where a_w – thermal diffusivity of the heating wall.

Kumada et al. [1] maintained that the bubble motion strongly depends on the geometry and orientation of heating elements. They proposed semi-empirical correlations of detachment frequencies for horizontal disks and thin wires. The detachment frequency for horizontal circular disks is weakly dependent on the flow rate of vapour or gas and is expressed by

$$f = 0.215[g(\rho_l - \rho_b)/\rho_l]^{5/9}/(\nu_l D^3)^{1/9} \tag{11}$$

The detachment frequency for horizontal thin wires varies with the diameter of bubbles or flow rate, and is classified into three regions with different dependence on the diameter of bubbles:

- $D \leq 4$ mm
$$fR^{-1/4} = C[g(\rho_l - \rho_b)/\rho_l]^{13/16}(\rho_l^3/\sigma^3\nu_l^4)^{1/16} \tag{12}$$
where $0.08 < C < 0.13$,
- 4 mm $< D <$ 15 mm
$$fR^{3/4} = 0.60[g(\rho_l - \rho_b)/\rho_l]^{5/12}(\nu_l/M^{0.25})^{1/6} \tag{13}$$
where $M = g(\rho_l - \rho_b)\nu_l^4\rho_l^2/\sigma^3$ – Molton number,
- $D \geq 15$ mm
$$fR^{1/4} = 0.11[g(\rho_l - \rho_b)/\rho_l]^{7/12}/(\nu_l^{1/6}) \tag{14}$$

Many boiling theories [14,21,22] equate the product of frequency and bubbles diameter occurring during the boiling with the rise velocity for a single bubble in large volume of quiescent liquid. It seems that Ivey [19] was the first who demonstrated that the two radically different concepts of velocity (vapour frequency times diameter and bubble rise velocity) are only approximately valid over the whole range of bubble diameters occurring in boiling. The most known correlation for the velocity of rise of a spheroidal bubble has been developed by Peebles and Garber [23]

$$w = 1.18[\sigma g(\rho_l - \rho_b)/\rho_l^2]^{(0.25)} \tag{15}$$

In the literature other expressions for w are available [24-26].

Generally, investigation of bubble motion and sizing in laboratory experiments has relied on high-speed photography [1,15,17,19,27-29]. Frequency data were taken by a stroboscope method [9,10,30] or application of photodiodes [8]. Mori *et al.* [31] have developed a new method to measure the rise velocity and the shape of a bubble with the electrical triple probe. Manasseh [2,32] has applied an acoustic technique coupled with high-resolution photographs for bubble sizing. More recently novel video techniques have been applied, e.g. Bergez [20] has obtained simultaneous recordings of bubble emission and wall temperature measured with thermochromic liquid crystal by use of high-speed colour video camera together with xenon flash, Tassin and Nikitopoulos [33] and Dias *et al.* [3] have developed the video-imaging method applied for a measurement of constant bubbling frequency based on stroboscopic video technique. In recent years several laser techniques have been developed for simultaneous measurements of bubble velocity and size. Among the latter are holography [34] and the phase-Doppler method [33,35].

In the present study, a technique based on Particle Image Velocimetry for measurement of bubble size and velocity has been developed and frequency of bubble departure was measured using a variable frequency stroboscope. Air and vapour bubbles were generated on artificial sites formed by glass nozzles, orifice plates and pin fins.

As it was shown above many attempts have been made to generalise the relationship between frequency and detachment diameter. One of the purposes of the present investigation was to obtain additional experimental data. Some boiling analysis equate the product of frequency and bubble diameter with the rise velocity for single bubble in a large volume of fluid. The question arises about the range of validity of such assumption and it was the second aim of this study. The third problem investigated was the relationship between the rise velocity of air and vapour bubbles. In order to check the validity of the widely assumed equivalence of these two concepts of velocity, namely vapour velocity and bubble rise velocity, the same experimental procedure was applied during measurements of gas and vapour bubble motion.

2. Experimental apparatus and procedure

2.1. Nozzles and orifice plates

Air bubbles were emitted from glass nozzles and metallic orifice plates submerged in distilled water at a depth of 9 cm in a glass box (15 × 15 × 18 cm). The settling chamber has 5 cm diameter and 8 cm height. The settling chamber is fed by air coming from a gas buffer reservoir through a pressure regulator and a rotameter. The pipe from the rotameter to the settling chamber is a 2.5 mm inner diameter aluminium tube. The scheme of the experimental equipment is shown in Fig. 1.

Three glass nozzle diameters were used, with internal diameters of 0.3 mm, 0.6 mm, and 0.9 mm. The internal diameters of orifice plates were 2 mm and 4 mm. The details of the injection devices are shown in Fig. 2. Experimental data were taken with decreasing airflow rate and frequency of bubble departure was measured using a variable frequency stroboscope.

The layout of the Particle Image Velocimetry system is shown in Fig. 3. The light source is the pulsed 2Nd-YAG (neodymium-doped yttrium aluminium garnet) laser. The pulse separation is from 200 ns to 300 μs. The images were recorded

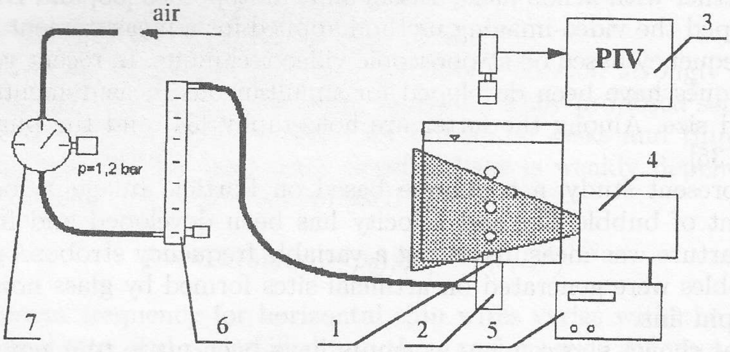

Fig. 1. Experimental equipment for gas bubbing: 1 – injection device, 2 – settling chamber, 3 – (PIV:CCD camera), 4 – stroboscope, 5 – frequency generator, 6 – rotameter, 7 – pressure regulator.

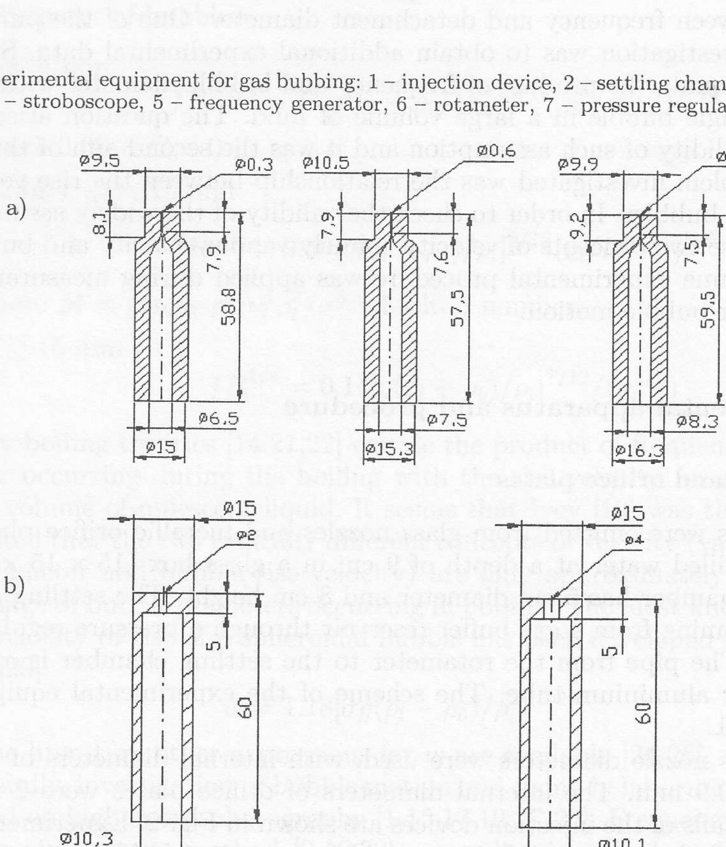

Fig. 2. Details of glass nozzles (a) and orifice plates (b).

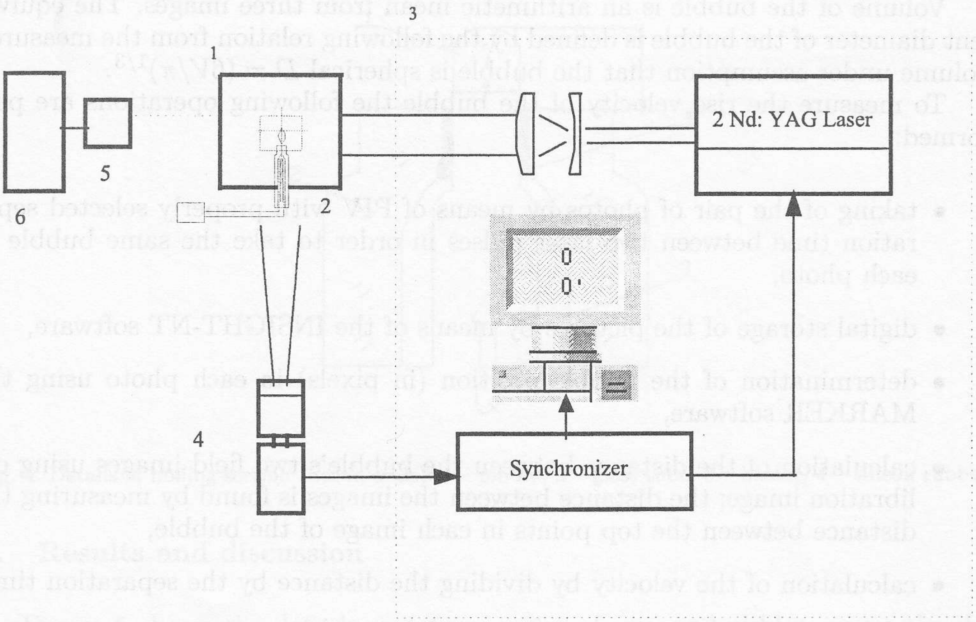

Fig. 3. Experimental equipment for boiling from pin fin: 1 – water tank, 2 – bubble generator, 3 – PIV, 4 – CCD camera, 5 – stroboscope, 6 – frequency generator.

with a CCD video camera. This digital image is processed using the INSIGHT software.

To measure the size of the bubble the following operations are performed:

- taking of the picture with calibration object placed in the field of view; the calibration image is a glass tube whose diameter has been accurately measured beforehand,
- digital storage of the picture by means of the INSIGHT-NT software,
- making of the contour of the bubble using the PHOTOSHOP software,
- copying of the contour with the same scale using the COREL DRAW software,
- conversion of the contour into set of points by means of the DXF-XY CONVERSION program developed,
- split of the contour (sets of points) into left and right half (due to of the lack of symmetry),
- approximation of the left and right half set points using the MATHCAD software,
- calculation of the volume of the bubble by integration using the MATHCAD software.

Volume of the bubble is an arithmetic mean from three images. The equivalent diameter of the bubble is defined by the following relation from the measured volume under assumption that the bubble is spherical $D = (6V/\pi)^{1/3}$.

To measure the rise velocity of the bubble the following operations are performed:

- taking of the pair of photos by means of PIV with properly selected separation time between two laser pulses in order to take the same bubble in each photo,
- digital storage of the pictures by means of the INSIGHT-NT software,
- determination of the bubble position (in pixels) in each photo using the MARKER software,
- calculation of the distance between the bubble's two field images using calibration image; the distance between the images is found by measuring the distance between the top points in each image of the bubble,
- calculation of the velocity by dividing the distance by the separation time.

The rise velocity of the bubble is an arithmetic mean from five pairs of images.

2.2. Pin fins

Electrically heated needles have been employed to produce vapour bubbles. The heating sections were mounted in the same glass box as discussed above, but in that case the sides are insulated with glass wool and each contains a heating cartridge, which allows water in the tank to be maintained at the saturation state. Experiments were conducted under atmospheric pressure. The needles made of brass and stainless steel were placed in glass tubes so a kind of pin fin were produced. The diameter of the pin fin at the base ranged from 0.27 mm to 0.78 mm and height from 0.48 mm to 4.8 mm. The nose radius of the pin fins ranged from 0.093 mm to 0.208 mm. The lateral surfaces of the pin fins were prepared by polishing with emery paper or lapping. Electric power is supplied to a heater, which is formed from insulated high-resistance wire and wound around a heating rod, from an AC stabilised power generator. The electric power ranged from 5 W to 15 W. Silicon rubber guaranteed the tightness of the assembly. The details of the heating sections are shown in Fig. 4. The procedures for determination of vapour bubble volume as well as vapour bubble rise velocity are the same as in the case of air bubbles described above. Because of the low detachment frequency of vapour bubbles the use of the stroboscopic method was not practical. The detachment frequencies were measured by direct counting of the departing vapour bubbles and using a stop watch. The detachment frequency is an arithmetic mean from fifteen measurements.

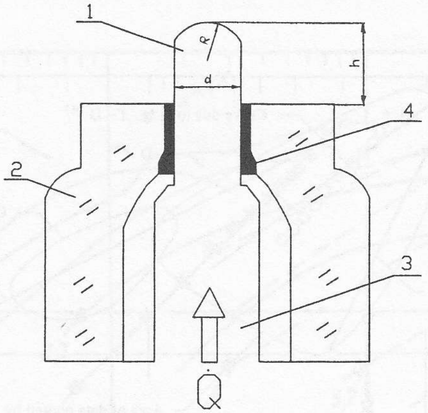

Fig. 4. Details of boiling section (not in scale): 1 – pin fin, 2 – glass tube, 3 – heater, 4 – silicon rubber.

3. Results and discussion

Figure 5 shows the detachment frequencies of vapour bubbles versus the detachment diameter. The key to the individual data points is given in Tab. 1. The

Table 1. The key to data points

	d[mm]	h [mm]	Fluid	Liquid: distilled water	Symbol
Pin fin	0.27-0.63	0.48-4.8	vapour	~ 99.0°C	◇, □ , △
Nozzle	0.3	–	air	21.5°C	x
Nozzle	0.6	–	air	21.5°C	*
Nozzle	0.9	–	air	21.5°C	o
Orifice	2	–	air	21.5°C	+
Orifice	4	–	air	21.5°C	−

quantities f and D are dependent variables in all experiments presented. The present results of vapour detachment frequencies from vertical pin fins are at least an order of magnitude lower than those obtained by other authors quoted by Ivey [19]. It is probably the result of the unique geometry under study and very low heat flux density applied which unfortunately has not been measured in this investigation. Such low frequencies ($f < 1$ Hz) have been recorded only by Hahne et al. [36] and the agreement with those data is quite reasonable – Fig. 5. During the experiments a big influence of geometrical parameters of boiling section (Fig. 4) and superheating of bulk water (water was slightly subcooled) on pin fin performance has been observed. Further work is required to investigate that phenomenon.

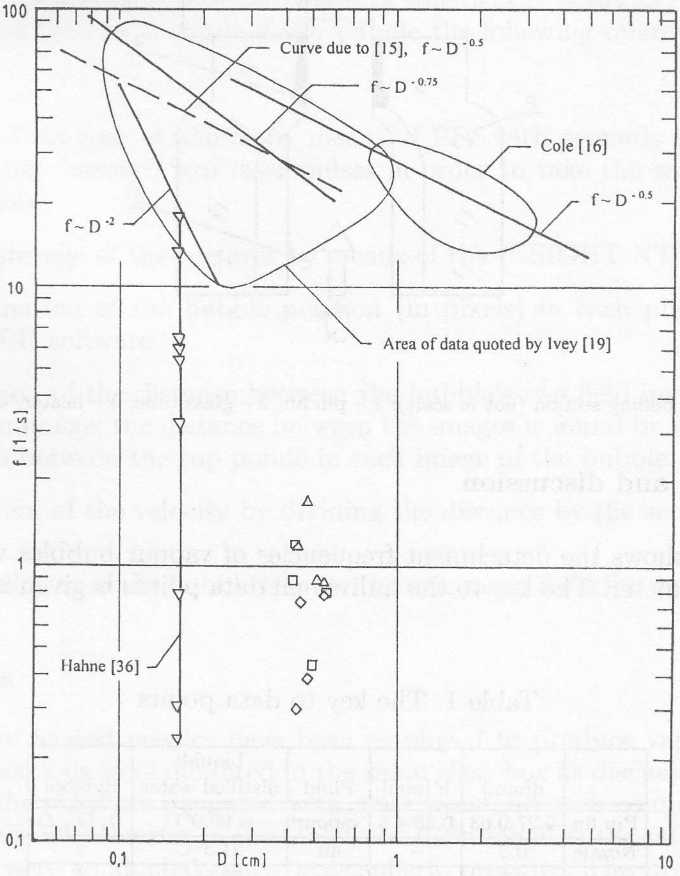

Fig. 5. Detachment frequencies of vapour bubbles.

Air bubble detachment frequencies versus air flow rate are plotted in Fig. 6. Present data, except for glass nozzle with internal diameter 0.3 mm, are in reasonable accord with the experimental data available from the literature. Stroboscope method used was not precise enough to measure the observed large values of frequencies ($f > 50$ Hz) for this glass nozzle. The big influence of the settling chamber volume on detachment frequencies should be pointed out – see data of Hughes *et al.* [37] in Fig. 6 – a) 61 cm^3, b) 4 cm^3. Figure 7 illustrates the rise velocity of air and vapour bubbles versus detachment diameter. The key to the individual data points is given in Tab. 1. The other data are quoted by Ivey [19]. Most of the present data lie in the regions reported in the literature. However, the velocities of air bubbles obtained lie above the air bubble curve. The reason explaining that fact probably is that in the present study the velocity of the top

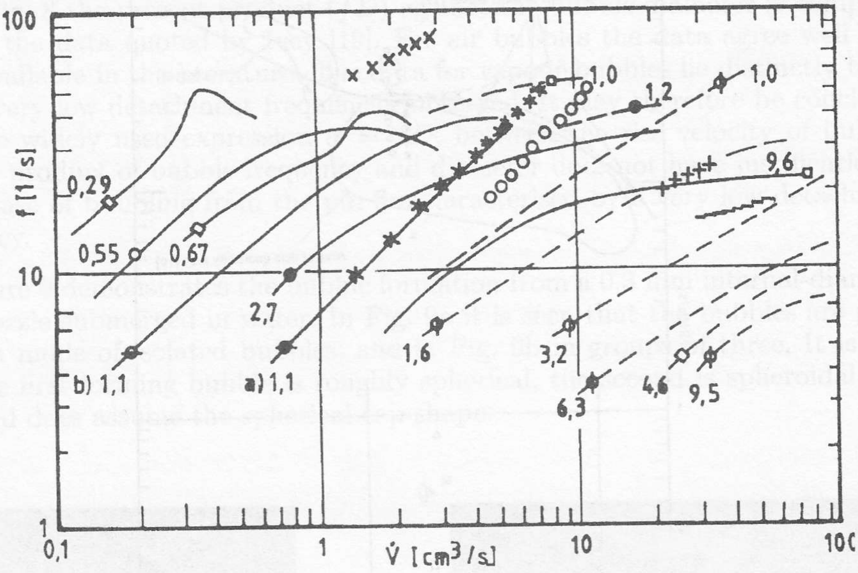

Fig. 6. Detachment frequencies of air bubbles; —□— – [6], —◇— – [30], -o- – [37], ϕ – [38], • – [39]; solid lines – nozzles, dashed lines – orifice plates; numbers – internal diameter [mm].

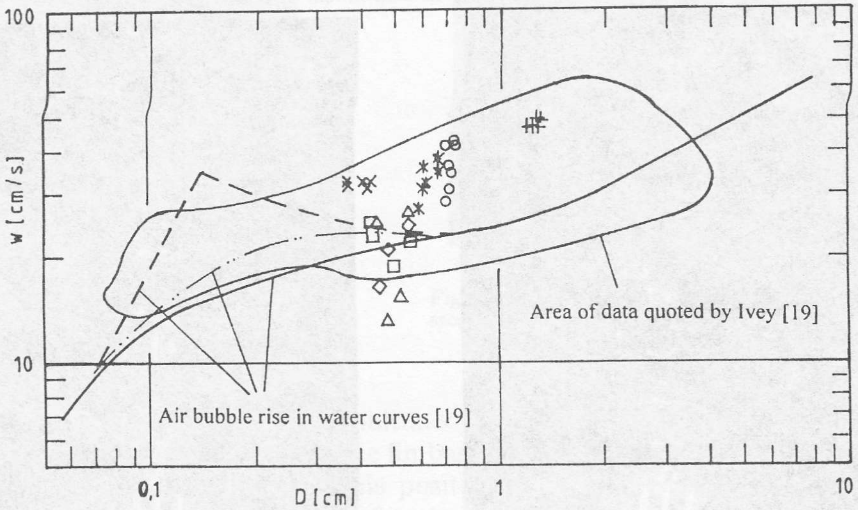

Fig. 7. Rise velocity of air and vapour bubbles.

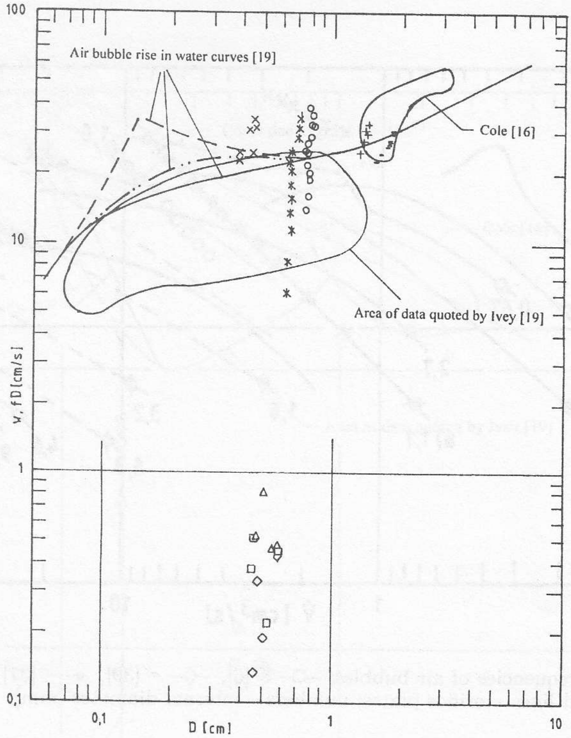

Fig. 8. Product (fD) vs detachment diameter.

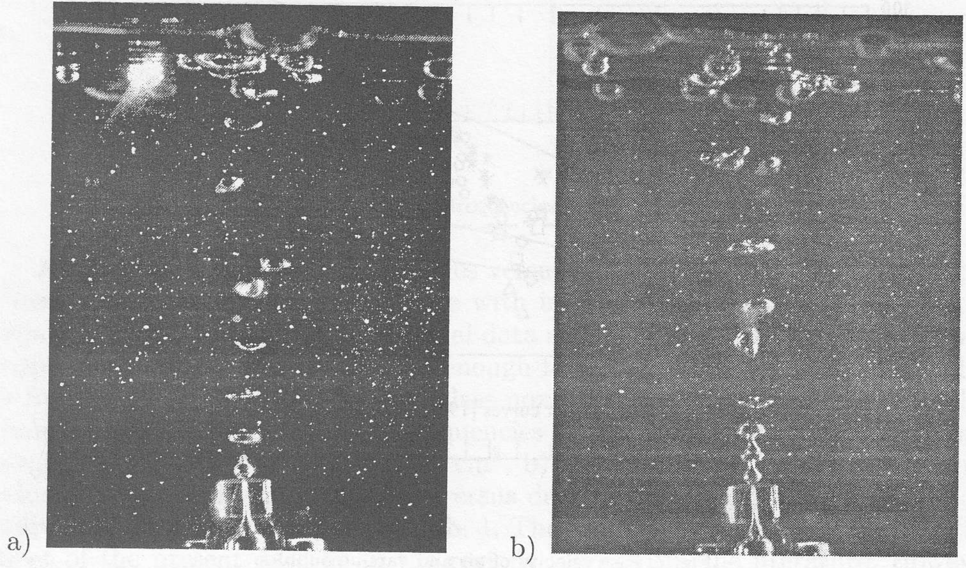
a) b)

Fig. 9. Bubble formation from a 0.3 mm glass nozzle; a) isolated bubbles (5 l/h), b) in groups of three (10 l/h).

points of the bubble was estimated instead of the centre of the bubble.

In Fig. 8 the present product (fD) against the bubble diameter is compared against the data quoted by Ivey [19]. For air bubbles the data agree well with those available in the literature. The data for vapour bubbles lie distinctly below due to very low detachment frequencies observed. It may therefore be concluded that the widely used expression $w = fD$, between the rise velocity of bubbles and the product of bubble frequency and diameter does not have justification as in the case of bubbling from the pin fin characterised by a very low detachment frequency.

Figure 9 demonstrates the bubble formation from a 0.3 mm internal-diameter glass nozzle submerged in water. In Fig. 9a it is seen that the bubbles are generated in mode of isolated bubbles, and in Fig. 9b in groups of three. It is seen that the first forming bubble is roughly spherical, the second is spheroidal, and the third does assume the spherical cap shape.

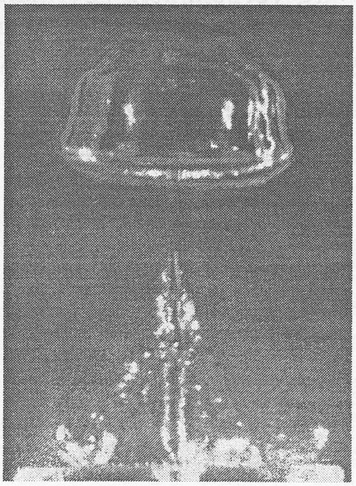

Fig. 10. Boiling on a vertical pin fin (brass, d=0.6 mm, h=4.2 mm).

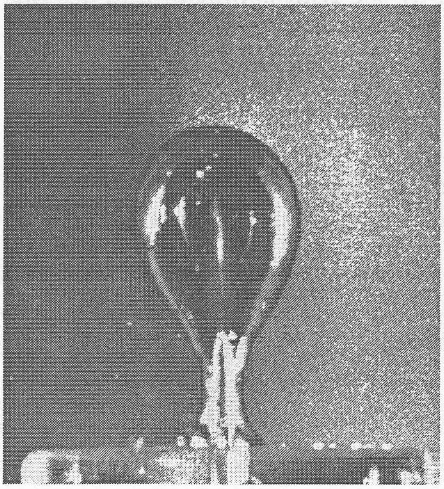

Fig. 11. Boiling on a vertical pin fin (stainless steel; d=0.6 mm, h=2.8 mm).

Figure 10 demonstrates the simultaneous occurrence of the three types of boiling on a vertical brass pin fin. The fin base is governed by film boiling because of the highest wall superheat at this position. At adjacent location transition boiling takes place. The end of a high fin can be controlled even by free convection.

Figure 11 shows the detachment of a vapour bubble from a stainless steel pin fin. The surface of a pin is covered with a vapour film, and the shape of a vapour bubble is very symmetrical.

4. Conclusions

The frequency and diameter of detachment, and the rise velocity of air and vapour bubbles were measured with glass nozzles, orifice plates and pin fins. A technique based on PIV has been developed for measurement of bubble sizing and motion. Unfortunately it was not possible to measure the detachment frequency by means of PIV because of difficulties in matching the stochastic detachment frequency with laser operating frequency. The most important conclusions are as follows:

- the rise velocity of vapour bubbles determined as a product of frequency and diameter cannot be used in the case of low detachment frequency,
- there exists quite a close relationship between air and vapour rise velocity for bubbles of the same radius.

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