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ANALYSIS OF GAS BUBBLE FORMATION AT THE NOZZLE OUTLET

BADANIE PROCESU TWORZENIA SIĘ PĘCHERZYKÓW GAZU U WYLOTU Z DYSZY

Abstract: The paper presented a short literature review of theoretical models of formation of gas bubbles. On this basis, was prepare a classification of model. In the next step, experimental research was conducted, on the basis of which three were selected basic structure of the formation of bubbles. On the next step Then presents the results of experimental studies on the basis of which three were selected basic structure of the formation of bubbles. The classifications of bubble formation structures were expressed by Eötvös and Reynolds numbers. Furthermore, on this basis, were constructed a map of the structures forming bubbles. This paper presents a measurement method used for determination of parameters of bubbles forming at jet attachment from which the bubbles are displaced upward.

Keywords: bubble formation, mathematical models, bubble volume measurement

Introduction

Formation of gas bubbles takes place in devices and apparatus, in which the mass transfer takes place. The way in which gas bubbles forming has influence on the quality of the mass transfer process. Due to the complex nature of the phenomena occurring in the process of bubble formation in practice a wide variety of theoretical models have been reported. These models are applicable only to selected structures of bubble formation. Therefore the scope of the present work is to classify. This paper describes the attempt to systematize the range of specific structures gas bubbles formation in relation to the known dimensionless number (Reynold and Eötvös).

The gas bubble formation in the liquids is affected by various system parameters related to the nozzle design ,the supply system and the properties of gas and liquid. In the literature these factors are generally divided on: stand parameters (*eg* nozzle

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diameter, tank volume), system environment factors (*eg* liquid or gas properties) and operating parameters (*eg* gas flow rate, pressure, free movement of liquid) [1].

This paper describes the experimental method used to determine the shape and volume of gas bubbles formation. On the basis of experimental investigation the classification of the structures formation was carried out. Such classification facilitates selection of theoretical models in the design of equipment for gas bubble generation.

Classification of theoretical models for bubble formation

Models for gas bubbles formation from the nozzle with a single circular hole, and the gas bubbles formed flow upwards are discussed. It is also assumed that the bubbles formed in the stagnant liquid. For such assumptions in the literature are many models describing the bubbles formation.

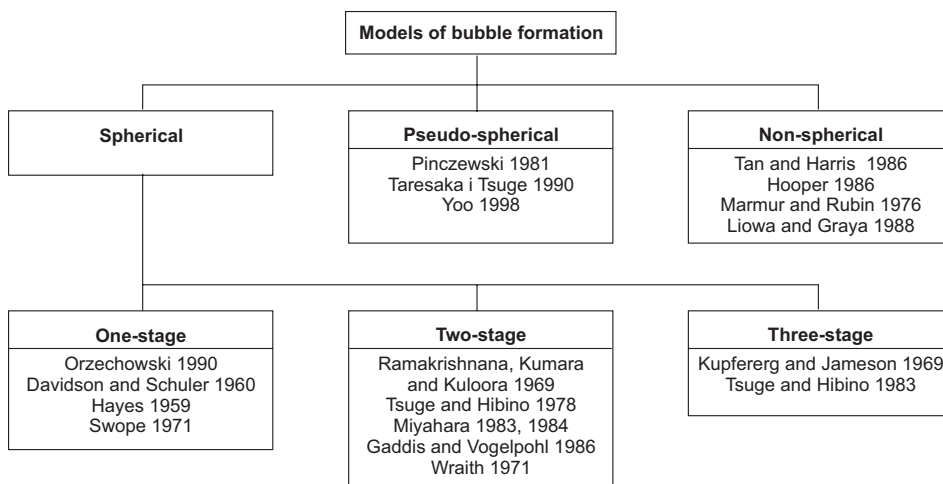


Fig. 1. Classification of theoretical model of gas bubble formation

In Fig. 1, the classification of theoretical models is proposed. Spherical models include all those arrangements, in which it is assumed that the bubbles formed are of spherical shape. Furthermore, they were divided into three groups called: one-stage, two-stage and three-stage.

This is due to the assumptions, consisting in calculating the final volume of the bubble on the basis of one, two or three phases of the bubble formation shape. One-stage models may include static models [2], which relate to very small flows, where dynamic forces are omitted. As well as dynamic models, but assuming that the bubble has a spherical shape which continuously increases in volume.

The most popular are models of Davidson, Schuler, Hayes, Swope [3–6]. Two-stage models are based on the assumption that the bubble detachment occurs in two stages. The first is the formation of a spherical bubble, followed by a second step of the bubble

detaching phase. The most famous models are Ramakrishna–Kumar–Kuloora, Tsuge and Hibino, Miyahara, Gaddis and Vogelpohl and Wraith [7–12]. Three-stage models assume that after the bubble detachment from the nozzle there is for some time resting state, that the increase in the volume of residue gas at the bubble detachment is not observed. Known models are models Kupfererg, Jameson, and Tsuge and Hibino [13, 14].

Non-spherical models assume that the shape of the bubble formed is dependent on the pressure distribution on its surface. Most frequently cited models in the literature are models of Tan, Harris, Hooper, Marmur, Rubin and Liow and Gray [15–19]. Additionally, introduced division into pseudo-spherical models, which included models of Pinczewski, Taresak, Tsuge and Yoo [20–21].

Test stand

The experimental set-up used to study the bubble formation is shown in Fig. 2. The basic element is a glass column (6): $50 \times 150 \times 200$ mm. The column is filled with water. In the bottom of the column (7) interchangeable nozzles of different shape and hole diameter are provided. The nozzle was so attached that forming bubbles were free to float to the top. Forming bubbles were illuminated by halogen lamp (5), and the image were recorded by the camera (8). DALSA camera with a resolution of 400×500 pixel, with image recording rate of 200 frames per second was used. Stream of gas supplied to the nozzle was controlled using a throttle valve (3), and measured by a flow meter 4. The air is produced by a membrane compressor with a tank (2). The tank volume is 5 dm^3 .

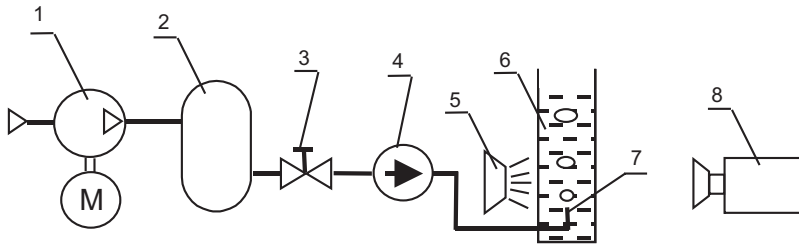


Fig. 2. The test stand

Gas bubbles were formed at the cylindrical and conical nozzles with outlet holes diameters d_0 : $\varnothing 1.5$ mm, $\varnothing 2$ mm, $\varnothing 2.5$ mm, $\varnothing 3$ mm, $\varnothing 4$ mm (Fig. 3). Nozzles were screwed into the pressure equalizing chamber in the shape of a cylinder with an internal diameter of 45 mm and a height of 40 mm. The holes lengths in the nozzles were greater than $10 d_0$, what ensures the stabilization of the gas flow. The use of two types of nozzles is to estimate the impact of changes in the liquid circulation around the bubble formed. In these two cases, the fluid flows from the bottom of the bubble formed at different angle. This results in a changing impact of dynamic forces associated with the liquid inernest.

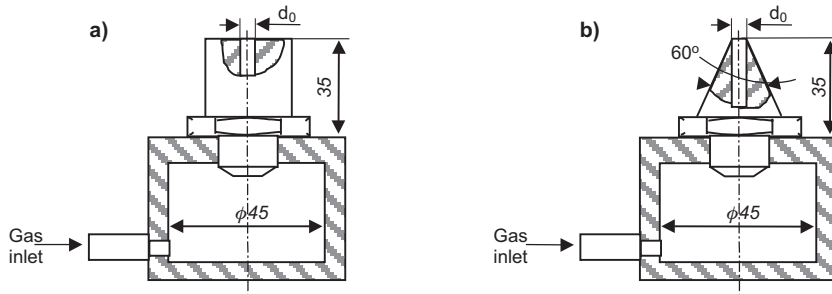


Fig. 3. The construction of nozzles for gas bubble generations a) cylindrical; b) cone

Results of observed the shape of bubble formation

Images recorded on the camera were subjected to image analysis based on which is possible to determine the characteristic parameters of the gas bubbles formation. Image of the gas bubbles recorded by camera is the image in 256 shades of gray. In practice, it is easier to analyze the shape of the bubble, when it is a distinct phase of gas and liquid. For this purpose, the camera images were subjected to Image Processing of image binarization [23].

To carry out the process of image binarization software Vision with the program LabView 7.1. was used. Images from the camera are subject to certain defects, such as reflections of light, different kinds of shadows and reflections. This causes that an image taken directly from the camera is not suitable for further analysis, it requires the appropriate image processing. An exemplary image is shown in Fig. 4a.

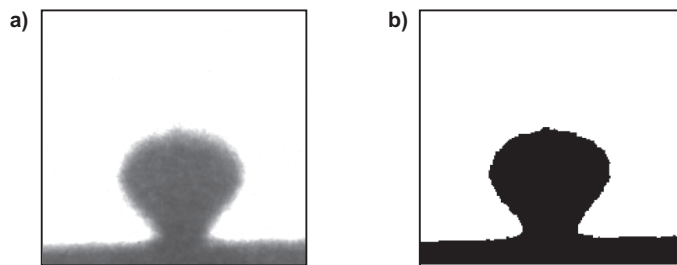


Fig. 4. Images of bubble a) from video camera; b) after binaryzation

Individual images were processed to brightness and improvement of contrast. In order to improve, the quality of the separation of bubble contours color inversion is performed. For such crafted image, image transformation is done on a one-bit map (Fig. 4b). As a consequence the transformation of the image is obtained, in which each pixel is assigned value 1 or 0. This corresponds to occurring a gas or liquid in a given location.

In Fig. 4a a white color represent the liquid, and black is for the gas. In order to remove of artifacts that arise in the image processing, the selective removal of small

objects was used. This operation involves the removal of objects whose size exceeds a threshold value. This value was chosen experimentally. At the end of the binarization process the empty space inside the bubbles was filled.

For such processed images shape of gas bubbles formed were analyzed. Three basic structure of the gas bubbles formation were separated (Fig. 5). Individual changes in the structure of gas bubbles formation are referenced by dimensionless number taking into account stand factors, the operating and design parameters. One of the dimensionless numbers that takes into account the diameter of the nozzle, the flow rate of gas and rheological properties of the liquid is the Reynolds number. This number is defined as follows:

$$\text{Re} = \frac{vd\rho_c}{\eta_c} \quad (1)$$

where: d – nozzle diameter [m],
 ρ_c – liquid density [kg/m^3],
 η_c – liquid viscosity [$\text{Pa} \cdot \text{s}$],
 v – average gas velocity [m/s].

The observed results shows that video sequences of bubbles formation correlate well with the theoretical models of the gas bubbles formation division (Fig. 1), which are divided into spherical models that assuming spherical shape of the bubble, pseudo-spherical taking into account the equations of motion and non-spherical taking into account the dynamic forces of equilibrium. Characteristic ranges for passage of structures of bubbles formation are the value of the Reynolds number. For a conical nozzle having a hole diameter of 3 mm at a gas flow $Q < 10 \text{ cm}^3/\text{minute}$ (Fig. 5a) the shape of the bubble formed is close to a sphere. Detachment of the bubble from the nozzle occurs at the dominance of static forces and the shape of the bubble during detachment is only slightly deformed.

For this structure for numerical calculation can be successfully used spherical models. For the same nozzle, but to the flow $Q = 10 - 150 \text{ cm}^3/\text{min}$ transition structure



Fig. 5. Typical structures of bubbles formations a) spherical; b) pseudo-spherical; c) non-spherical

is formed, characterized by pseudo-spherical shape of gas bubbles formed (Fig. 5b). The characteristic is spherical bowl with a clear narrowing portion cylindrical. This shape very well approximate the theoretical models classified as pseudo-spherical (Fig. 1). For streams $Q > 150$ shapes of bubbles formation are irregular (Fig. 5c), their shape resembles the shape of the fungus. There is no shape repeatability during successive bubbles formation. For this structure seems to be a reasonable use of non-spherical models for numerical simulation. Ranges of values for Reynolds numbers for nozzles with different hole diameters take different values.

Measured of bubbles volume

Reconstruction and thereby determination the volume of the bubble detachment volume is to approximate the shape of a series of cylinders (Fig. 6a). The values of each diameter of the base of the cylinder is determined based on the binary image bubble (Fig. 6b). The diameters are calculated on the basis of the number of pixels in a given line of an image, then based on the pixel value in millimeters. A succession of diameters are measured with a constant step size of one pixel, and base on it the height of the cylinder h .

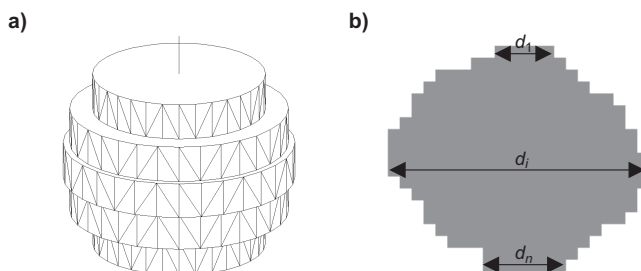


Fig. 6. Bubble volume calculation a) idea of bubble shape reconstructions; b) calculation of cylinder diameter

The volume of the bubble is the sum of the cylinders volumes making up the bubble. For the approximation of the bubble shape by elliptical cylinder, the formula for the volume takes the following form:

$$V = \sum_{i=1}^{n-1} V_i = \frac{h\pi}{4} \sum_{i=1}^{n-1} d_i^2 \quad (2)$$

where: V_i – volume of one cylinder [m^3],
 d_i – diameter of cylinder [m],
 h – height of the cylinder [m],
 n – numbers of cylinders.

Example of bubbles images are shown in Fig. 7. The error of the shape reconstruction and the precision of the designation of volume largely depend on the

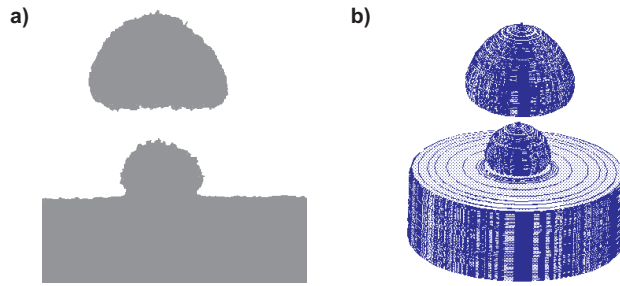


Fig. 7. Reconstruction of bubble shape a) image of bubble after binarization; b) 3D images after reconstruction

bubble image resolution. The shape reconstruction of the bubbles formed not only allows the calculation of its volume, but allows analysis of changes in the shape. Such an analysis is essential for verification of theoretical models of gas bubbles formation.

Test results

Based on the volume measurements of bubbles formation, the limits for the dimensionless quantity at which a change the structure of the bubble formation is occurs, was set. The dimensionless quantity should take into account stand, system and environmental factors (operating and design parameters). One of the dimensionless numbers, that takes into account the diameter of the nozzle, the gas flow rate and liquid rheology is the Reynolds number.

Taking into account the environmental factors of the process, results were referred to the Eötvös number. It takes into account properties of the liquid and gas and the diameter of the gas bubbles detaching. This number is defined based on the equivalent bubble diameter. The equivalent diameter d_e is taken as the sphere diameter that has the same volume as the bubble that separated from the nozzle. Eötvös number was calculated by the formula:

$$Eo = \frac{g (\rho_c - \rho_g) d_e^2}{\sigma_c} \quad (3)$$

where: d_e – equivalent bubble diameter [m],
 ρ_g – gas density [kg/m^3],
 σ_c – surface tension coefficient [N/m],
 g – acceleration of gravity [m/s^2].

Afterwards, attempted to determine the map of gas bubbles formation. The bubble formation maps expressed by Eötvös and Reynolds numbers were constructed. Figure 8 shows the results of gas bubbles formation for two different nozzles. Individual points marked with circles in the graph represent the structure of a spherical bubble formation. The triangles are for pseudo-spherical structure, and squares represent a non-spherical

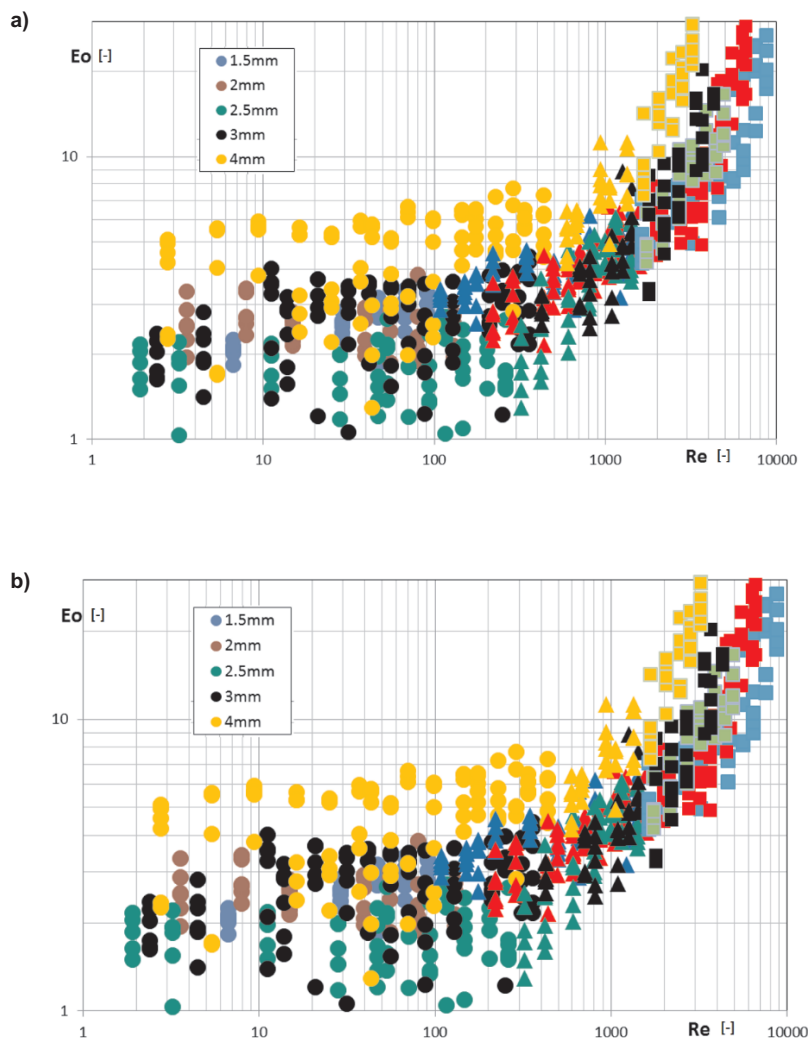


Fig. 8. Maps of gas bubble formation for a) cylindrical nozzle; b) core nozzle

structure. Different colors denote values of the gas flow coming out from the nozzle. As shown by the presented maps for the cylindrical nozzle (Fig. 8) spherical structure formed at Reynolds numbers under 300. As indicated Reynolds numbers in the range from 300 to 1500 represent the formation of a pseudo-spherical structure. Further, for the Reynolds number higher from 1500 a pseudo-spherical is created. For a spherical structure Eötvös numbers assume a constant value. However, for non-spherical structures a rapid increase in Eötvös number was observed. As Eötvös number is defined by the bubble diameter, this means that in spherical structure formation the gas flow rate does not significantly affect the final volume of the bubble. It affects only the

frequency of their formation. On the other hand, not spherical structure has a completely different nature, here the gas flow velocity is crucial for the final volume of the bubbles. The influence of the nozzle shape for the range in which individual structures are formed is small. For example, for a conical nozzle spherical structures are formed for Reynolds numbers less than 200 while the chain structure is formed at Reynolds numbers above 1500. Compared with the cylindrical nozzle intervals are very similar. In addition a great similarity of the Eötvös numbers was observed.

Conclusions

In this work, the phenomena of bubble formation were investigated. The effect of different parameters on the regimes of bubble formation and their transition was investigated experimentally. It has been shown that forming bubbles can be divided into three basic structures. The maps of gas bubble formation base on Reynolds and Eötvös number were proposed. Finally, on this basis it is possible to determine the limits of Reynolds numbers at which a change in the structure of the formation of bubble is occurred. The ranges reported in present work are expected to facilitate design of equipment and machines in which there is formation of gas bubbles.

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Abstrakt: Praca zawiera krótki przegląd literaturowy modeli teoretycznych tworzenia się pęcherzyków gazu. Na tej podstawie przeprowadzono klasyfikację modeli. Następnie przedstawiono wyniki badań eksperymentalnych, na podstawie których wyłoniono trzy podstawowe struktury tworzenia się pęcherzyków. Klasyfikacje struktur oparto na liczbach kryterialnych Reynoldsa oraz Eötvösa. Posłużyło to do opracowania map struktur tworzenia się pęcherzyków. Ponadto w pracy przedstawiono metodę pomiarową do wyznaczania objętości tworzących się pęcherzyków gazu.

Słowa kluczowe: tworzenie pęcherzyków gazu, modelowanie matematyczne, pomiar objętości pęcherzy