XX Polish Fluid Mechanics Conference,
Gliwice, 17-20 September 2012

INVESTIGATIONS OF GAS BUBBLE FORMATION BY MEANS OF THE OPTICAL TOMOGRAPH

Mariusz R. Rząsa
Opole University of Technology, Poland
E-mail: m.rzasa@po.opole.pl

Abstract

Desigers of any types of devices used for oxygenation and aeration must know the mechanism of gas bubble formation. This paper presents a measuring method for determination of parameters of bubbles forming at the jet attachment from which the bubles move upward. The measuring system is based on the optical tomograph containing five projections. An image from the tomograph allows to observe shapes of the forming bubbles and determine their volumes and formation rate. Moreover, the paper presents some theoretical models known from literature. The measurement results have been compared with simple thworetical models. The paper contains also a study on possibilities of application of the presented method for determination of forming bubble structures and observation of intermediate states.

Key words: bubble formation, optical tomography, bubble flow measurement

INTRODUCTION

Designers of many devices, especially aerators and pressure aerators, have to know a mechanism of gas bubble formation. In pressure aerators, gas is forced under pressure into the liquid by means of diffusers equipped with a system of nozzles generating fine gas bubbles. The generated bubbles have different concentrations and shapes depending on the nozzle diameter. In the case of a single hole, big bubbles are formed, and they cause pulsation. In the case of perforated grates, much smaller bubbles are generated, and they join at some distance from the nozzle. The smallest bubbles form in the case of the porous plate, but it requires a high gas overpressure, so such situation is rarely met in industry. Under low rate of gas discharge from the nozzle, bubbles are ball-shaped and they form at the nozzle edge (e.g.: Orzechowski, 1990). In practice, such phenomena take place only in the case of gravitational gas discharge. As the gas flow rate increases, a diameter of the forming gas bubble depends on not only the hole diameter, but the volumetric gas flow intensity as well. For large gas streams, phenomena caused by resistances to gas motion and connected with the gas rate become dominating, and the bubbles start to form at a long distance from the nozzle. In such a case, the forces connected with surface tension become to play a less important role.

The paper describes the tests of the forming gas bubbles at the nozzle with a hole 2 mm located at the bottom of the round column and diameter 80mm. The optical tompgraph with five projections was used for measurements of volumes of the forming bubbles (e.g.: Rząsa et al., 2007, Rząsa et al., 2003). The test results were compared with theoretical relationships known from literature (e.g.: Dziubiński et al, 2010).

THE MODELS OF BUBBLE FORMATION

The problem of gas bubble formation was limited to the nozzle with a single circular hole, and the forming bubbles flow upward. It was also assumed that the bubbles form in the steady liquid. In literature we can find many models describing the bubble formation process under such assumptions. Static models concern very small flows where dynamic forces are neglected (e.g.: Orzechowski, 1990). Such models are rarely applied, so the further considerations are limited to dynamic models. The well known and most popular models were formulated by Davidson - Schuler, Ramakrishnan- Kumar-Kuloor, Swope (e.g.: Dziubiński et al, 2010). In this paper a static model completed with the force of inertia was proposed, and the obtained results were compared with the experimental data.

The static model completed with the force of inertia

It is assumed that the bubbles form at the nozzle tip, and that a bubble does not react with other bubbles or walls, and the surrounding liquid is at rest. Moreover, it is assumed that the gas volume which flows out from the nozzle causes increase of the bubble volume and the forces connected with gas compressibility are neglected (e.g.: Rząsa, 2002, Rząsa et al., 2004). Distribution of the forces acting on the bubble during its formation is shown in Fig.1.

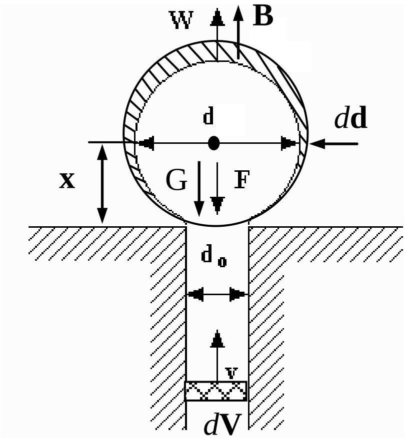


Fig. 1 Static model of gas bubble formation

According to the balance of forces acting on the forming bubble, its diameter is calculated on the assumption that at the moment of the bubble separation the balance is equal to zero. The equation of the balance of forces takes the following form:

$$W + B - G - F = 0$$

where:

W	– force of uplift pressure	$W = \frac{\pi d^3}{6} \rho_C g$
G	– weight of bubble,	$G = \frac{\pi d^3}{6} \rho_G g$
F	– force of surface tension,	$F = \delta \pi d_0$
B	– force of inertia,	$B = \rho_G \frac{\pi d^3}{6} \frac{dv}{dt} = -\rho_G \frac{4 Q^2}{6 \pi d^2}$
ρ_C	– density of liquid,	
ρ_G	– density of gas,	
v	– velocity of bubble centre of mass,	
t	– time,	
Q	– gas stream flowing from the nozzle.	

The Davidson – Schuler model

The Davidson-Schuler is based on the balance of forces acting on the bubble while continuous increase of the bubble volume. It is assumed that the bubble is ball-shaped, and separation of the bubble from the nozzle takes place at the moment when the bubble centre displaces at the distance equal to the sum of the hole radius and the bubble radius. Uplift pressure force and inertia of the liquid layer moving near the bubble are the most important forces. On such assumptions, the equation proposed by the authors takes the following form (e.g.: Davidson et al., 1960, Davidson et al., 1997,):

$$v_p(\rho_c - \rho_g)g = \frac{d}{dt}\left\{\left(\frac{11}{16}\rho_c + \rho_g\right)v_p\frac{dx}{dt}\right\}$$

where:

x – distance between the bubble centre and the nozzle [m].

For the given gas stream at the moment of the gas bubble separation from the hole its volume is calculated from the equation:

$$V_p = 1{,}378 q_g^{6/5} g^{-3/5}$$

The Ramakrishnan – Kumar – Kuloor model

The model assumes two stages of the bubble formation. The first stage of growth assumes that the bubble forms at the hole edge and gradually increases its volume. The bubble shape is close to the ball. If the forces displacing the bubble upward are greater than the forces acting to the bubble downward, the second stage (i.e. stage of separation of the bubble from the hole) starts. At this stage, so-called gas neck forms; it keeps the contact of the bubble with the hole. The moment of the bubble separation takes place when length of the gas neck becomes equal to length of the bubble radius r_I in the last phase of its growth (e.g.: Khurana et al., 1969, Kumar et al., 1970, Satyanarayan et al., 1969). The equation of balance of forces acting to the bubble is used for determination of the final volume of the first stage

$$V_{pI}^{5/3} = \frac{11 q_g^{2}}{192\pi\left(\frac{3}{4\pi}\right)^{2/3} g} + \frac{3\eta_c q_g \cdot V_{pI}^{1/3}}{2\left(\frac{3}{4\pi}\right)^{1/3}\rho_c g} + \frac{\pi d_0 \sigma_c \cos\Theta\, V_{pI}^{2/3}}{g\rho_c}$$

where:

Θ – wetting angle.

The final volume of the bubble V_{pII} after separation from the nozzle is calculated from the following equation (e.g.: Kumar et al., 1970):

$$\sqrt[3]{\frac{3}{4}\frac{V_{pI}}{\pi}} = \frac{B}{2\cdot q_g(A+1)}\left(V_{pII}^{2} - V_{pI}^{2}\right) - \frac{C}{q_g A}\left(V_{pII} - V_{pI}\right) - \frac{3D}{2q_g\left(A-\frac{1}{3}\right)}\left(V_{pII}^{2/3} - V_{pI}^{2/3}\right)$$

where:

r_I – final radius of the bubble in the first phase of formation,

$$r_I = \sqrt[3]{\frac{3}{4}\frac{V_{pI}}{\pi}}, \qquad A = 1 + \frac{1.25\cdot 6\pi\cdot r_I\eta_c}{q_g\left[\rho_g + \frac{11}{16}\rho_c\right]} \approx 1 + \frac{120\pi\cdot r_I\eta_c}{11\rho_c q_g}, \qquad B = \frac{(\rho_g + \rho_c)g}{q_g\left[\rho_g + \frac{11}{16}\rho_c\right]} \approx \frac{16g}{11q_g}$$

$$C = \frac{\pi d_0\sigma_c\cos\Theta}{q_g\left[\rho_g + \frac{11}{16}\rho_c\right]} \approx \frac{16\pi d_0\sigma_c\cos\Theta}{11\rho_c q_g}, \qquad D = \frac{3\eta_c}{2\left(\frac{3}{4\pi}\right)^{1/3}\left[\rho_g + \frac{11}{16}\rho_c\right]} \approx \frac{24\eta_c}{11\rho_c\left(\frac{3}{4\pi}\right)^{1/3}}$$

The Swope model

It is a very simple model. It is based on the dimensionless equation for determination of the bubble diameter (e.g.: Swope, 1971):

$$Fr \cdot d_E^{\ 5} + (1 - \frac{1}{We}) d_E^{\ 2} + (\frac{1}{We} - \frac{1}{\mathrm{Re}}) d_E - \frac{1}{12} = 0$$

where:

Froud number, $$Fr = \frac{g\pi^2 d_0^5 (\rho_c - \rho_g)}{24\rho_c \cdot Q^2}$$

Wezer number, $$We = \frac{4\rho_g Q^{\ 2}}{\pi^2 d_0^3 \sigma_c}$$

Reynolds number, $$\mathrm{Re} = \frac{3\rho_g Q\ (\mu_c + \mu_g)}{d_0 \mu_c \cdot \pi (2\mu_c + 3\mu_g)}$$

d_E – dimensionless diameter of the bubble, $$d_E = \frac{d_p}{d_0}$$

THE MEASURING SYSTEM

The measuring system includes an optical tomograph with the scattered light beam (e.g.: Rząsa et al, 2007). The beam is emitted from one point light source, and next detection is done within a radius of the beam scattering (Fig.2a).

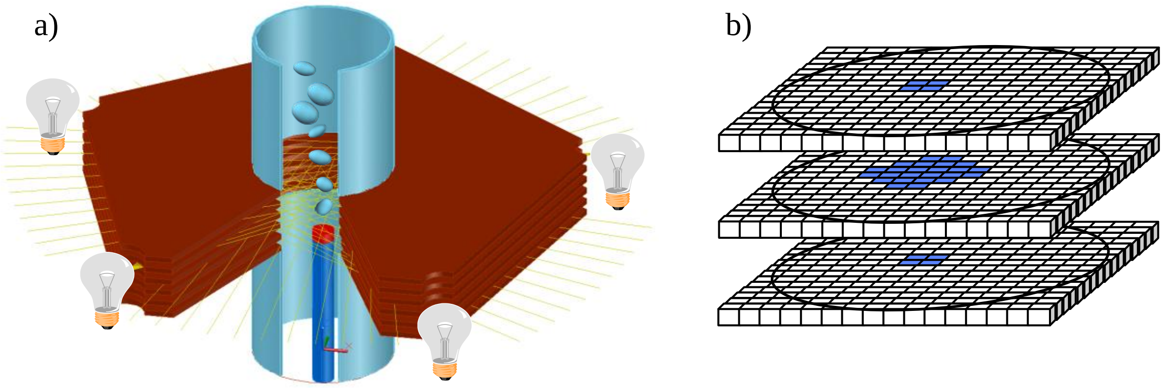


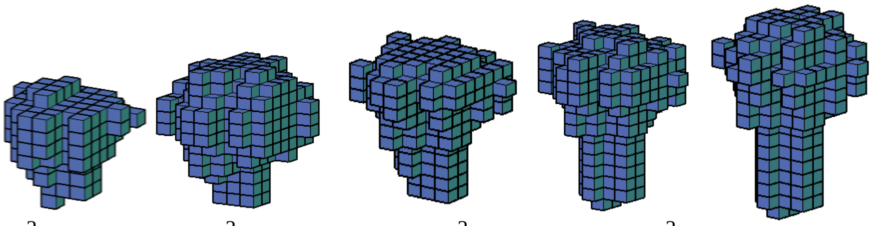
Fig. 2 Optical tomograph a) structure of the measuring system, b) idea of the shape reconstruction

The system included a pipeline 76 mm in diameter. Five light sources were located around the pipeline. A light bulb 55 W was a light source. The scanning planes were arranged at different distances along the pipeline axes, so it was possible to determine velocities of the moving objects. Sixty four phototransistors were used as detectors of the light beam for each of five projection.

The measuring space of the tompgraph was filled with water where a nozzle with a hole 2 mm in diameter was placed. Air was delivered from a gas cylinder, and the gas stream was measured by means of an electronic flow sensor AWM3100V made in Honeywell. The image reconstructed by the tomograph includes a regular net, particular pixels of which define range occupied by gas. Each successive frame of the image is registered with a constant time step (Fig. 2b). Thus, it is possible to reconstruct bubble shape and calculate its volume.

THE RESULTS OF MEASUREMENTS OF THE FORMING BUBBLE SHAPE

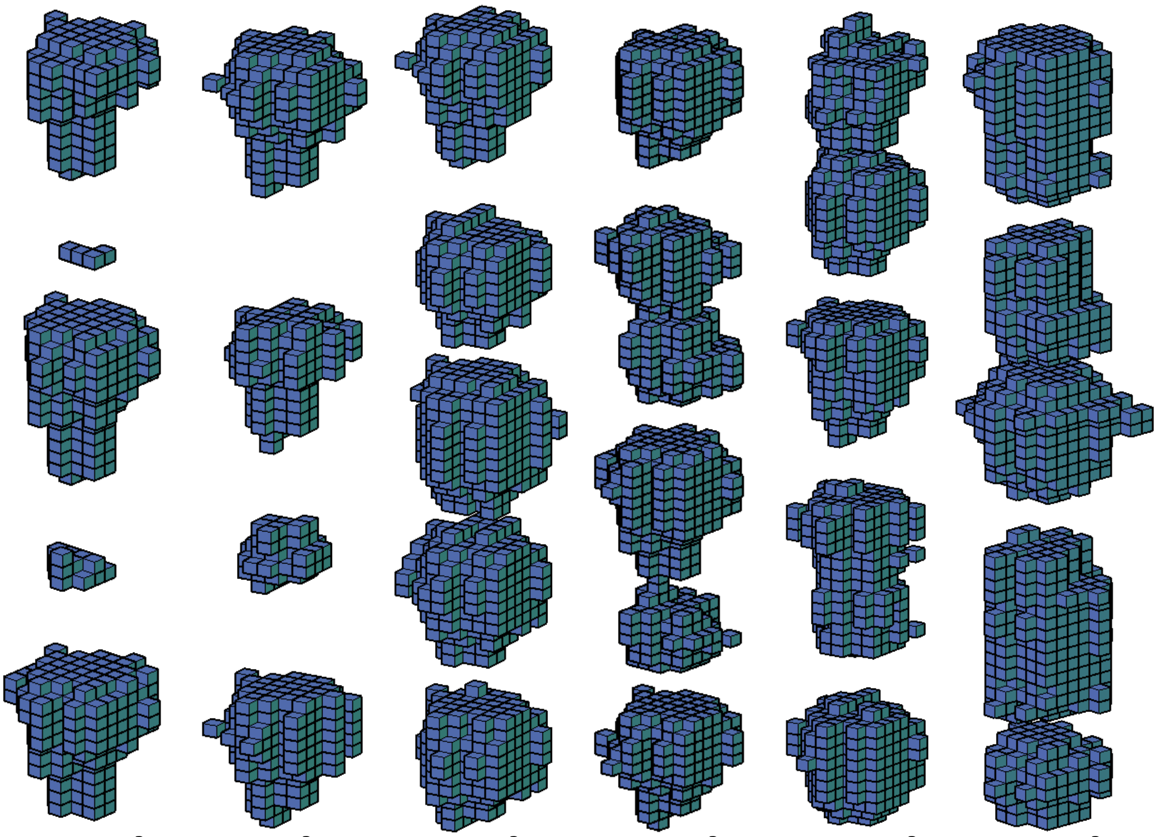
Under low gas flow rates, the bubbles are ball-shaped and they form at the nozzle edge. In practice, such phenomena take place only in the case of the gravitational gas flow. As the gas flow rate increases, the diameter of the forming bubble depends on not only the hole diameter but a value of the volumetric gas flow rate as well.



0.1cm^3/s 0.2cm^3/s 0.33cm^3/s 0.53cm^3/s 0.6cm^3/s

Fig.3 Results of measurements of the bubble shapes for the unrestricted flow

In the case of very low flow rates, the bubbles get out as groups of some or several bubbles, and next there is a break in their emission. As the gas flow increases, the breaks become shorter and a number of bubbles in one group increases. Bubbles take a characteristic ball shape with a cylindrical foot at the bottom (Fig.3). As the gas stream increases, this part becomes longer causing increase of the volume of the forming bubble.

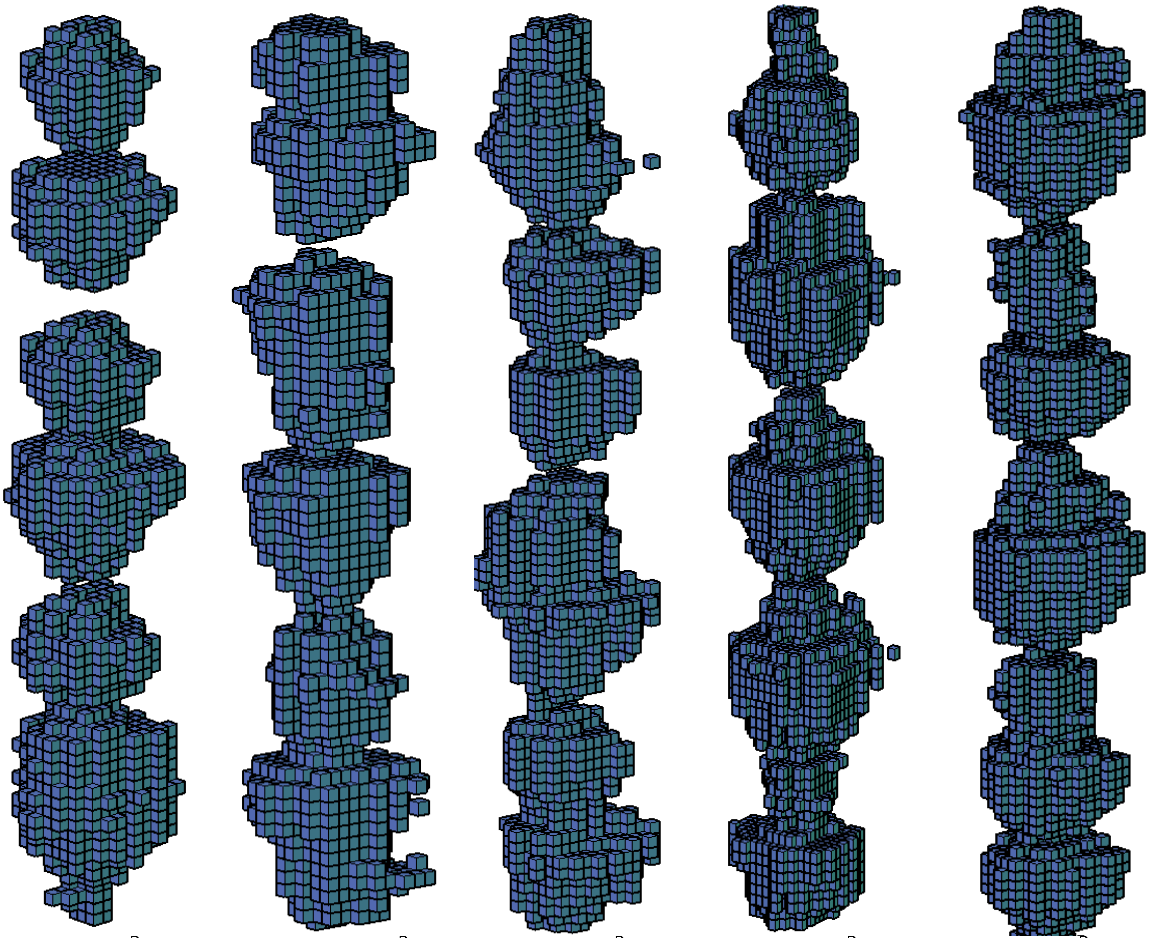


0.78 cm^3/s 1 cm^3/s 1.4cm^3/s 1.8 cm^3/s 2.5 cm^3/s 3.3 cm^3/s

Fig. 4 Results of measurements of the bubble shapes for the transient flow

Increase of the gas stream flowing from the nozzle causes increase of influence of dynamical forces on the bubble formation. It causes increase of the diameter of the spherical part and decrease of the cylindrical part (Fig.4). It is caused by the greater resistances to motion of gas flowing with high velocity. The liquid swirls caused by such a gas flow influence successive forming bubbles and cause differences in volumes and shapes of separating bubbles. We can observe formation of the ball-shaped bubbles with no the cylindrical parts. It is a beginning of the transient state leading to chain formation of bubbles.

During the transient flow, increase of the gas stream does not lead to a significant change of diameters of the ball-shaped parts of the forming bubbles. However, it influences the bubble formation intensity. Bubble formation in a short time, one by one, causes liquid circulation in the surroundings of the forming bubble. It causes formation of additional forces which deform forming bubbles. Irregularity in bubble formation and the gas flow increase become more intense, and the cylindrical part decays.



4.3 cm^3/s 5.25 cm^3/s 5.8 cm^3/s 6.9 cm^3/s 8 cm^3/s

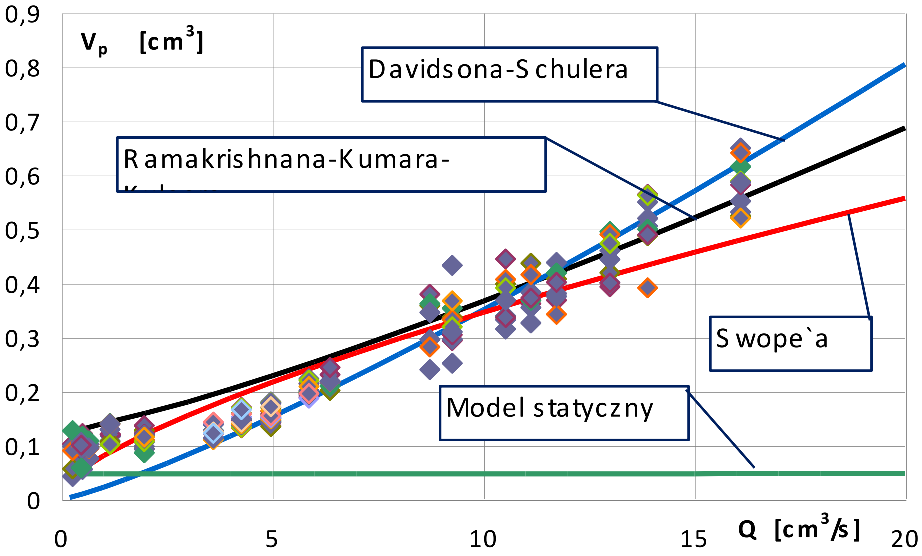
Fig. 5 Results of measurements of bubble shape for the chain flow

As the gas stream increases, turbulence of bubble formation increases, too. It is more difficult to define a point where the bubbles separate. At the nozzle tip there is a continuous gas flux which takes different shapes. We can observe characteristic chains which separate from the nozzle. Next, while motion, they divide into successive bubbles. Characteristic formation of the chains is shown in Fig. 5. As the gas stream increases, intensity of the bubble chain separation increases, too.

CONCLUSIONS

The realized measurements prove that the chosen measuring method for investigations of gas bubble formation is right. This method allows to measure both shapes and velocity of the forming bubbles in a wide range of the gas stream delivered to the nozzle. The method can be applied for investigations of gas bubbles forming at the slot or other devices for bubble distribution.

Theoretical models were compared with experimental data (Fig.6). The bubble volumes for different gas streams were measured by means of the optical tomograph, and three-dimensional images were applied for calculations of volumes of particular bubbles. In the figure, the solid lines mean the calculation results for the static model and models proposed by Davidson-Schuler, Ramakrishnan-Kumar-Kuloor and Swope. The theoretical results are different depending on the model. The static model can be applied only in the case of free formation of bubbles. The experimental results are included between divergences of theoretical models. It proves correctness of the models and convergence with the theoretical data. Some divergences of the measuring results for greater gas streams can be explained by non-stationary course of phenomena occurring during bubble formation. Moreover, the models assume bubble formation in a motionless water, and in practice, for great gas streams water does not remains at rest, but successive bubbles cause its circulation.



modal statyczny – static model, nazwiska – bez –a na końcu

Fig 6 Comparison of the measuring results obtained for volumes of the forming bubbles with theoretical models

REFERENCES

Davidson J.F., Mech A.M.I., Schüler B.O.G (1997).; *Bubble formation at an orifice in a viscous liquid*, Chemical Engineering Research and Design, Vol. 75, Supplement 1, December 1997, pp. S105-S115

Davidson J. F., Schuler B.O. (1960), Bubble Formation at an Orifice in a Viscous Liquid, Transaction of Institut of Chemical Engenering, 38, pp. 144-154.

Davidson J. F., Schuler B.O. (1960), Bubble Formation at an Orifice in an Inviscid Liquid, Transaction of Institut of Chemical Engenering, 38, pp. 335-342.

Dziubiński M., Prywer J. (2010): *Mechanika płynów dwufazowych;* WNT, Warszawa

Khurana A. K., Kumar R. (1969), *Studies in Bubble Formation—III*, Chemical Engineering Science, 24, pp. 1711-1723.

Kumar R., Kuloor N.R. (1970), *The formation of bubbles and drops,* Advances in Chemical Engineering Vol. 8 Academic Press, New York, London, pp. 255-368.

Orzechowski Z. (1990): *Przepływy dwufazowe jednowymiarowe ustalone adiabatycznie,* PWN Warszawa.

Rząsa M.R. (2002), *Dynamiczny przepływomierz do pomiaru bardzo małych przepływów gazu;* IV Sympozjum nt. Pomiarów dynamicznych; Gliwice 7-8 listopad 2002

Rzasa M. R., Grudzien K., Przywarski R., Romanowski A., Wajman R. (2007): *The Discrete Optical Tomograph Including Five Projections;* 5th World Congress on Industrial Process Tomography, Bergen Norway.

Rząsa M.R., Pląskowski A. (2003): *Application of optical tomography for measurements of aeration parameters in large water tanks,* Measurement Scince and Technology; Vol.14 No.2 pp. 199-204.

Rząsa M.R., Sawicki J. (2004), *A Flowmeter for Measurements of Very Small Gas Flows*, Sensors & Transducers Magazine Vol.40, Issue 2, pp.128-136.

Satyanarayan A., Kumar R., Kuloor N.R. (1969), *Studies in Bubble Formation - II. Bubble Formation under Constant Pressure conditions*, Chemical Engineering Science, Vol. 24, pp. 749-761.7

Swope, R.D. (1971), *Single bubble formation at orifices submergedin viscous liquids,* The Canadian Journal of Chemical Engineering, Vol.49, pp.169-174.