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Flow Field around Growing and Rising Vapour Bubble by PIV Measurement

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Abstract : A study on flow field measurement around growing and rising vapour bubbles by use of PIV technique is presented. Bubbles were generated from single artificial cavities. Experiments have been conducted with saturated boiling of distilled water at atmospheric pressure. In the experiment fluid velocity field surrounding the bubbles was visualized by use of polyamide tracer particles and a sheet of a YAG pulse laser beam. The images were recorded with a cross-correlation CCD-camera. It has been shown that for lower heat flux density bubble growths in an almost quiescent bulk of liquid. For higher heat flux density the train of bubbles creates a vapour column with strong wake effect. Maximum liquid velocity recorded is approximately equal to the terminal velocity of bubble rising in a stagnant liquid.

Keywords : Pool boiling, Bubble growth, PIV.

1. Introduction

In so called mechanistic approach of nucleate boiling modelling formation of bubble is of crucial importance, because successful prediction of the nucleate boiling heat flux requires a precise evaluation, among others, two key parameters, i.e. vapour bubble size and bubble release frequency. According to Dhir (1991) fluid motion in the vicinity of an active site can substantially alter the growth pattern as well as the waiting period, and as a result release frequency and diameter.

Bubble growth and departure was studied extensively in the past six decades (Zeng et al., 1993), among others. Quite recently a complete simulation of a growth cycle yielding velocity fields around growing bubble was presented (Bai and Fujita, 1999; Dhir, 2001). The influence of convection flow around growing and departing single bubble on heat transfer in the macro-region was studied by Genske and Stephan (2002). As usually, experimental validation of both analytical and numerical models is unavoidable.

High-speed photography has been applied in many laboratory experiments on bubble motion investigation, e.g. (Ivey, 1967). In recent years several laser techniques have been developed for measurements of bubble flow, among the latter are holography, the phase-Doppler method, Particle Tracking Velocimetry (Monji et al., 1999), and Particle Image Velocimetry (PIV) which is non-invasive measurement technique yielding quantitative, instantaneous velocity maps of the flow (Misawa and Ichikawa, 1998; Saad and Bugg, 2001), among others.

The majority of studies conducted with using of PIV technique has concentrated on the formation of gas bubbles (Maeda et al., 1998; Fujiwara et al., 2001), and very few studies on vapour bubble motion have been carried out (Arebi and Dempster, 1999; Qiu and Dhir, 2003). Only Kowalewski et al. (2000) and Pakleza et al. (2002) have applied the optical flow PIV method in order to compute velocity and temperature fields in the liquid during vapour bubble growth stage. The measurement system consists of CCD camera, strobe illumination and frame grabber (Quénot et al., 1998). Because of the colour play range (35ºC – red, and 38ºC – blue) of the termochromic liquid crystals used by Kowalewski et al. (2000) and Pakleza et al. (2002) as the tracers, the experiments with boiling of water were conducted at subatmospheric pressure.

Because of enormous complexity of boiling, even in a simple configuration, it is an acceptable practice up to day to investigate the process from a single artificial nucleation site (Shoji and Takagi, 2001; Cieslinski et al., 2002). Secondly, in order to visualize bubble motion, particularly using laser beam, it is necessary to create bubbles on definite points on the heating surface.

The fundamental difference between non-condensable gas bubble growth and departure in comparison with vapour bubble dynamics is heat and mass transfer exchange at the vapour-liquid interface, which makes the bubble formation process more complex.

In this study a flow field around growing, departing and rising vapour bubble in a pool of saturated water was investigated by use of PIV. In the experiment, velocity field was visualized by use of tracer particles and a sheet of a YAG pulse laser beam. The images taken by CCD camera were processed, and the velocity fields and the shape of bubbles were obtained. The experiments have been conducted with saturated boiling of distilled water at atmospheric pressure under controlled conditions (heat flux density and wall superheat). As nucleation site served artificial cavities drilled on the flat end of the copper rod.

2. Experimental Apparatus and Procedure

2.1 Pool Boiling Equipment and Bubble Generation System

The pool boiling rig used in this study is shown in Fig 1. Two inspection windows, at the perpendicular side-walls of the vessel were furnished for visual observations. The water level in the tank was maintained at about 120 mm above the heating surface. In order to suppress undesirable vibrations the entire apparatus was mounted on an optical bench supported on air cushions. The cavities were drilled on the flat end of the rod 8 mm in diameter made of electrolytic copper. The diameter of the cavities was 0.25 mm, 0.60 mm, and 1.0 mm and the depth was approximately 0.4 mm, 0.90 mm, and 1.6 mm, respectively. The heat flux density and the temperature of the heating surface were determined by using three thermocoax chromel-alumel thermocouples 0.25 mm in diameter placed along the axis of a heated copper rod. The readings from these thermocouples were extrapolated to give the surface temperature with good approximation. The heat flux density was calculated by using Fourier conduction equation with the thermal conductivity of the rod material.

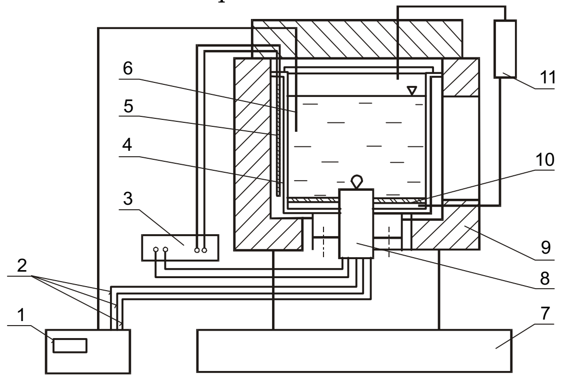


Fig. 1. Scheme of the boiling setup (not in scale): 1- logger Almemo 3290-8, 2- thermocouples, 3- power supply, 4- experimental vessel, 5-auxiliary heater, 6- thermocouple, 7- optical bench, 8- boiling section, 9- insulation, 10- acrylic plate, 11- condenser.

2.2 Laser and Optical Arrangement for PIV

The PIV images were obtained seeding the liquid with tracers and illuminating it with a laser light sheet. The 2Nd:YAG-laser can fire at about 7.5 Hz. The pulsed laser produces short duration (10 ns) high energy pulses of light with a wavelength of 532 nm (green). The energy of each pulse is 200 mJ. The light sheet optics transforms the beam from the lasers to a flat, diverging light sheet with a thickness of 0.7 mm in the focus point where the bubble is located. This very thin light sheet produces scattering light only in the plane of light sheet. The energy of the light sheet is set to low emission. In the images one can see a clear contour of the bubble. The bubble diameter is in the range between 1 and 3 mm. The tracer particles which indicate the fluid motion around the bubble are visible very close to the bubble surface and scatter enough light to be detected. The error of the obtained velocity values resulting from scattering of laser light on the bubble surface is very low. The synchronizer is the basic interface in the PIV- system. The synchroniser provides the universal timing control for all connected components. The images of the particles in the flow were recorded with a cross-correlation CCD-camera with a frequency 15 Hz. The resolution of the CCD-chip is 1000 x 1000 pixel. This camera is specially designed for capturing sequential frames with a very short time between them. Cross-correlation analysis can then be performed on the successive frames to obtain a two-dimensional flow field. The postprocessing of the obtained data is carried out with an additional program. The program calculates vector velocity field and corresponding streamlines. The neutrally buoyant polyamide seeding particles with a mean diameter of 5 μm were employed in the present study. The volumetric concentration of tracers was estimated to be below 10^{-4} so their effect is supposed to be negligible on the bubble dynamics.

3. Results and Discussion

Experiments were conducted with saturated boiling of distilled water at atmospheric pressure. The ambient temperature was 23.0±1 °C. The recorded pool temperature was 99.9±0,1 °C, heat flux density ranged from 0.4 W/cm^2 to 10.3 W/cm^2 and wall superheat changed from 1.8 K to 10.2 K. Generally the measurements were conducted with increasing heat flux density. The maximum error in heat flux density was estimated to be about ±15% and in wall superheat ±10%.

Figure 2 displays a vapour bubble just prior to – Fig. 2a), and just after detachment – Fig. 2b), from a drilled cavity of 0.6 mm in diameter. Characteristic is almost axisymmetrical shape of the growing bubble (Fig. 2a)). Figure 2b) gives an evident that succeeding bubble grows from a small amount of vapour which remains in a cavity from the previous one. Because of the surface tension action after the neck break the lower part of the bubble becomes flat.

a) b)

a) Bubble just prior to detachment b) Bubble just after detachment

Fig. 2. Bubble detachment from a cavity of 0.6 mm in diameter for Re = 499 and Ja = 24.

The dimensionless Reynolds and Jacob numbers are defined as follows

$$\mathrm{Re} = q\, b / \left(h_{fg} \rho_v v_l \right) \tag{1}$$

$$Ja = \frac{\rho_l c_{pl} \Delta T}{\rho_v h_{fg}} \tag{2}$$

where b is equal to

$$b = \sqrt{\sigma / [g(\rho_l - \rho_v)]} \tag{3}$$

As an example Fig. 3 displays flow pattern around growing vapour bubble. The green arrows show the direction of the liquid flow. After data processing vector velocity field and corresponding stream lines can be obtained – Fig. 4a) and Fig. 4b), respectively. Using the velocity scale in Fig. 4a) it can be concluded that for the discussed case (cavity of 1 mm in diameter and q = 2.8 W/cm^2) during the growing phase, the wake effect becomes negligible and bubble growth is most probably dominated by surface tension, liquid inertia and buoyancy forces. The maximum liquid velocity recorded is below 0.01 m/s – arrows of red colour.

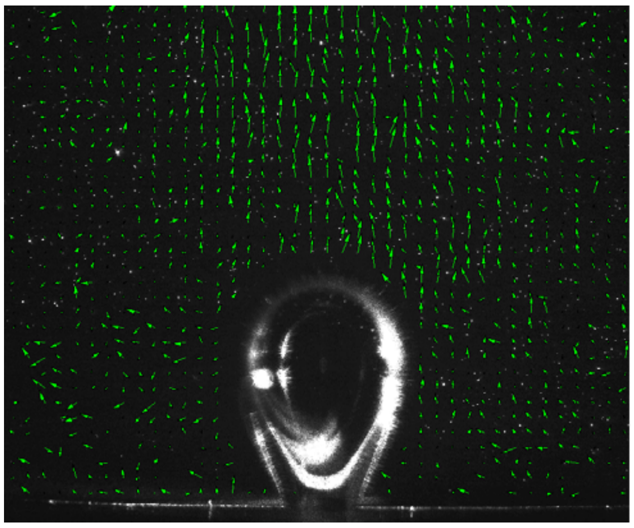
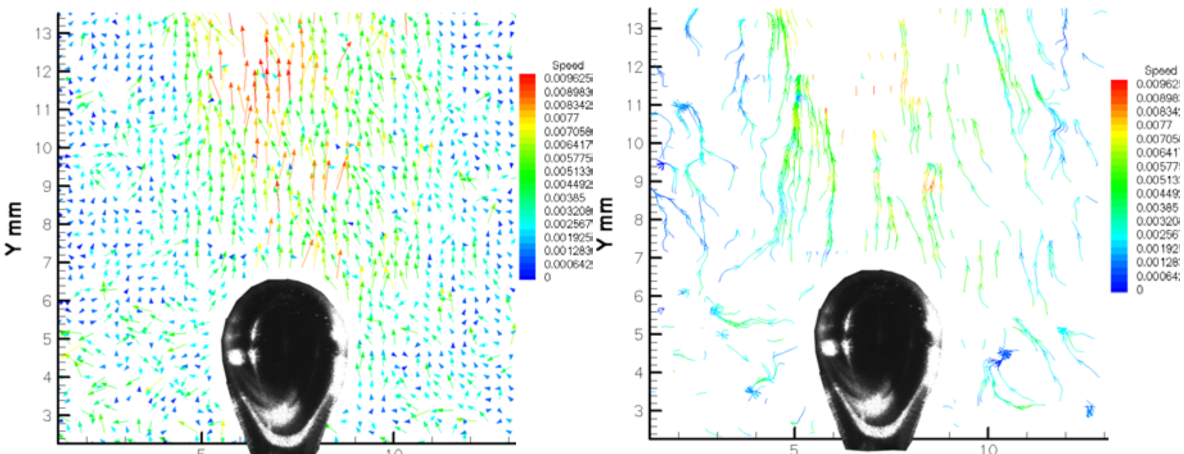


Fig. 3. Flow pattern around growing vapour bubble at a cavity of 1 mm in diameter for Re = 159 and Ja = 0.3.

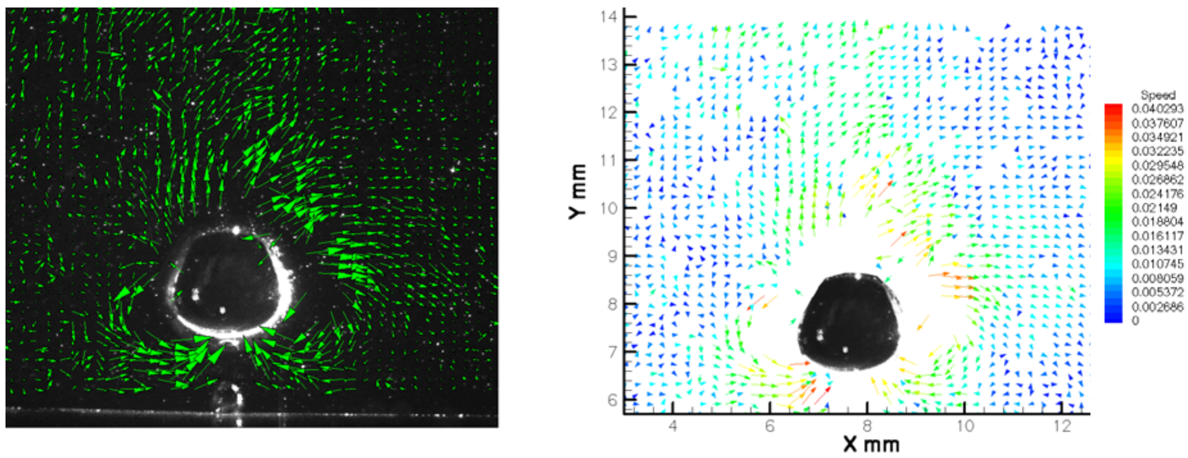


a) b)

a) Vector velocity field b) Stream lines

Fig. 4. Vapour bubble growing at a cavity of 1 mm in diameter for Re = 159 and Ja = 0.3.

Figure 5 presents velocity field around vapour bubble departing from cavity of 0.25 mm in diameter. Very strong liquid inflow into the wake can be observed as it was suggested by Mitrović (1983). Simultaneously, in the frontal portion of a bubble liquid is seen to be pushed upwards. The flow pattern presented in Fig. 5a) portrays almost exactly the concept of a *wake flow* envisaged by



a) Flow pattern

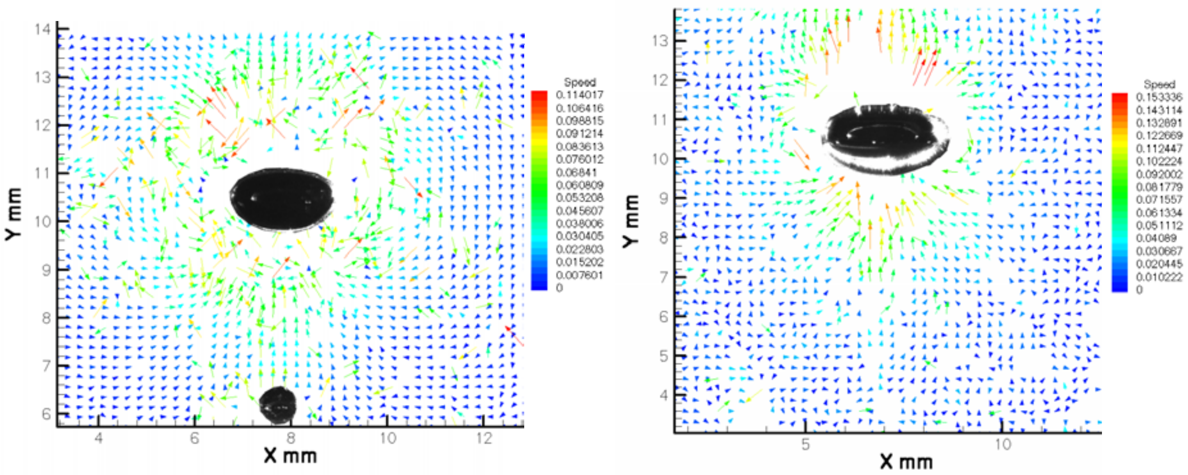
b) Vector velocity field

Fig. 5. Departing vapour bubble from a cavity of 0.25 mm in diameter for Re = 68 and Ja = 15.

Zuber (1963). The maximum velocity of the inflowing liquid as well as pushing away is equal to 0.04 m/s (scale in Fig. 5b)).

Figure 6 illustrates vector velocity field around rising vapour bubble for two cavities investigated – 0.25 mm and 0.60 mm. It is of great interest that the rising vapour bubble induced flow toward the vortex ring forming in the wake within a circle circa twice of its horizontal diameter. Such observation confirms assumption made by Han and Griffith (1965) that the area of influence is four times the projected area of the bubble at departure.

The velocity in the vicinity of a rising bubble – with maximum of circa 0.12 m/s (scale in Fig. 6a)) and 0.15 m/s (scale in Fig. 6b)) is an order of magnitude higher than in the bulk of liquid – below 0.01 m/s.

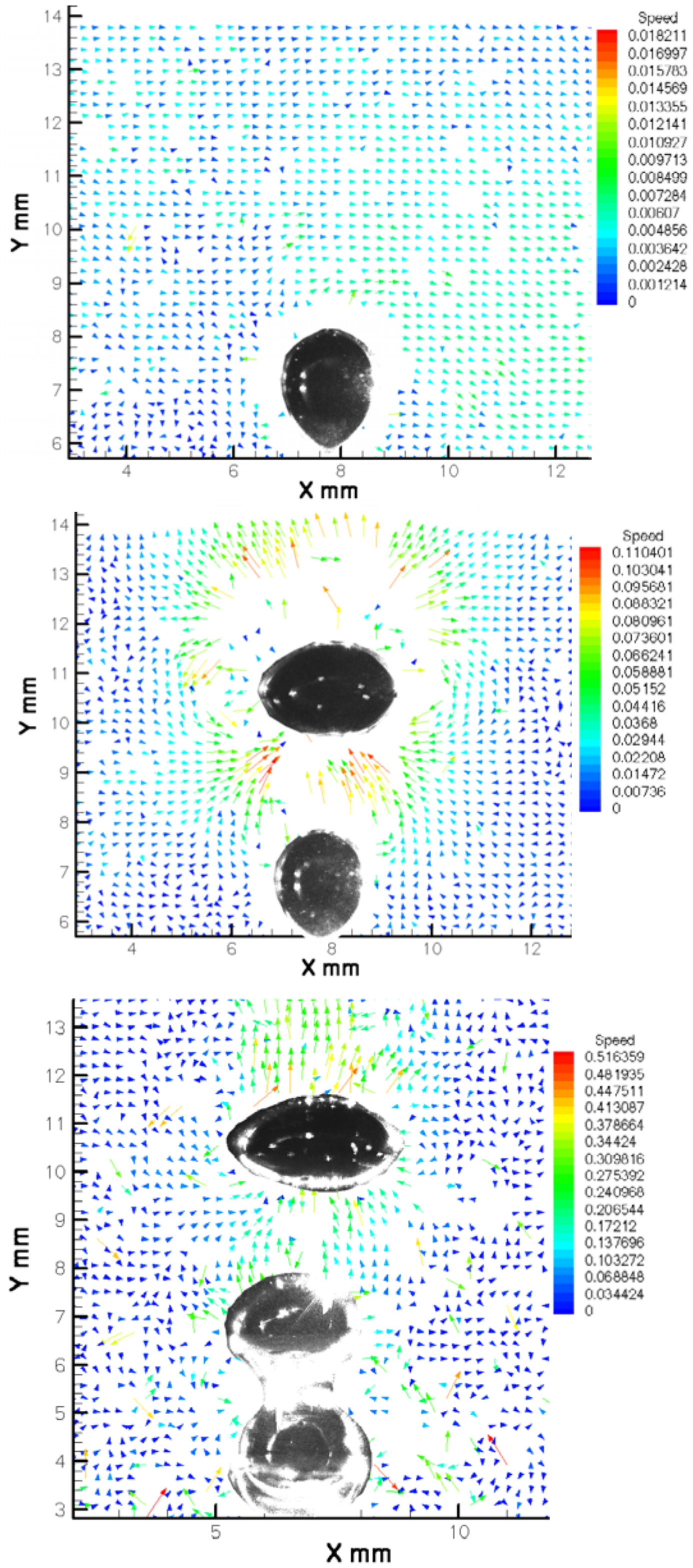


a) Cavity diameter - 0.25 mm, Re = 68 and Ja = 15

b) Cavity diameter - 0.60 mm, Re = 46 and Ja = 17

Fig. 6. Vector velocity field around rising vapour bubble.

Figure 7 illustrates influence of heat flux density on velocity field around growing and departing bubbles. For smallest heat flux density applied bubble growths in an almost quiescent bulk of saturated liquid – Fig. 7a). As results from a velocity scale in Fig. 7a) the maximum velocity of a liquid surrounding growing bubble is equal to 0.018 m/s. With increasing heat flux density bubble release frequency increases too and thus the distance between succeeding bubbles decreases – Fig. 7b).



a) q = 0.8 W/cm^2, Re = 46, Ja = 9

b) q = 1.2 W/cm^2, Re = 68, Ja = 15

c) q = 1.6 W/cm^2, Re = 91, Ja = 21

Fig. 7. Vector velocity field around growing and rising vapour bubble for cavity of 0.25 mm in diameter and increasing heat flux density.

Strong liquid inflow with velocity equal to 0.11 m/s can be observed in a wake of a rising bubble. It can be concluded that upper part of a growing bubble is influenced by the wake of a proceeding bubble. The flow pattern presented in Fig. 7c) portrays the concept of a *first transition region* proposed by Gaertner (1965) for higher heat flux density. It is worth noting, that train of bubbles creates a vapour column, and in the bulk of liquid a number of small vortical structures along this vapour column can be observed. Nevertheless, liquid velocity outside the vapour column is low – below 0.05 m/s. In the upper part of Fig. 7c) very strong wake flow - generated by bubble which is not seen in Fig. 7c), is observed. Liquid velocity in this area (circa 0.3 m/s) is equal to the terminal velocity of bubble rising in a saturated liquid as established by Celata et al. (2001).

4. Conclusion

In the present work PIV technique is used to study flow field around vapour bubbles growing and rising in a saturated distilled water under atmospheric pressure. The 2Nd:YAG-laser coupled with a cross correlation CCD-camera has been applied in order to take the images. Bubbles were generated from a single artificial cavities under controlled thermal conditions. Vector velocity fields have been obtained for three stages of bubble dynamics: growing at cavity, just after detachment and during rising in a bulk of liquid. Depending on heat flux density different flow patterns have been observed. For low heat flux density bubble grows in an almost quiescent bulk of liquid. For higher heat flux density the train of bubbles creates a vapour column. Maximum liquid velocity recorded is approximately equal to the terminal velocity of bubble rising in a stagnant liquid. Results obtained can serve for validation of both analytical and numerical models of bubble growth and departure. However, despite of effort made, volumetric illumination around a bubble introduces uncertainty to measurement of the velocity field in the close vicinity of bubble interface. Further development work is needed to apply the PIV technique to study vapour bubbles dynamics.

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