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EXPERIMENTAL ANALYSIS OF VAPOUR BUBBLE GROWING ON A HEATED SURFACE

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ABSTRACT

Using high speed video camera and numerical processing of the digital images transient description of the geometry and the interface velocity for vapour bubble growing at the heated surface is achieved. Particle Image Velocimetry and Thermometry are applied to obtain details about velocity and temperature in the surrounding flow field.

Keywords: vapour bubble, evaporation, high speed imaging, PIV & T.

INTRODUCTION

From the recent numerical simulations it is possible to generate solutions describing bubble growth from inception to departure without any assumption being made about the bubble shape but axial symmetry and more or less realistic modelling of the wall contact line. To validate these simulations suitable experimental data are required. The bubble shape, the growth rate or the radius of the dried area that are usually employed for comparison are still useful but need to be completed by measurements of additional quantities. In the following we describe summary of experimental investigations of vapour bubble growth performed in our two laboratories. An image analysis is performed and yields an accurate determination of several relevant parameters. Specific attention is devoted to describe dynamics of the moving bubble. Deformation of the interface and frequently observed shape oscillations are analysed to estimate the interface temperature. Velocity and temperature fields in the liquid phase are also visualized seeding the fluid with thermochromic liquid crystals.

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1. EXPERIMENTAL APPARATUS AND PROCEDURE

Isolated bubbles are generated on a horizontal surface inside a 30 cm^3 cube shaped cavity. The working fluid is water boiling under sub-atmospheric pressure. Some experiments are performed for methyl alcohol and PP1 under normal atmospheric pressure. All six walls of the cube are equipped with optical openings for observation or illumination of the internal chamber. In the present experiments the bottom opening is used to mount an electrical heater of a brass plate used for bubbles generation. By changing the metal part of the heater the boiling area can be varied in the range of 1 to 20 mm. The cell construction allows for experimentation in the low-pressure environment. The system pressure was controlled in the range 1 – 100 kPa using a vacuum pump and a 0.5m^3 reservoir [1].

Back light illumination is applied to obtain images of a well-defined bubble interface. For this purpose both a strobe light or a halogen spot lamp are used. The field of view is approximately 3 mm x 3 mm. Several acquisition methods are used to collect images. The high resolution 8-bit images of 768x544 pixels are acquired by standard 50 Hz camera and frame-grabber. Stroboscopic illumination used at steady thermodynamic conditions in the cavity allows us to obtain sequences of high resolution images of bubbles appearing on the heater with a constant period. To verify temporal resolution of the stroboscopic method and to obtain precise description of the selected time regime the multi-exposure is used, with typical 4 – 6 single images overlapping on each frame. Such images after appropriate image filtration and analysis procedure are merged to describe temporal development of the interface. A precise description of the bubble growth process is achieved using a Fastcam-HS40 high speed video camera running from 4500 (full frame) up to 22.500 frames/s. Using this camera up to 8000 images of 256 x 256 pixels are acquired for each run. These images give valuable information on the dynamics of bubble growth and departure, however less accurate in the near wall regions due to the limited spatial resolution of the camera.

A typical image of the bubble observed in the bright field of the parallel light shows dark shadow of the central cross-section with an additional bright spot at the centre. To describe properly the bubble shape, the edge extracting technique is applied to distinguish the external contour and its contact with the heating surface, to connect extracted points and to find a smooth functional representation of the pixel set for the further analysis. This description is used to define the bubble shape and contact angles and assuming axial symmetry of the bubble to calculate its volume. After departure vapour bubbles usually exhibits ellipsoidal shape, which can be well approximated by series of Legendre polynomials. Their coefficients describe degree of deformation for each oscillation mode. The main oblate-prolate deformation of the sphere is given by the amplitude $a_2(t)$ of the fundamental oscillation mode. This method of shape description, already successfully applied to oscillating liquid droplets [2], allows for direct comparison of the shape dynamics with analytical models for free oscillating bubbles. We hope that analysis of these oscillation can deliver information about variation of the surface tension and indirectly indicate variation of the interface temperature.

The flow visualization around the bubble is performed seeding the fluid with thermochromic liquid crystals. Illumination is realized with a 1 mm light sheet: a halogen light source is located perpendicularly to the optical axis of the 3 CCD colour camera. The 24-bit images of 576x574 pixels correspond to a field of view of 7.1 mm x 7.1 mm. These images are used for the temperature and velocity evaluation (Particle Image Thermometry and Velocimetry [1]).

2. SELECTED RESULTS

Figure 1 shows typical history of the single vapour bubble observed at low pressure conditions using high speed video imaging. The bubble generation starts at the nucleation site of the wall in the superheated layer of liquid. The measured superheat of the wall necessary to obtain vapour bubbles is about 15K. Due to the back light illumination, cross section of the bubble appears as a dark shadow. The first observable bubbles have diameter of about 30um, far above the inertia controlled growth range, described by the simplified Rayleigh model. The initial growth time is much shorter than the temporal resolution of our system, and measured growth time is close to the total growth time. The bubble presented in Figure 1 displays a hemispherical shape then turns very rapidly ($\approx$0.7 ms) to a truncated spheroid. Afterwards, the bubble grows regularly without any significant modification of its form. At time of about 6 ms, the bubble base shrinks that finally leads to the departure process. The whole bubble growth, from time inception to lift-off from the wall takes about 10 ms. Temperature of fluid above the wall boundary layer is about 4K below saturation temperature. Intensified by the bubble motion cooling of the interface initiates rapid vapour condensation and finally bubble collapses almost completely. The remaining small residual vapour bubbles have diameter of about 15 um, close to the system spatial resolution. But before the final bubble implosion takes place a few volumetric oscillations can be observed. Such oscillations can be responsible for generation of acoustic waves. Figure 2 collects main characteristics of this experiment depicted form the sequence of images. The bubble volume is computed assuming an axial symmetry and D_0 – diameter of the equivalent sphere is plotted together with its base diameter D_b and distance from the bottom for the bubble centre of mass H. The growth of the bubble may be divided in three main stages. A first one where all quantities increase with time. This corresponds to the early period ($0 < t \leq 2.5$ ms) where strong vaporization is observed, associated with a hemispherical growth. A second one where D_B gets smaller while D_0 still increase ($2.5\ \text{ms} \leq t \leq 7.2$ ms). Afterwards the bubble base starts to shrink, the vapour production is not strong enough to balance the deficit at the base, and the bubble diameter D_0 decreases. One may see that only during the first 6ms evaporation exceeds condensation and the net volume of the bubble grows. During this time history of the bubble diameter D_o follows very closely $t^{1/2}$ diffusion controlled regime. This variation of the diameter as well as that of the base diameter looks qualitatively very similar to numerical prediction of Fujita and Bai [3].

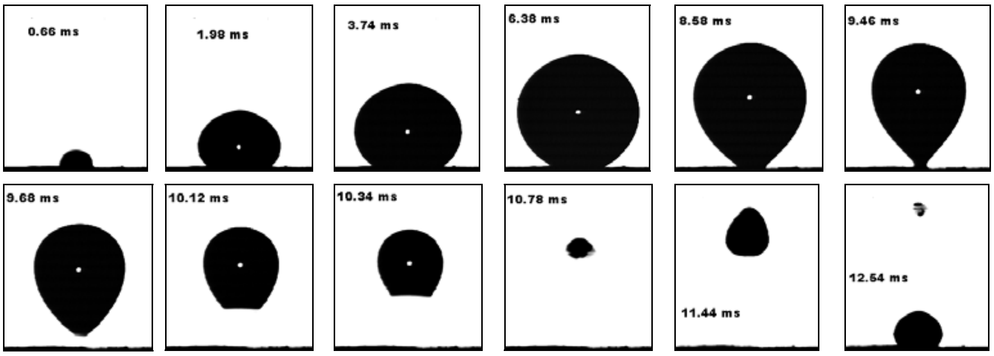

Fig. 1. Growth process of a vapour bubble (water P = 4 kPa, T_l = 25.1°C, T_s = 21.7°C) observed at 4500 frames/s by high speed camera. Frames shown at few selected time steps. Bubbles are generated at the hot spot of 1.42 mm diameter. The frame width corresponds to 2.9 mm

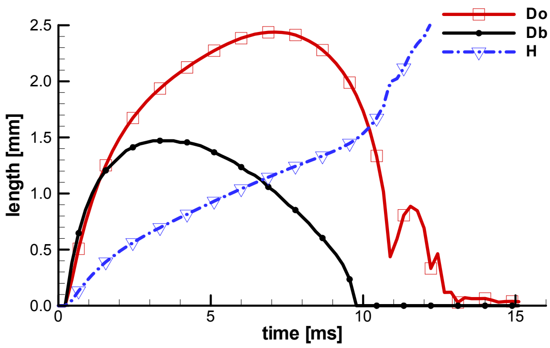

Fig. 2. Time history of the bubble equivalent diameter D_0 (squares), base diameter D_b (circles) and height H of the bubble centre of mass evaluated from the sequence of 86 images of the experiment shown in Figure 1

The optical flow based PIV method [4] is used to evaluate local displacements of the contour from tracer-less images of growing vapour bubbles: for each image, the set of pixels corresponding to the bubble contour is first identified. Then, considering two consecutive images separated by a time step of 0.22 ms, the velocity is computed at any point (pixel) of the bubble edge. This calculation is displayed in figure 3 for images from the above described experiment. Initially the growth rate of the bubble is nearly uniform, bubble expands radially outwards displaying this way a hemispherical shape. The highest displacement speed, observed at earliest stages reaches 1.5 m/s. After about 6ms growth rate significantly decreases and becomes restricted mostly to the upper part of the bubble surface. The lower part of the edge, corresponding to the bottom third of the bubble height, is no longer exposed to vaporization and looks motionless. After about 8ms the buoyancy starts to elongate the bubble and its lower part is pushed back by the liquid. The bubble no longer expands. The last picture (t = 9.33 ms) shows the bubble just before departure, the contact area being nearly zero. The surface speed is negative everywhere and its magnitude is not uniform: the bubble cap looks nearly motionless while the bottom edge contracts by surface tension at increasing velocity (≈-0.3 m/s). Similar behaviour of the interface can be found in the numerical simulations by Fujita and Bai [3].

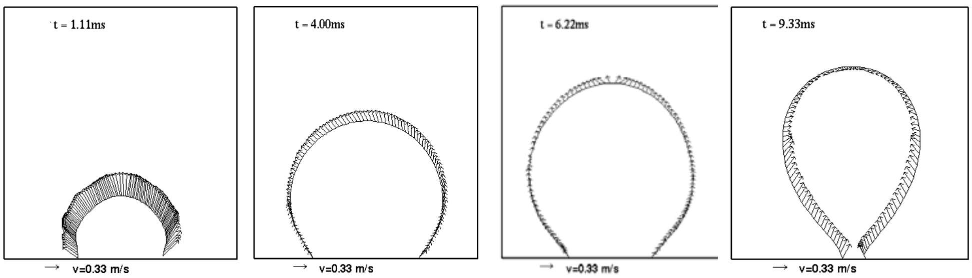

Fig. 3. PIV evaluated velocity at the bubble edge. Computations are performed considering two consecutive frames taken at the time interval 0.22 ms

Observations of vapour bubbles departing from the surface and quickly collapsing in the upper, colder fluid layers indicate that during this period very often the rising velocity rapidly increases. Sudden change of the added mass obviously accelerates imploding bubble. Figure 4a exemplifies this effect, with strongly decreasing volume, the bubble velocity almost triples before its final size is stabilized. Strong shape oscillations of bubbles departing from the surface are often observed, particularly for alcohol and PP1 boiling under normal atmospheric pressure. Figure 4b shows temporal variation of the deformation parameter a_2, representing second mode of the Legendre representation for the bubbles shape. We may find that initially elongated shape (positive values of a_2), changes to flattened shape as the bubble accelerates. Several characteristic local maxims of the deformation describe observed shape oscillations. The frequency of these oscillations is directly related to the known bubble dimension and to the surface tension. The last parameter strongly varies with temperature and by proper analysis of the phenomenon can be used as an indicator of the surface supercooling.

The velocity and temperature fields in the liquid phase were investigated applying PIV&T technique. The velocity fields are computed considering the motion of liquid crystal particles and variation of their colour (hue) is analysed to obtain temperature field. An example of such evaluation is given in Figure 5. The main feature revealed by the tracers is presence of the convection pattern in the cavity induced by temperature gradients and motion of bubbles.

a) b)

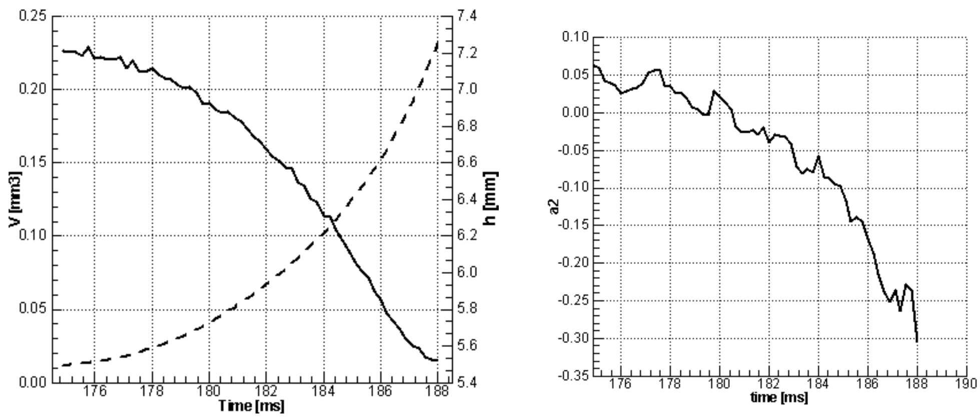

Fig. 4. Methyl alcohol vapour bubble departing from the heated surface under atmospheric pressure: a – volume (solid line) and vertical position of the bubble (dashed line); b – deformation parameter a_2.

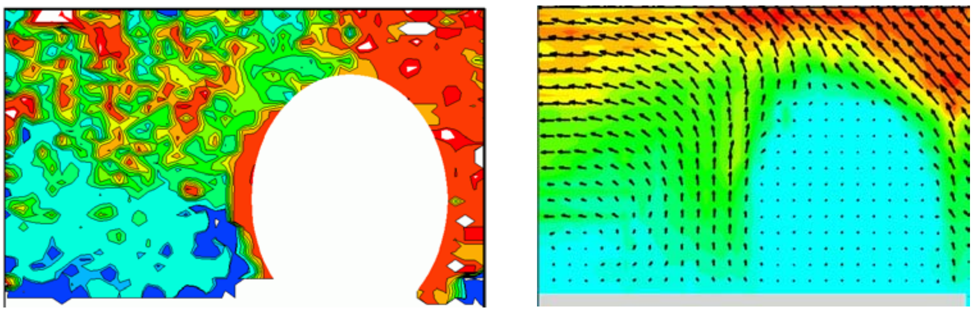

Fig. 5. Vapour bubble of water growing at the heated surface: P = 5.3 kPa, T_l = 35.5°C, T_b = 66.5°C. Evaluated temperature field (left) varies from 35-37.5°C, PIV evaluated velocity(right) has maximum magnitude 3 mm/s

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