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VISUALIZATION OF VAPOR BUBBLE GROWTH

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ABSTRACT

The growth of a single microscopic water vapor bubble under low-pressure condition at the heated surface is investigated experimentally. Details about the shape development of the bubble and velocity of the interface are studied using an image-processing scheme specifically developed for this purpose. The interface velocity is evaluated using an optical flow based PIV technique. The flow seeded with thermochromic liquid crystals is used to evaluate velocity and temperature fields surrounding the bubble. It is found that under the investigated conditions observed bubbles usually exhibit non-spherical shape. The bubble detachment precedes development of a neck-like structure. In many details it recalls images of large air bubbles moving through a very viscous fluid or the break-up of a liquid jet.

1 INTRODUCTION

Modeling heat transfer during nucleate boiling is essential for many industrial processes. Despite a large number of studies devoted to this phenomenon during the last fifty years the problem is still far from being completed. In fact, numerous attempts have been undertaken to develop a general correlation for nucleate boiling heat transfer, but none has led to a satisfying result in a broad range of governing parameters. One of the still unsolved problems is the proper description of the process of formation, growth and detachment of a single vapor bubble. This fundamental problem for the boiling process phenomenon appears to be very difficult both for experimental investigations and for theoretical or numerical modeling. In the modeling of bubble detachment characteristics, a challenging thermodynamic problem must be solved. On the one hand, vapor bubble evolution involves complicated liquid and vapor flow against an unknown moving boundary. On the other hand, this flow is greatly influenced by at least three heat fluxes: from the bulk fluid around the bubble, from the hot solid surface through hypothecate liquid microlayer and from the vaporization at the interface. Heat transfer is, in turn, strongly affected by the flow. Solution of this complex, nonlinear problem appears intractable without drastic simplifications substantiated by empirical data. However, due to experimental difficulties most thermal and dynamic details concerning the growth and detachment of a single vapor bubble are rarely available. With this objective in view, in the following we describe our attempts to develop or adopt new experimental techniques for improving quantitative analysis of the dynamic development of a single vapor bubble. Our present work mainly concerns the development of the experimental apparatus and methodology. The microscopic observations supported by high-speed illumination system, CCD camera, and frame grabber are used to obtain a quantitative description

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of the vapor bubble interface dynamics. Seeding of the fluid with thermochromic liquid crystals is used to visualize the temperature and velocity fields surrounding the bubble. The experiments are performed for water boiling in a low-pressure environment inside a small cube shaped cavity.

2 EXPERIMENTAL PROCEDURE

Measurements of bubble growth are conducted for distilled water boiling in a low-pressure environment on a heated horizontal surface. The vapor bubbles are generated inside a 30cm^3 cube shaped cavity (Fig. 1). Our primary aim was to conduct bubble observations from two directions simultaneously, recording its shape through the side window and the wetting area through the bottom opening. For this purpose all six walls of the cube are equipped with optical openings for observation or illumination of the internal chamber. To allow for vapor condensation the upper opening is armed with 10cm long glass tube (see Fig. 1). The bottom opening is used to mount a heater. In order to observe the bubble detachment through the heated surface, a sandwich of two glass walls with hot water circulating between them is used to create the heater. However, problems with stabilizing the bubble position at the glass surface forced us to use non-transparent heaters. Two types of specifically modeled brass plates were prepared to replace the glass sandwich. The brass plate is pressed into insulation material (Teflon) and mounted in such a way that only a small metal surface comes out into contact with the water filling the cube interior. The electrically heated metal rod attached to the external part of the brass plate is used to control its temperature. Such construction of the heater seems to be favorable to ensure precise control of temperature of the heated surface and to obtain stable generation of vapor bubbles. By changing the metal part of the heater two diameters of heated surface are used in the present experiments: 0.2mm and 1.2mm.

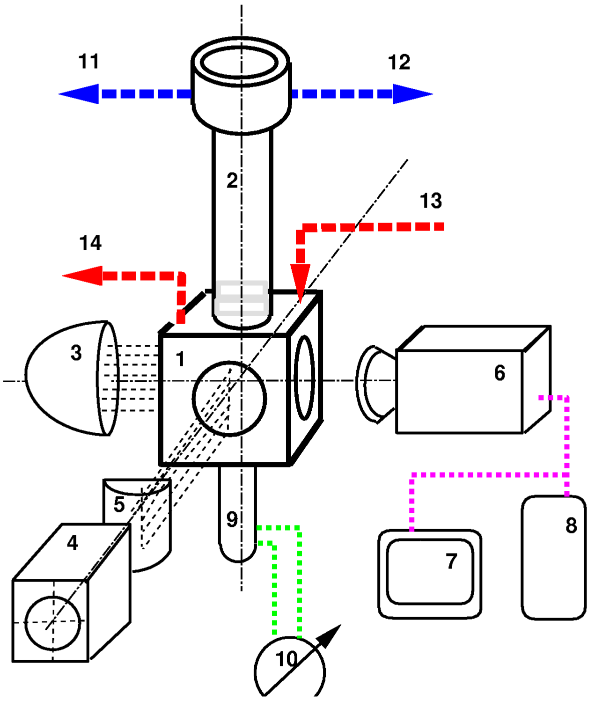


Fig.1 **Schematic diagram of the experimental apparatus: 1- cube cavity with glass windows; 2 – condensation tube with the glass window; 3- strobe illumination; 4, 5 - halogen lamp with a cylindrical lens; 6 – CCD color camera; 7 – monitor; 8 – PC with frame grabber; 9, 10 – electrically heated rod with power supply; 11, 12 – connection to vacuum system and liquid supply; 13, 14 – water supply from the thermostat**

The six walls of the cavity are equipped with several internal passages for water circulation from the thermostat. It allows for maintaining the cavity and the fluid inside at constant temperature within ± 0.1^{o}C. In the experiments the bulk temperature of the liquid T_l varies in the range 30^{o}C – 42^{o}C. The temperature of the heated surface T_b is in the range 41^{o}C - 76^{o}C and that of the hot rod from 70^{o}C -190^{o}C. The temperatures are measured using K-type thermocouples.

The cell construction allows for experimentation in the low-pressure environment. The system pressure P was controlled in the range 1kPa – 10kPa using a vacuum pump and a 0.5m^3 reservoir. The system used allows for keeping a constant pressure in the cavity for more then 20 hours. Our aim is to perform well-controlled boiling of water in its own vapor environment. Hence, special care was undertaken to evacuate the cavity before the experiments. Also the liquid was degassed for about 2 hours before each experimental run. However, some deviations from the saturation curve, noticed during present experiments indicate that small amount of air could still be present in the system, changing the partial pressure of vapor.

The bubble and flow in the cavity can be observed through six (five, when the brass heater was used) glass windows. In the present experiment the bubble was observed through one of the side widows using a 3CCD-color camera. To obtain images of a well-defined bubble interface back light illumination is applied using the opposite window. For this purpose both a strobe light and a halogen spot lamp are used. The second light source equipped with the halogen lamp is located perpendicularly to the optical axis of the camera. It is used to produce a 1mm light sheet for flow visualization around the bubble. The 24-bit images of 768x544 pixels are acquired by the three-channel color frame-grabber on-line into the computer memory.

The bubbles are observed through a 50mm lens using an extension tube. A typical bubble diameter is about 2mm, and the mean velocity of the interface exceeds 0.1m/s. It means that the relative velocity in the plane of the CCD sensor is very high, requiring short illumination time and high-speed imaging. To obtain sharp images of the interface when a halogen light was used we applied the electronic shutter of the camera with a typical opening time 4ms. The strobe illumination from a standard stroboscopic lamp was used to study bubble dynamics. The steady thermodynamic conditions in the cavity allow us to obtain very stable, regular production of bubbles appearing on the heater with a constant period. The typical frequency of bubble generation is about 20Hz. For a standard video camera this frequency is slow enough to acquire single images but too high to analyze the bubble detachment process. However, using strobe illumination and synchronizing its pulses with the bubble generation frequency almost steady images could be obtained. By slight variation of the strobe frequency a stroboscopic beat-frequency technique [1] could be applied. By this means, the stroboscopic observed phenomenon slowly changes its phase, extending the recorded period of the bubble generation into several video frames.

3 IMAGE ANALYSIS

As mentioned before, two systems of illumination are used. The parallel light beam is used for the backlight projection to analyze dynamics of the bubble interface. 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 center. 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 further analysis. A filtering / thresholding technique specially designed is used to identify bubble edges. It is based on applying a modified two-dimensional Kirsch operator with a small mask (3x3 or 5x5 pixels) rotating along the analyzed edge. By selecting optimal number of iterations and mask size it is possible to obtain a well defined one pixel thick representation of the bubble edge. In the second step, pixels representing the edge are used to find a functional interpolation of the bubble shape with Bézier polynomials. In the fitting procedure developed only one initial point is required to start the search for the best fitting curve. The surrounding pixels are then analyzed step by step and optimal continuation of the Bézier polynomial is selected. The method allows us to obtain smooth (up to the second derivative) representation of the bubble cross-section. This description is used to define the bubble shape and contact angles and, assuming axial symmetry of the bubble, to calculate its volume [2].

The sequence of images taken at a constant time interval is used to evaluate the velocity of the interface. We are interested to find precise description of the local interface velocity, i.e. to obtain tangential and normal components of the velocity vector attached to the surface. The tangential component describes local deformation of the bubble and its behavior may explain the effects of the temperature non-uniformity or of surface tension variation. The normal velocity component describes the "growing process" of the bubble. Both velocity components depend on the vapor production, the local pressure and also the buoyancy force acting at its surface. In view of the above the image correlation technique is applied to determine temporal and spatial evolution of the local velocities of the interface of a vapor bubble growing at the heated surface. The recently developed optical flow based PIV method [3] is used to evaluate local displacements of the interface from tracer-less images of growing vapor bubbles. The chosen technique is based on matching of elastic image strips (either horizontal or vertical). Using an analytical description of the contour, the interface velocity can be calculated at any arbitrary point defined by Bézier polynomials, not necessarily at a pixel location. It allows us to find a smooth distribution of the velocity vector field along the bubble perimeter (Fig. 2). A well-defined, analytical form of the bubble contour permits easy and accurate evaluation of both tangential and normal velocity components. More details can be found in Kowalewski et al [2].

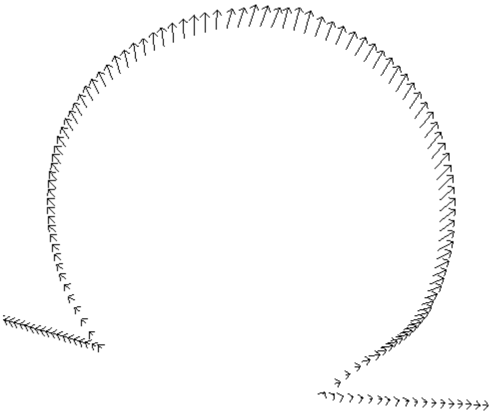


Fig. 2. **Velocity vectors evaluated at the bubble interface [2]**

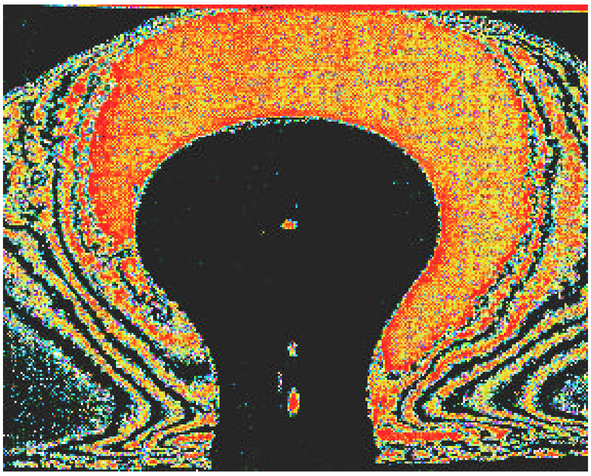


Fig.3 **Visualization of the temperature field of liquid during the vapor bubble detachment**

The parallel light beam passing close to the hot surface and bubble interface deflects due to the variation of liquid refractive index caused by temperature. This effect can be used to visualize the temperature variation (integrated across the cavity) from shadowgraphs of the bubble (Fig.3). However, quantitative interpretation of the shadowgraphs is difficult. We expect to obtain precise temperature evaluation by color analysis of the liquid crystal tracers used for the flow seeding. The 1mm light sheet perpendicular to the camera axis allows for the acquisition of images of the flow field surrounding bubbles. These images are used for the velocity and temperature evaluation (Particle Image Velocimetry and Thermometry [4]). Particle Image Velocimetry is based on the temperature-dependent reflectivity of the tracers. When illuminated by white light their color changes from blue to red within a well-defined temperature variation. In the present experiments unencapsulated tracers with a mean diameter of 25μm and the color play range 36°C (red) to 39°C (blue) are used to visualize temperature distribution in the flow. As the volumetric concentration of tracers is very low (below 10^{-5}) we believe that their effect on the bubble creation process is negligible. At least we have not discovered any differences comparing images of bubbles generated with and w/o seeding. The local fluid temperature is determined by relating the color (hue) to a temperature calibration function [4], obtained from images taken for the same illumination conditions. During the present experimentation it appeared that application of this technique to the images of vapor bubble is obscured by very strong diffuse light reflected from their highly reflecting surface. This effect could be only partly attenuated with help of the polarization filter. Hence, in practice the resulting images can be used to determine the fluid temperature only at distances not closer than about 0.3mm from the bubble surface.

Two subsequent images of the tracers are used to measure the 2-D velocity field distribution by the Particle Image Velocimetry (PIV) method previously mentioned. For this purpose, the color images of the tracers are transformed to B&W intensity images. After applying special filtering techniques bright images of the tracers, well suited for PIV, are obtained.

To get a general view of the flow pattern, several images recorded within a short period of time are added in the computer memory. A similar effect is achieved by long time exposure of a single video field. For low concentration of tracers displayed images show complexity of the flow, with large number of local vortices generated after bubble departure. Such fine structures cannot be detected by PIV technique using a standard resolution camera.

PRELIMINARY RESULTS

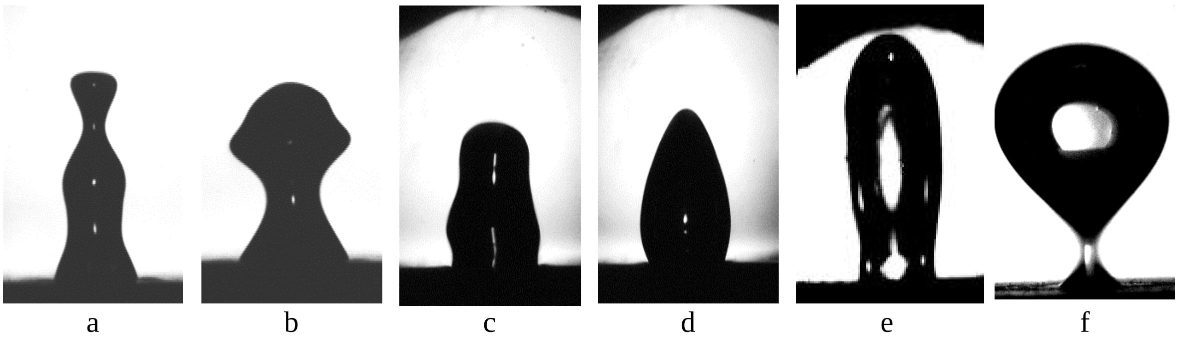
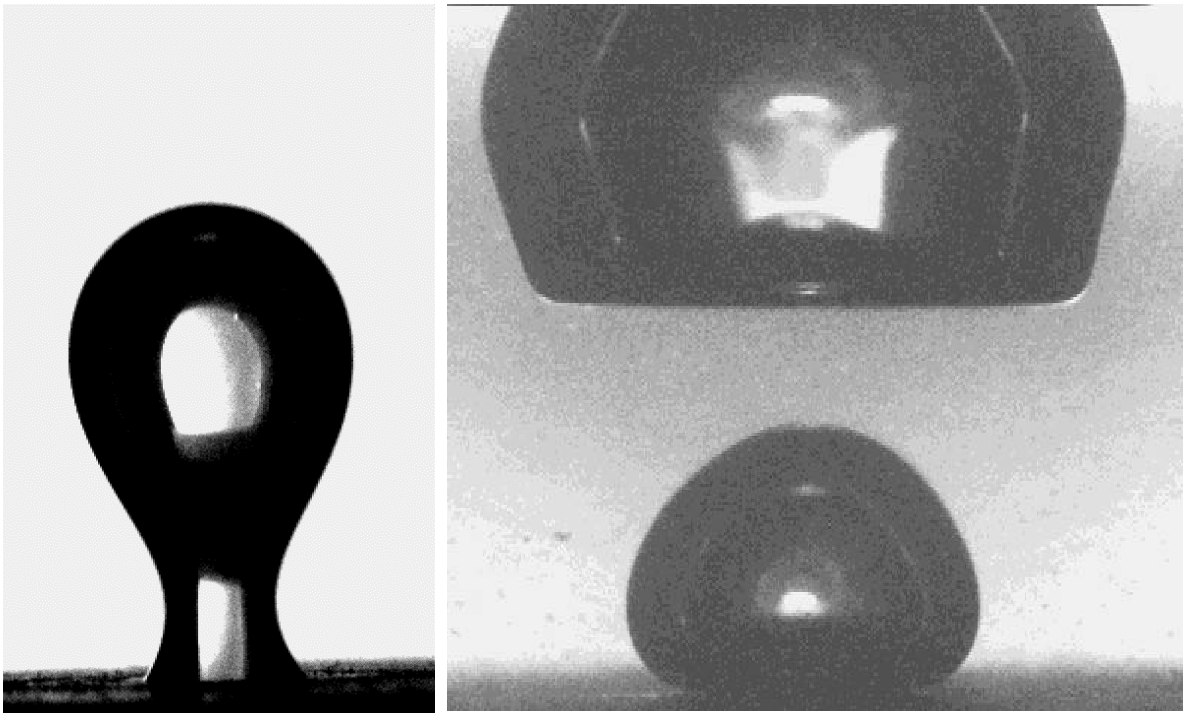


Fig. 4. **Vapor bubble detachment from the heated surface: variety of different shape forms observed.**

The experiments are carried out with pure water at the pressure range *P = 1 to 10kPa*. Several different shapes of vapor bubbles departing from the heated plate are observed (Fig. 4). Depending on the heater size, its surface superheat and liquid subcooling the bubble shape varies from a spherical to a strongly deformed almost cylindrical column. The movie (Fig. 5a) shows a sequence of the more or less regular detachment process for bubbles rising from the 1.2mm heater. The forces governing the bubble detachment arise from gravity action, viscosity, inertia and surface tension. As we may find in the movie (Fig. 5a), bubble grows from a small amount of vapor, usually remainder from the previous bubble hidden in the surface cavity. In the first stage of the bubble growth, the bottom part expands on the plane of the heated surface. The sliding velocity is governed by evaporation, surface tension and wetting properties of the surface. At the moment when the hydrostatic force exceeds that of the vapor pressure, the sliding of the bottom contact line vanishes and the detachment process of the bubble starts. The surface tension becomes dominant, the bottom part forms a thin neck-like vapor tube, which finally breaks up. This breakup process resembles in many details the detachment of droplets from a liquid jet (comp. [1]).

After the break-up the bubble can be partially absorbed by the preceding vapor bubble and partially shrinks back to the hot plate, forming a new site of nucleation. This indicates strong thermal and hydrodynamic couplings between the boiling fluid and the vapor film generated on the hot plate. Decreasing the surface superheat the vapor-liquid-solid contact line changes, influencing both the shape and size of the bubble before detachment.

In most of our experiments it was possible to reach stable, periodic generation of the vapor bubbles under quasi-steady thermal conditions. It allows detailed observation of the detachment process by stroboscopic means. Figure 5b shows a sequence (movie) of bubbles departing from the smaller (0.2mm) heater. The bubbles are relatively large (3mm) and detaching from the heater follow quite close the previous one. It is worth noting a dramatic change of the bubble shape just after departure. The bottom part becomes flat, its top often deforms to a mushroom like form. More careful observation indicates that in fact the bottom surface is strongly concave with a conical hollow shape filling sometimes almost half of the bubble. Its penetration into the bubble interior apparently increases the visible contour of the bubble, bringing up the false impression that the bubble expands after detachment. It is believed that surface tension forces initiate this process. Just after the detachment the surface tension shrinks the broken liquid neck leading to its fast acceleration towards the bubble. It causes the lower part of the bubble to suddenly flatten and quite often to become concave. The bulk liquid temperature is lower than the vapor temperature. Hence, the sudden drop of the vapor pressure and its condensation additionally accelerate quenching of the bottom surface.



a b

Fig. 5. **Two movies showing detachment of vapor bubbles obtained by strobe backlight illumination: (a) - 1.2mm heater, image width 6mm, time interval Δt =5ms, P= 4.8kPa, T_l=33.2°C, T_b=52°C ; (b) - 0.2mm heater, image width 3.9mm, time interval Δt =3ms, P= 4.3kPa, T_l=33.2°C, T_b=54°C**

Depending on the liquid temperature the bubble reaches the free surface or collapses completely before. The second case is illustrated by the sequence of images shown in Fig. 6. A semispherical bubble detaches from the 0.2mm heater and almost immediately implodes. This process generates strong fluid recirculation, transporting some cold liquid radially into the bubble location. The following Fig. 7 shows a sequence of images (movie) displaying the flow field observed using light sheet technique and taken for the same experiment. The flow is visualized using liquid crystal tracers. In order to visualize the flow pattern the images are obtained over an integration time of 60ms. Hence, the image of a moving bubble appears blurred and strong light reflections from the bubble surface fade color of the liquid crystal tracers in its surrounding. One may note that the color of tracers away from the bubble surface varies strongly in the whole field of observation. It seems that despite strong mixing effects associated with departure and implosion of the bubble, a non-uniformity of the local temperature in the range of few degrees Celsius exists in the fluid. Examining the movie we may find that images showing the flow field after the bubble implosion contain relatively long, white traces emanating from the bubble remainders. These are micro bubbles accelerated up to the velocity of 0.1m/s by imploding parts of the main bubble.

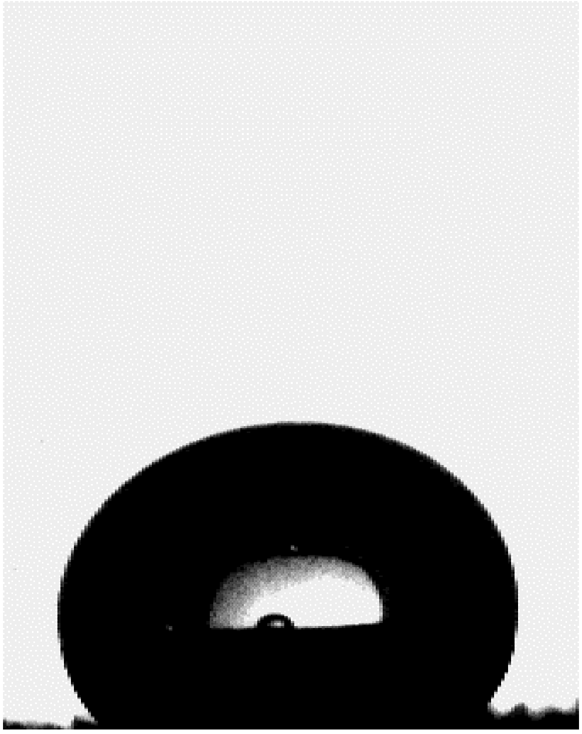


Fig 6. **Movie shows departure and implosion of the vapor bubble detachment from the 0.2mm heater; strobe backlight illumination, image width 4.1mm, *P= 4.9kPa, T_l=34°C, T_b=46°C, Dt=1.2ms***

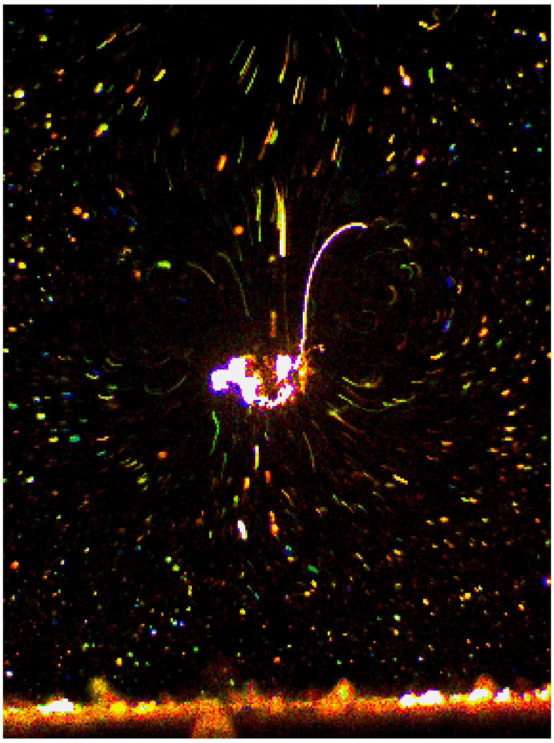
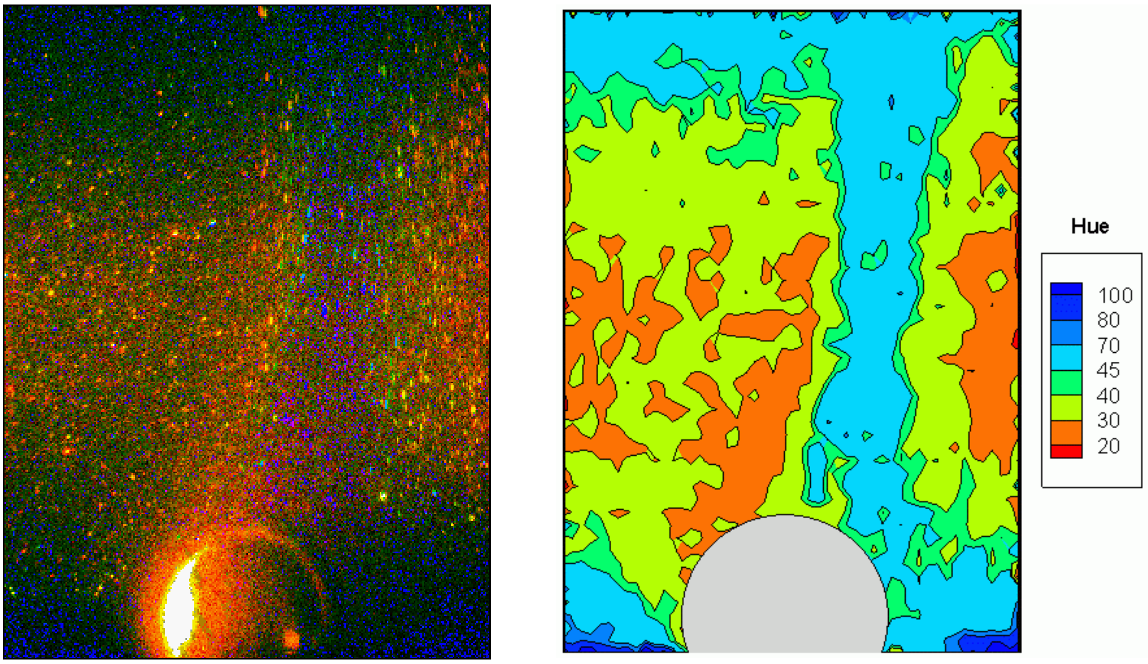
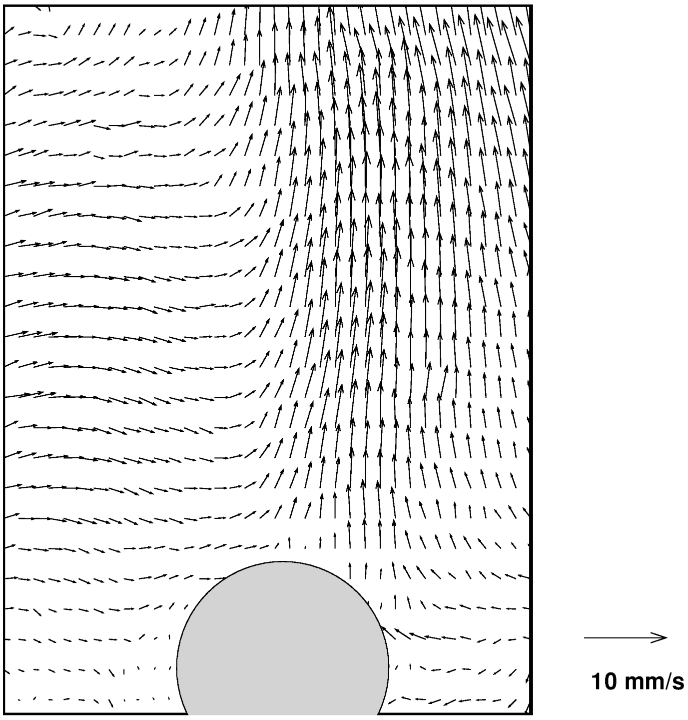


Fig 7. **Movie shows flow field associated with departure and implosion of the vapor bubble; light sheet illumination, liquid crystal tracers, image width 7.7mm, *Dt=20ms***

The flow and temperature field surrounding the departing bubble appears to be very complex and difficult for analysis. The wide range of velocities, the sudden change of the flow direction, the generation of local vortices were typical for all our experiments. Hence, our images of the flow, see for example the movie in Fig. 7, offer only a qualitative description of the phenomenon. To separate the flow field induced by the growth of a bubble from the flow and temperature field generated in the cavity by natural convection, a sequence of images is taken, where the vapor bubble remains in a thermodynamic equilibrium. Under this condition, a flow in the cavity is driven by natural convection generated by temperature gradient between the heater and the bulk fluid. Figure 8 shows the original image with liquid crystal tracers, and results of its evaluation. A hot plum of fluid is visible as a blue stream emanating from the bubble surrounding. We may note that the presence of the bubble deforms the initial symmetry of the temperature and velocity field (Fig. 8b,c). Also the cold liquid sucked by the hot stream seems to very slightly affect surrounding of the bubble. It is well visualized by PIV evaluation of the flow field (Fig. 8c). For comparison Fig. 9 shows the velocity field evaluated for the growing vapor bubble. The flow field surrounding the bubble is strongly coupled with the motion of the expanding interface. The velocity of fluid close to the bubble is several times higher than the velocity in the bulk fluid. It indicates that the natural convection plays here rather secondary role and is insignificant for the total heat transfer and the bubble growth. It is worth noting that the flow field shown in the figure appears to be far from the symmetric one. The instantaneous flow field in the cavity results not only from the interaction of the bubble interface with the fluid but is also affected by the wake field remaining after departure of the previous bubble. This causes development of complex, three-dimensional flow structures that are impossible to resolve using simple means.



(a) liquid crystal tracers (b) evaluated isotherms (PIT)



(c) evaluated velocity field (PIV)

Fig. 8 **Flow field surrounding the steady vapor bubble visualized with liquid crystal tracers; evaluated temperature field (b) and velocity field (c);** ***P= 6.1kPa, T_l=35.7°C, T_b=57°C***

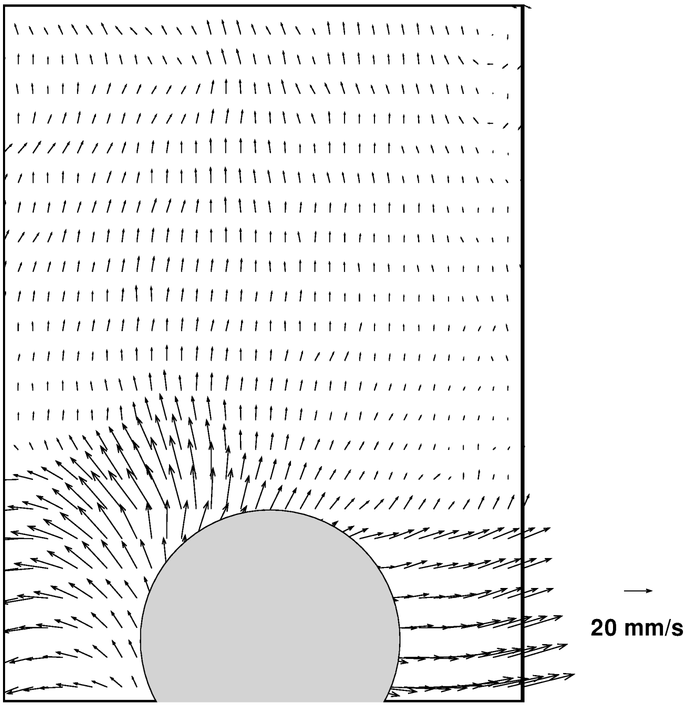


Fig. 9 **Velocity field (PIV) evaluated for the vapor bubble growing an the 2mm heater;** ***P= 5.6kPa, T_l=35.9°C, T_b=73°***

CONCLUSIONS

Our analysis of the experimental images shows possibility to obtain a precise description of geometry and dynamics of a single vapor bubble observed using back light illumination. By applying liquid crystal tracers measuring of both the temperature and velocity fields surrounding the vapor bubble appears to be possible. The experimental results obtained can be used for validation of the assumptions done in the numerical models. Future observation of the growing vapor bubble with two CCD cameras, from the bottom and front directions, may help to correlate dynamics of its growth with a development of the contact area with the heater.

Present experiments performed in a low-pressure environment, demonstrate the possibility to obtain regular, periodic generation of vapor bubbles departing from the heated surface. It allows for using a stroboscopic technique of observation, seriously simplifying the acquisition procedure. However, this method fails when motion of the tracers has to be recorded for the PIV method. To analyze the flow field surrounding a bubble departing from the surface and eventually imploding above it, the use of high-speed imaging system seems inevitable.

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