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PARTICLE IMAGE VELOCIMETRY FOR VAPOUR BUBBLE GROWTH ANALYSIS

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Abstract. The growth of a single microscopic vapour bubble is investigated experimentally. Details of the shape development of the bubble and velocity of the interface are studied using especially developed image processing scheme. The interface velocity is evaluated for sequences of images using advantageous of *ODP-PIV*[1] method for non-seeded flow. The edge detection procedure used allows to resolve location of the bubble contour within 2 - 3 μm resolution. Its shape interpolated using Bézier polynomials is used to evaluate the local components of the interface velocity. Profiles for all components of the interface velocity are given for an exemplary analysed 150μm bubble of methyl alcohol growing on a thin wire.

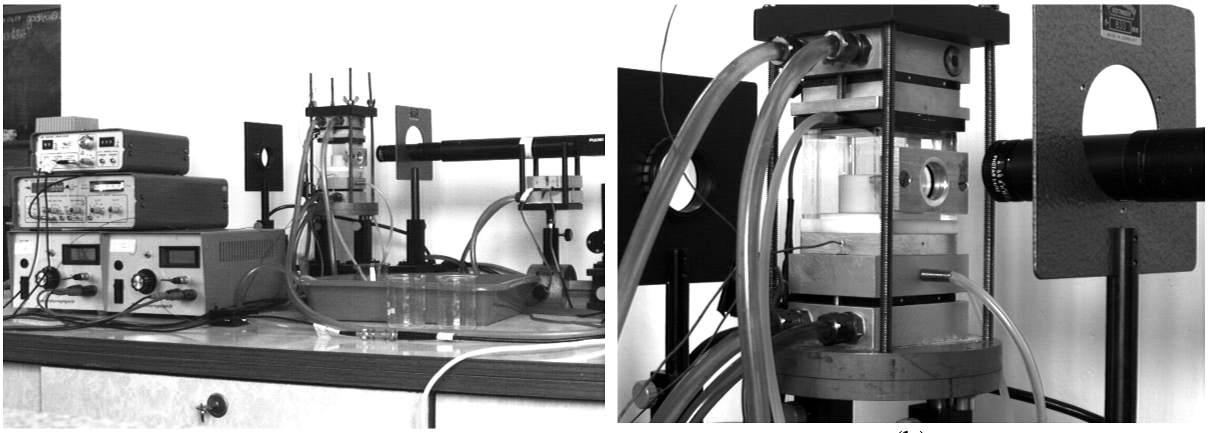
1. INTRODUCTION

Since time of the pioneer work of Rayleigh, many experimental and theoretical investigations have been published, which intended to explain the phenomenon of boiling process. Despite the large effort there are still many unknown fact about the heat transfer mechanisms controlling growth of a single vapour bubble. When modelling the process several doubts appear, which are difficult to resolve both experimentally and theoretically. They concern such important parameters as geometry and boundary conditions set at the contact line between heating surface, liquid and vapour phase. There is also problem with a so called *microlayer,* presumable micromolecular liquid layer existing between the vapour bubble and the solid surface. Its existence, very important for modelling the evaporation process, is still not fully documented. Hence, theoretical and numerical descriptions of this complex process are usually based on more or less vulnerable assumptions. With this objective in view, in the following we present our attempt to develop an experimental technique allowing quantitative analysis of the dynamic development of a single vapour bubble under nucleate boiling conditions. Our preliminary experiments are performed for bubbles departing from a smooth metal surface kept at constant temperature and for bubbles on a metal wire heated by electric pules. Microscopic observations are supported by high speed illumination system, CCD camera and frame grabber. Especial developed image processing procedure allows to describe details of the bubble surface, its dynamic development and local velocity.

[1] Orthogonal Dynamic Programming - Particle Image Velocimetry

2. APPARATUS AND OBSERVATION METHODS USED

The overall view of our experimental arrangement is shown in Fig. 1. It consists basically of a cube shaped plexiglas cavity filled with a working fluid. The bottom and top walls are made of aluminium. They are kept at constant temperature using two Peltier elements. Bubbles are generated at an upper surface of a short metal cylinder attached to the bottom wall. The remaining parts of the bottom wall and the cylinder are thermally insulated from the liquid with a tick layer of Teflon. The heating surface was polished and an artificial nucleation site was produced by a mechanical puncture. The cavity has about 4 cm, its two opposite walls are equipped with glass windows for illumination and observation. The same arrangement was used in the experiments with bubbles generated on the wire. The electrically heated 50μm thin tungsten wire was mounted about 5mm above the heating surface of the cylinder. The temperature of the liquid was kept to be very close to the boiling point. Short electric pulses (10μs) applied to the wire initiated generation of the vapour bubble.



(a) (b)

Fig. 1 General view of the experimental setup (a), and close-up showing the cavity, Peltier elements and optical arrangements.

The observation system consists of the CCD camera (Sony XC77CE), PCI frame grabber (AM-STD Imaging Technology Inc.) and pulsed LED illumination system. It is the modified version of the apparatus used previously to study the break-up of liquid jets [1]. The bubbles are observed through a 50mm microscope lens in bright field illumination. Using a 200mm long extension tube the view area of the camera corresponds to about 2mm physical size. The use of a high resolution CCD sensor and precise optics allowed us to obtain the spatial resolution of the recording better than 3μm. A pulsed Light-Emitting-Diode (LED) is used as a light source. Typical exposure time is 1μs. Data acquisition and storage are performed with a 64MB Pentium Computer. Typical images have resolution of 768x548 pixels and are taken in long series directly into the host computer memory. Image processing software was used to improve the quality of the bubble images as well as to perform series of evaluation procedures allowing to measure bubble dimension, local velocity of the interface and local curvature. These data permit us to evaluate bubble volume, tangential and normal components of the surface velocity. To determine the velocity of the surface either two sequential images are

used or double exposed images can be taken and the relative shift of the recorded structures measured. The first method is possible for slow transient as inter-frame video time is 40ms. In most of the analysed cases this time was sufficient. Double exposed images allow to analyse transients with a temporary resolution of few microseconds.
Bubbles generated at the heated surface appear in a irregular way. Hence, long series (140) of images are taken periodically to find interesting us sequence. After fast search of images kept in the computer memory, selected images are saved in the computer disk or removed, and the procedure repeated again. To control the bubble generation some experiments are performed using a thin wire heated by short electric pulses. Synchronising the electric pulses with the video frame frequency a stroboscopic beat-frequency technique as described in [1] could be applied. A specially designed digital frequency mixer was used to change continuously the phase of the pulses triggering the LED driver relative to the phase of the electric pulses modulating bubbles growth rate. By this means, the stroboscopic observed phenomena slowly changed their phase and their development in time could be easily recorded.
The investigations have been performed under normal pressure for 99% methyl alcohol and PP1 (perfluoro-n-hexan). The main physical properties of the liquids are collected below.

liquid	molar weight M.	boiling temperature T_b [K]	critical temperature T_c [K]	critical pressure [MPa]	density [kg/m^3]	surface tension [mN/m.]
methyl alcohol	32,04	337,69	512,64	8,09	746	19,1
PP1	338,44	330,31	447,7	1,9	1610	7,6

These liquids characterise relatively low boiling temperature under atmospheric pressure. It simplifies to maintain uniform temperature in the cavity. PP1 distinguish low surface tension and relatively low critical pressure. It was selected to verify their effect on the bubble shape.

3. METHOD OF IMAGE ANALYSIS

3.1 Edge detection

Our aim is to describe precisely geometry and dynamics of the bubble growth. For this purpose sequences of bubble images are processed to obtain geometrical details of their shape. The mean diameter of the bubbles analysed is about 0.2mm. The microscopic observation of such objects is not trivial. The relatively fast displacements, optical non-uniformities appearing in the heated liquid and reflections from the walls cause smearing of the observed object and inaccuracy in defining its boundaries. Hence, one of our primary tasks is the precise detection of the bubble boundaries and their extraction for further analysis.
A typical image of the bubble (comp. Fig. 2) 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 applied have to distinguish the external contour and its contact with the heating surface, connect points and find a smooth functional representation of the pixel set for the further analysis. Especially developed filtering / thresholding technique is used to identify bubble edges. It is based on applying modified two-dimensional Kirsch operator with a small mask (3x3 or 5x5 pixels) rotating along the analysed edge. Selecting optimal number of iterations and mask size it is possible to

obtain well defined, one pixel thick representation of the bubble edge. In the second step, pixels representing the edge are used to find functional interpolation of the bubble shape. We found that standard functions give rather poor results, when forced to follow irregular fluctuations of the pixel positions. Hence, we decided to use Bézier polynomials for the interpolation. These curves, especially developed for generating smooth surfaces for computer aided design, have several useful properties allowing flexible and smooth description of very complex geometry. The fitting procedure developed needs only initial point to start its search for the best fitting curve. It analyses step by step surrounding pixels and selects optimal continuation of the Bézier polynomial. 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.

3.2 Velocity field

The sequence of images taken at the constant time interval is used to evaluate 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 behaviour may elucidate us effects of the temperature non-uniformity or surface tension variation. The normal velocity component describes "growing process" of the bubble. The both velocity components depend on the vapour 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 vapour bubble growing at the heated surface. Usually in fluid mechanics the velocity vector field is evaluated using FFT based PIV technique for pairs of images. This approach is not well suited for such objects like moving interface. For the classical PIV the images have to consist of well visible tracers. In the present investigation recently developed ODP-PIV method [1] is applied for tracer-less images of growing vapour bubbles. The technique chosen is based on matching of elastic image strips (either horizontal or vertical). The strip matching is performed using dynamic programming which enforces continuity and regularity constrains. A global, continuous image matching is iteratively updated and refined alternatively for horizontal and vertical strips, reducing their width and spacing at each step. Analysing our images of vapour bubbles we may note that there is no clearly visible texture which motion could be detected. Despite that, the ODP-PIV algorithm successfully recovers the velocity field, using mainly intensity information available for the image region covered by the bubble. We are convinced that this information is sufficient to evaluate velocity of the bubble contour. Hence, in the next step of analysis, the velocities only for the pixels coinciding with the bubble contour are extracted from the whole vector field. Using analytical description of the contour, the velocity can be calculated at any arbitrary point defined by Bézier polynomials, not necessarily at a pixel location. It allows us to find smooth distribution of the velocity vector field along bubble perimeter. Well defined, analytical form of the bubble contour permits easy and accurate evaluation of both tangential and normal velocity components.

4. SELECTED RESULTS

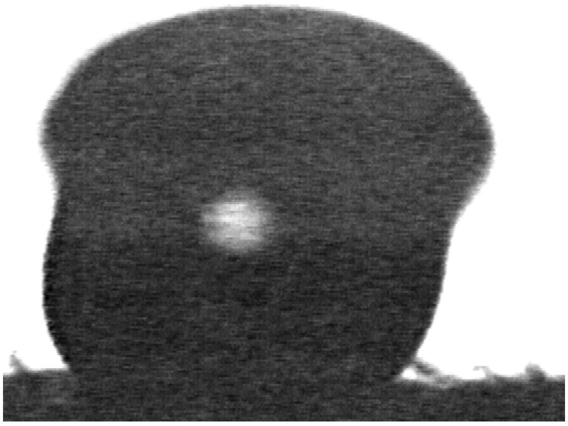


Fig.2. Typical image of a PP1 vapour bubble detaching from the heated surface. The frame width corresponds to 0.5mm.

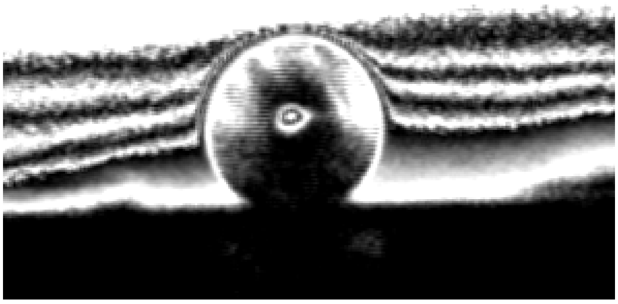


Fig.3. Methyl alcohol vapour bubble detaching from the heated surface. The bubble diameter is 155μm. Temperature field visualized.

Preliminary experiments performed for the heated surface gave us clear evidence that vapour bubbles are not necessary spherical, as it is usually assumed. Particularly for PP1, liquid characterised by small surface tension, strongly deformed vapour bubbles are characteristic for the process (Fig. 2). For alcohol bubble deformation is much smaller, often we could describe their shape assuming almost ideal sphere. By processing images obtained for the bubble detaching from the surface it is possible to detect deformation of the thermal boundary layer encircling the bubble (Fig. 3). For the bright field illumination using parallel light source small variations of the liquid refractive index generate images typical for the classical shadowgraphy. Displayed deformation of the thermal boundary layer qualitatively is in a good agreement with the numerical model [3].

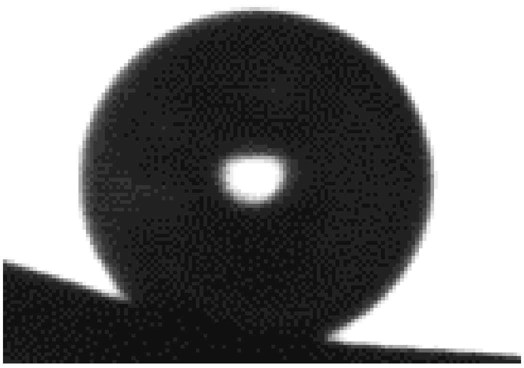


Fig.5. Cropped image of the alcohol vapour bubble growing at the wire. Bubble diameter is 0.2mm.

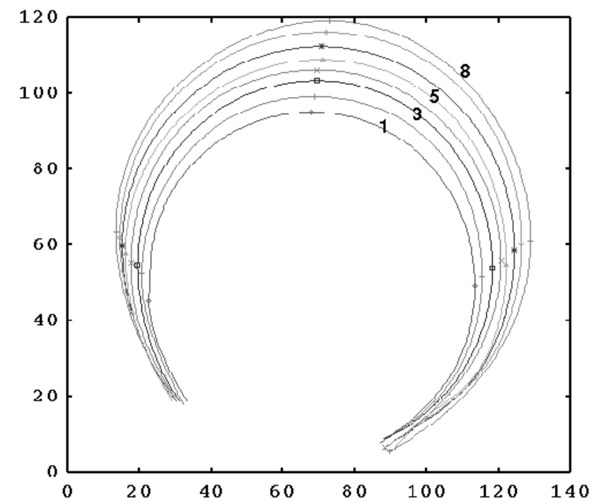


Fig.6. Sequence of bubble contours interpolated by Bézier polynomials. Marked point of extremum for normal and tangential velocity components.

The experiments performed for vapour bubbles growing at the flat surface appeared to be relatively difficult to evaluate. Bubbles do not necessarily appear at the location expected and are often out of focus. Also presence of the metal surface reflecting light creates difficulties in the correct detection of the contact angle. The accuracy of the calculated contour function and the resulting volume appears to be lower than for bubbles generated at the wire [4]. Therefore, in the following we present a few exemplar results obtained for the analysed experimental data obtained for the vapour bubble of methyl alcohol growing at the wire. The main aim of this preliminary experiment is to test our set of the image processing procedures and collect information necessary to prepare a new experimental set-up for the two-directional observation of the bubble. For this purpose a series of 9 images of the bubble taken at 40ms interval is analysed in details. The images are numbered from zero to eight. Figure 4a shows image already cropped to extract area of 137x131 pixels from the original. Smaller dimension of the image speeds up subsequent evaluation procedure but needs human intervention to define region of interest. Following step is the edge detection using modified Kirsch operator. The polynomials interpolation with Bézier functions allows us to obtain smooth analytical description of the bubble shape (Fig. 4b). This description is used to calculate volume of the bubble (Fig. 7), as well as to calculate normal and tangential components of the interface velocity.

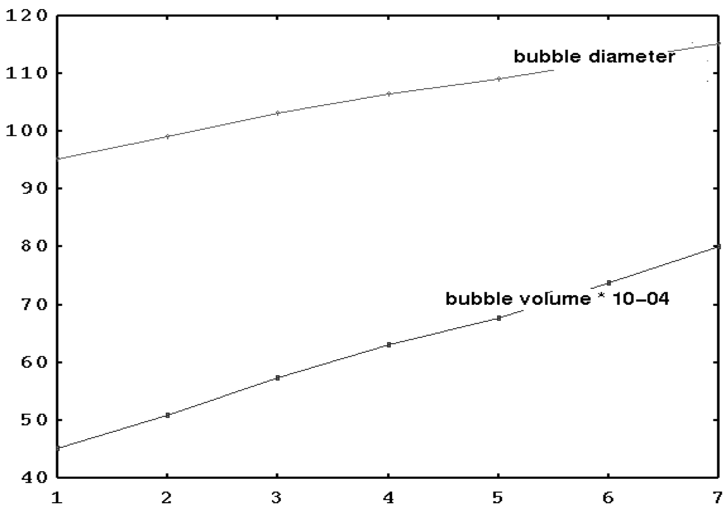


Fig.7. Mean diameter and volume of the alcohol vapour bubble growing at the wire; values are given in pixels (1 pixel = 2.6μm.). Time interval between images 40ms

To obtain the velocity field the before mentioned ODP-PIV evaluation procedure is applied. The ODP-PIV allows to analyse more then two sequential images at once to evaluate the mean displacement velocity. For our images we found that the sets of three images are preferable, the small irregularities of the vector field are better smoothed out. In practice it means that the velocity at the time step t_i is evaluated using images taken at time t_{i-1}, t_i and t_{i+1} . Using nine images we obtain velocity field for the seven of them. The velocity field obtained contains displacement vectors for each pixel of the image. Only velocity at the bubble edges have physical meaning. It is due to the lack of tracers and well define texture outside contours of bubbles. To extract the velocity, previously described analytical description of the interface is used. At each contour point given by Bézier function the velocity vector is found, using values found at the surrounding pixel positions. In such a way sub-pixel accuracy of the position and the velocity is obtained. Figure 8 shows velocity vectors found at the interface for the second and last but one image of nine images sequence. As we mentioned before, to evaluate the vectors three images are used, the one analysed together with the previous and subsequent images. Hence the velocity of interface represents the mean value for 80ms time interval. From Figure 8 it can be noticed that the interface growth rate slows down in time, the mean velocity for the later time step (Fig. 8b) appears to be almost 50% smaller. Direction of the velocity vectors is not necessarily normal to the surface. In opposite, most of the vectors exhibit rather strong tangential components. It may indicate that evaporation process is not uniform along bubble perimeter due to the temperature and surface tension variations.

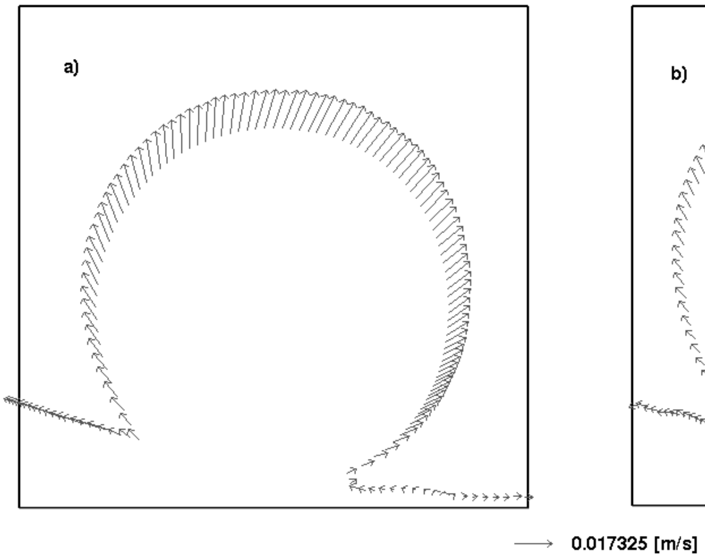


Fig.8. Velocity vectors of the bubble interface at the initial time step (a) and for the last image (b) taken after 240ms.

Having well defined description of the interface and the velocity vector at each point we may find both interesting us velocity components, i.e. normal and tangential. Figure 9 shows velocity profiles obtained for the analysed images. The velocity profiles are given along the contour line of the bubble. It can be seen that the bubble growth rate is far from being monotonic. Highest velocities correspond to the initial time steps for the small bubble. After some time the growth rate slows down, also the location of the maximum moves. Detailed analysis and comparison of such velocity profiles give us quantitative description of the process. This information together with details about surface curvature are essential for direct comparison and verification of the numerical models.

SUMMARY

Our analysis of the experimental images allowed to obtain precise description of the geometry and dynamics of the single vapour bubble growing at the heated surface. The velocity of the interface could be evaluated from the images using the new *ODP-PIV* method. The experimental results obtained can be used for validation of the assumptions done in the numerical models. Further development concerns extension of both the experimental and evaluation techniques to three-dimensional analysis. Observation of the growing vapour bubble with two CCD cameras, from the bottom and front direction, allows us to analyse the dynamics of its growth and the contact area with the heating surface. Applying liquid crystal tracers measuring of both the temperature and velocity fields surrounding vapour bubble soon will be made possible.

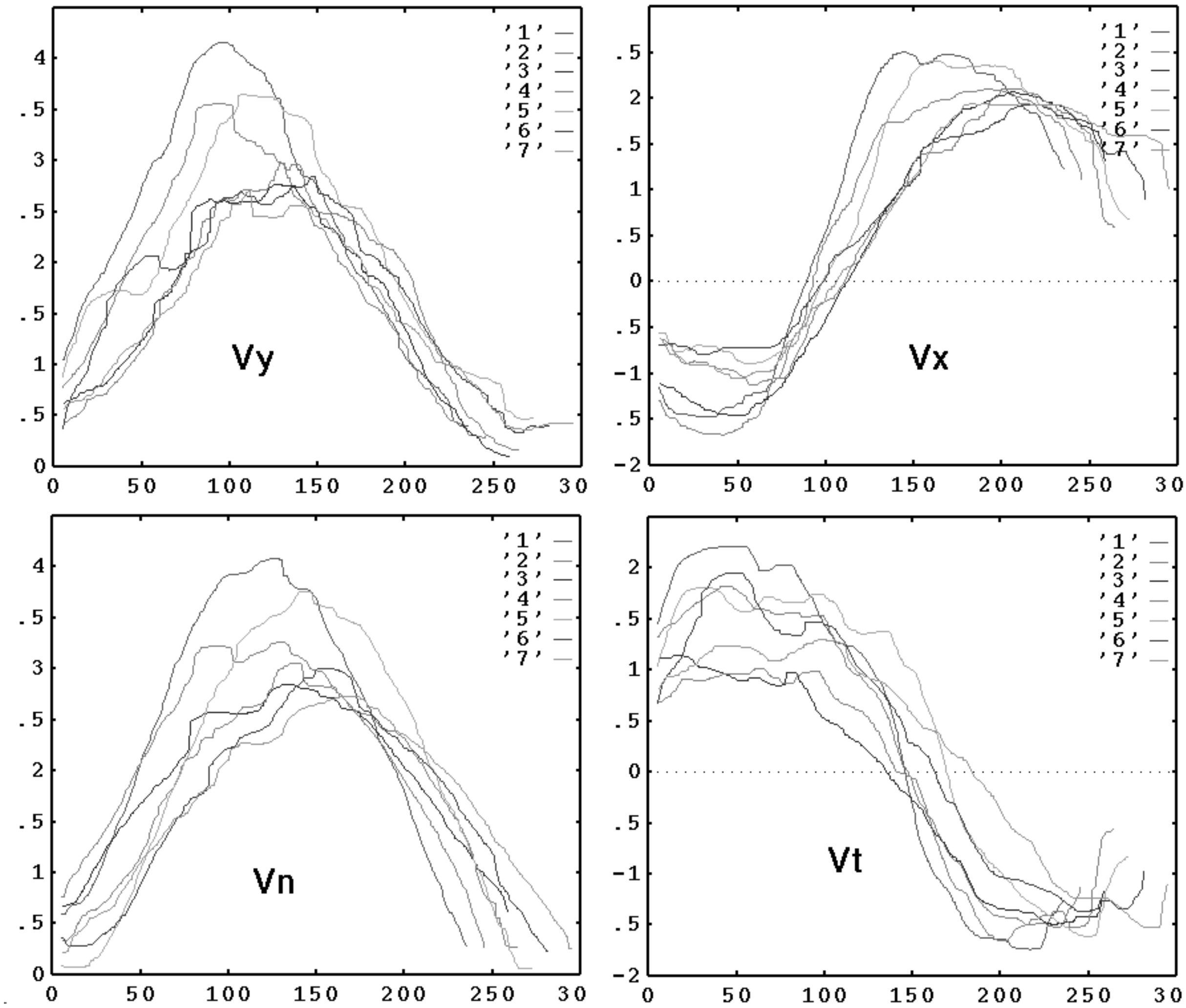


Fig.9. Velocity profiles of the interface along perimeter of the growing vapour bubble evaluated at seven time steps. Upper row: vertical (Vy) and horizontal (Vx) velocity components; bottom row: normal (Vn) and tangential (Vt) velocity components.

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