THERMODYNAMIC PARAMETERS OF VAPOUR BUBBLE GROWTH BY IMAGE ANALYSIS

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Summary: 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.

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 visualised seeding the fluid with thermochromic liquid crystals.

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. The technical details can be found in [1].

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 exhibit 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. Frequency of the bubble oscillations delivers information about variation of the surface tension and indirectly indicate variation of the interface temperature.

Shape of the bubble contour may deliver most of essential thermodynamic parameters of the interface. The local curvature of the interface depends on the balance of pressure, local surface tension and buoyancy. Solving reverse problem the local surface tension can be evaluated and used to obtain local temperature of the interface. For this purpose interpolation of the bubble shape with help of Bézier polynomials is used to obtain smooth (up to the second derivative) representation of the bubble cross-section. It is used to describe local interface velocity (tangential and normal components of the velocity vector) and to evaluate the thermodynamic state of the interface.

The flow visualization around the bubble is performed seeding the fluid with thermochromic liquid crystals. These images are used for the temperature and velocity evaluation (Particle Image Thermometry and Velocimetry [1], [3]).

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. Due to the back light illumination, cross section of the bubble appears as a dark shadow. The first observable bubbles have diameter of about 30 μm, 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 (≈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 µm, 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 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.

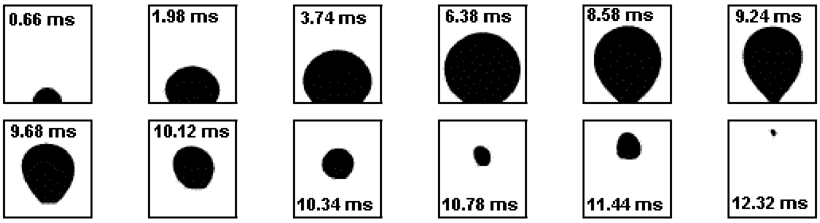

Figure 1. Growth process of a vapour bubble (water P = 4 kPa, T_l = 25.1 °C, T_s = 46.8 °C) observed at 4500 frames/s by high speed camera. Frames shown at few selected time steps. The frame width corresponds to 2.9 mm.

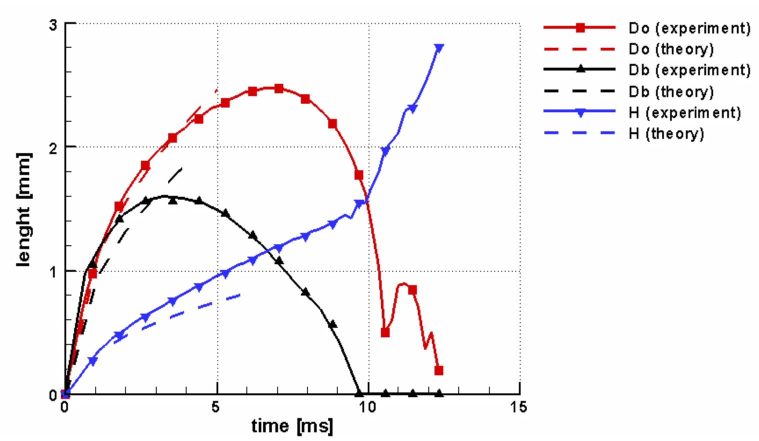

Figure 2. Time history of the experimental and theoretical bubble equivalent diameter D_0, base diameter D_b and height H of the bubble centre of mass evaluated from the sequence of 56 images of the experiment shown in Figure 1.

The other geometric parameters such as maximum and minimum diameter or height of the bubble have also been measured but are not included into the Figure. The experimental results are compared with the theoretical prediction obtained with the aid of a simple mathematical model based on the works of Mei *et al.* [4], Gentile and Pakleza [5], Banerjee and Dhir [6] and other authors. The growth of the bubble may be divided into 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. In this stage we observe the best agreement between experimental and theoretical results, especially for the equivalent diameter D_0. A second one where D_b gets smaller while D_0 still increases (2.5 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_0 follows very closely $t^{1/2}$ diffusion controlled regime. In further stages the agreement of experimental and theoretical results is no longer observed. To obtain satisfactory solution the numerical simulation should be applied as it was declared in the Introduction. Evaluation of the local temperature distribution based on previously described methods gives us the opportunity to correct assumption of the isothermal interface correcting heat balance used in the model.

References

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