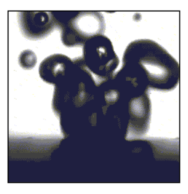
THERMODYNAMIC PARAMETERS OF VAPOUR BUBBLE GROWTH BY IMAGE ANALYSIS

A. Zachara [1], J. Pakleza [2], S. Blonski [1], R. Trzcinski [1], T. A. Kowalewski [1]

[1] Institute of Fundamental Technological Research, Polish Academy of Sciences, Poland

[2] LIMSI – CNRS, France



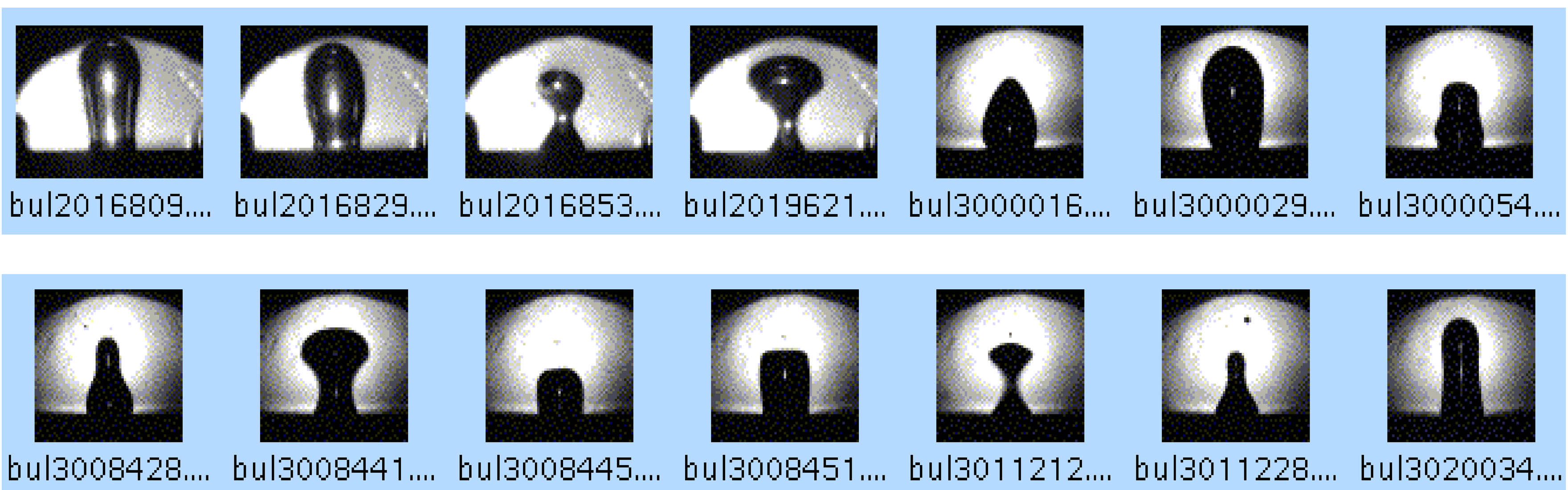
„Boiling is an extremely complex and illusive process, which continues to baffle and challenge inquisitive minds"

V.K/Dhir, Proc. 9th Int. Heat Transfer Conference, Jerusalem, 1990

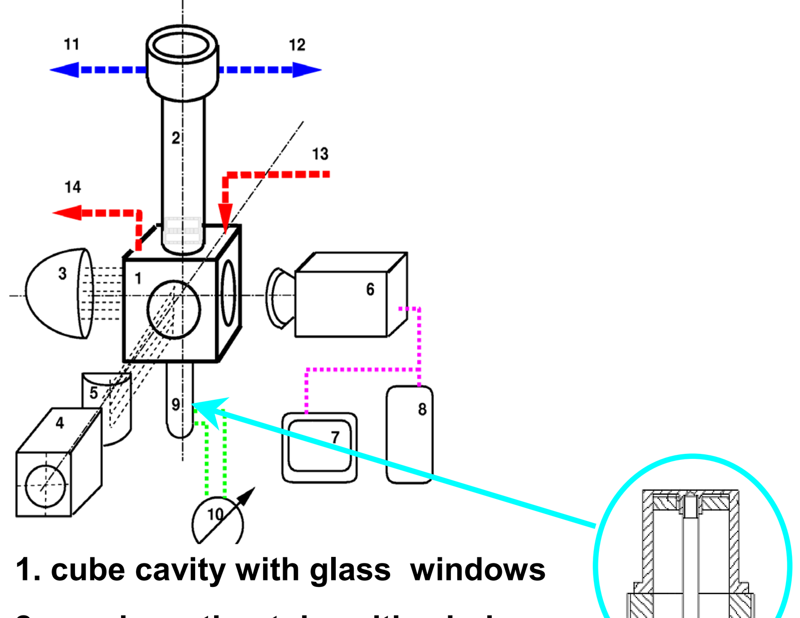
COMPLEXITY OF THE BOILING PROCESS

- Vapour and liquid dynamics as moving boundary problem
- Variability of a bubble volume and shape as a result of local phase change and corresponding physical mechanism
- Full description of the boiling process may be obtained by simultaneous solution of the three physical process which take place in the connected fields: heater – liquid – vapour
- Stochastic behaviour observed at bubbles formation
- Temperature field on the heating surface

COMPLEX BUBBLE SHAPES – CHALLENGE FOR NUMERICAL SIMULATIONS

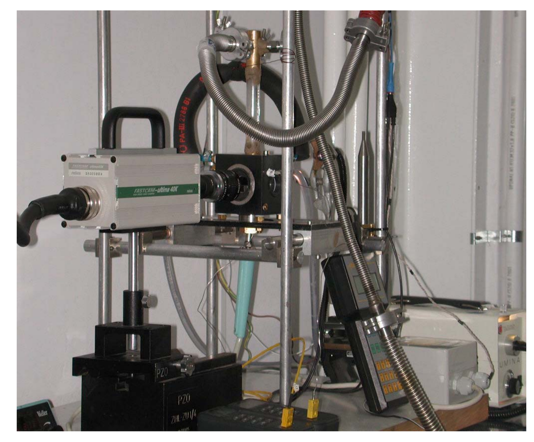


EXPERIMENTAL SETUP



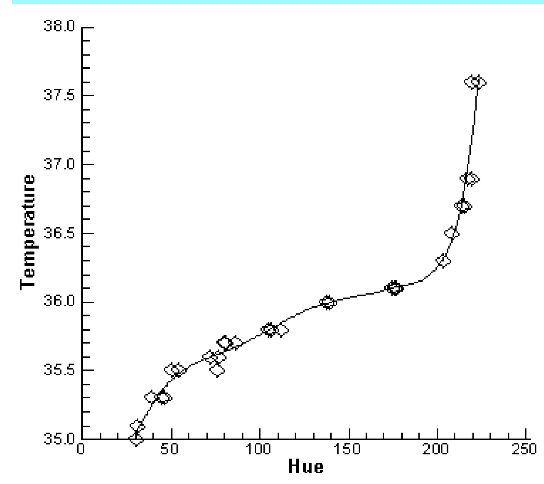
1. cube cavity with glass windows
2. condensation tube with window
3. strobe illumination
4. 5. halogen lamp with a lens
6. CCD colour camera and high speed camera
7. monitor
8. PC with frame grabber
9. 10. electrically heated rod
11. 12. to vacuum system
13. 14. to thermostat

Cavity



High Speed Camera

TLC CALIBRATION



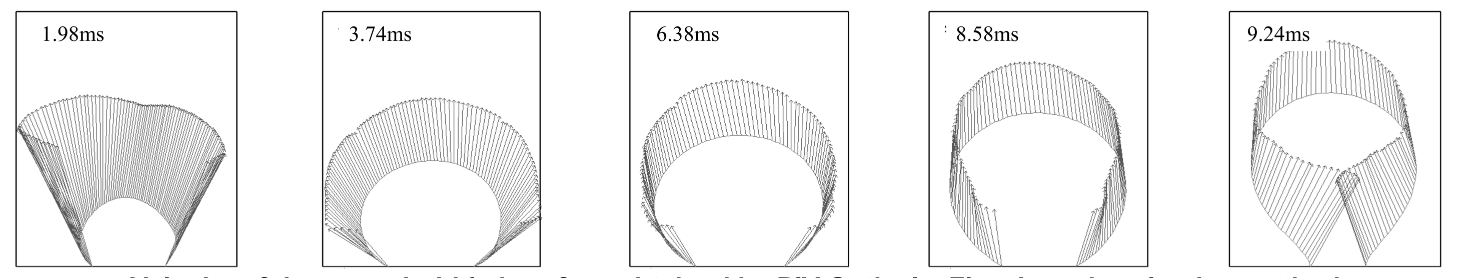
Calibration curve for the seeding of thermochromic liquid crystals used for evaluating temperature field in fluid surrounding vapour bubble

ADVANCED ANALYSIS OF HIGH SPEED CAMERA IMAGES OF BUBBLE GROWTH

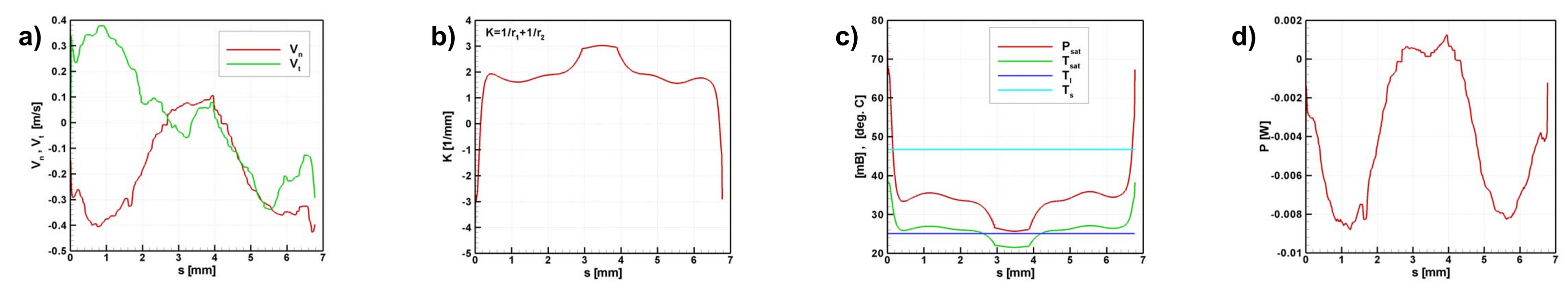
for better understanding of the physical phenomena and validation of numerical simulation models

- From the mathematical description of the bubble shape (Bezier functions continuous and differentiable) radii of curvature may be calculated in any number of points on the interface liquid – vapour.
- From the Laplace law for the free surface we calculate Δp_{tot} and then Δp_{dyn} on the interface using measured pressure p_{stat} in the experimental cell.
- The temperature distribution in any point of the bubble surface can easily be found from the relation between temperature and static pressure on the interface liquid – vapour, determined from the saturation curve.
- Iterative correction of the local surface tension value for real temperature distribution is applied to obtain precise values of the local dynamic pressure.
- From previous calculations of the distributions of normal velocity on the interface for two consecutive time steps and for dynamic pressure distributions we can calculate local vapour production and consequently distribution of temperature gradients and heat fluxes on the bubble surface.
- Integration of heat fluxes on the whole interface for single time step (represented by one image) from start of growth to departure of vapour bubble allows to calculate quantity of heat for each time step.

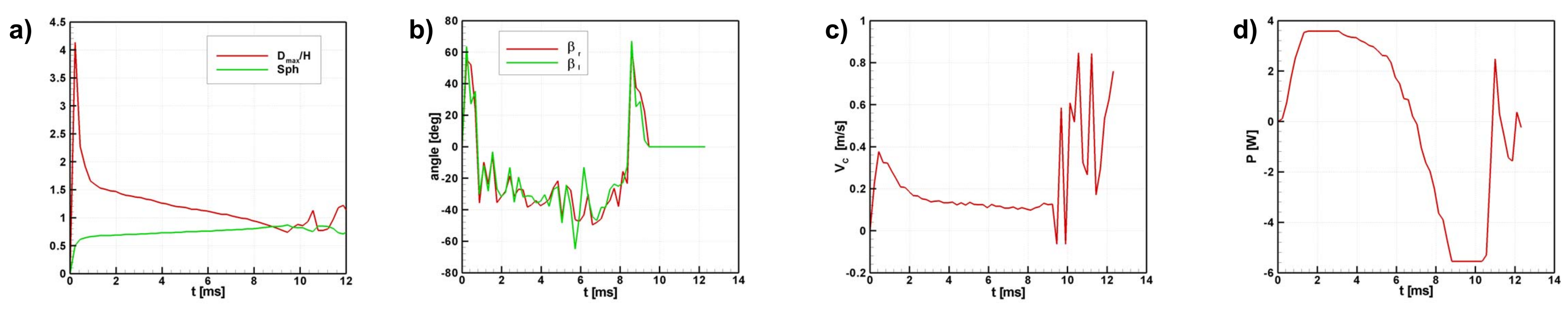
EXAMPLES OF ADVANCED NUMERICAL ANALYSIS OF HIGH-SPEED CAMERA IMAGES



Velocity of the vapor bubble interface obtained by PIV Optical – Flow based evaluation method

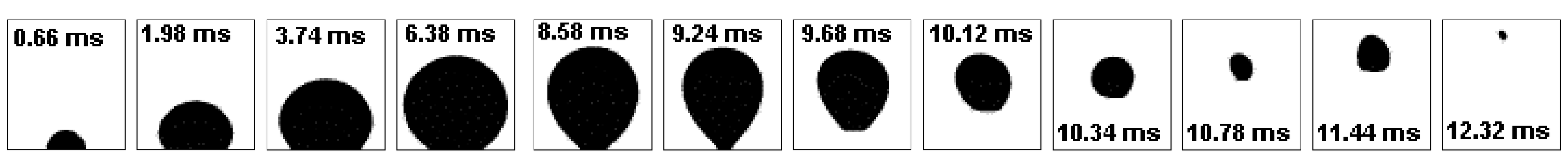


Distribution of physical and geometrical local parameters on the bubble surface as a function of curvilinear coordinate *s* around the bubble: a) normal and tangential velocity components V_n ,V_t on the bubble surface, b) curvature of the bubble, $K=1/r_1 + 1/r_2$, c) saturation temperature T_{sat} and pressure P_{sat} on the bubble surface, temperature of heater T_s and liquid T_l, d) thermal power distribution P(s) on the bubble surface.

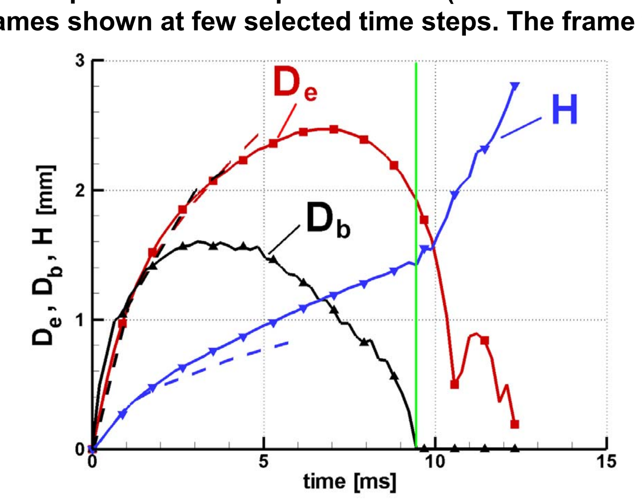


Physical and geometrical global parameters as a function of time: a) sphericity Sph = $(S / V)*(D_e / 6)$ and the ratio D_{max} / H (S is a bubble surface, V is a bubble volume), b) right and left contact angles, β_r and β_t , c) velocity of the bubble mass centre V_c after departure, d) evolution of the thermal power for the whole bubble.

HIGH SPEED IMAGING



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.



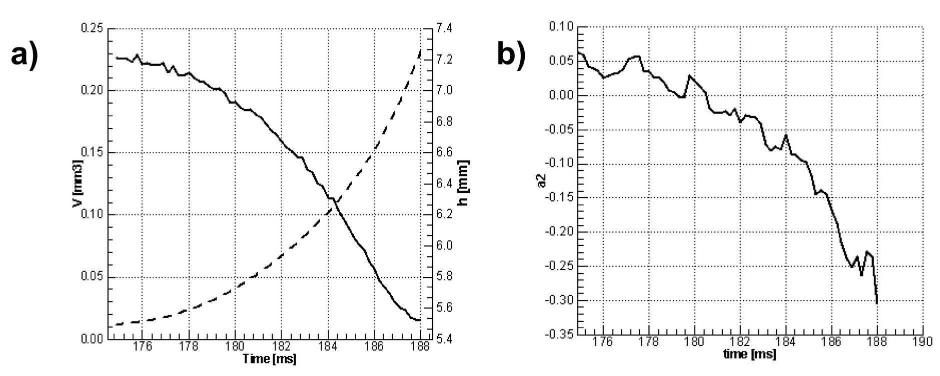
Time history of the water vapour bubble equivalent diameter D_e , base diameter D_b and height H of the bubble centre of mass. Experimental results (solid lines) are evaluated from the sequence of 56 images shown above. Theoretical results (dashed lines) are calculated on the base of the simplified mathematical model describing the first stage of the bubble growth (0 < t < 2.5 ms).

The following relation has been obtained for time evolution of the bubble diameter

$$D = \frac{2}{f_v(C)}\left[\frac{C^2}{C_1}\cdot\frac{Ja_s}{(\mathrm{Pr}_l)^{1/2}} - \frac{2}{\sqrt{\pi}} f_s(C)\cdot Ja_l\right]\cdot(a_l\, t)^{1/2}$$

where Ja_s and Ja_l are Jakob numbers, Pr_l is Prandtl number, α_l is thermal diffusivity, $C=D_b/D$, $f_1(C)$, $f_2(C)$ are bubble shape parameters. Hence

$D_e = [f_1(C)]^{1/3} D$, $D_b = C D$, $H = 1/2\,[(1 - C^2) + 3/16\, C^4 / f_1(C)]D$



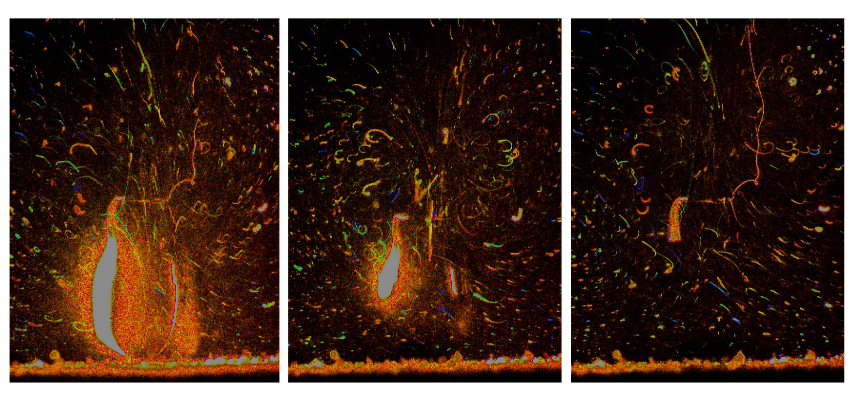
Methyl alcohol vapour bubble departing from the heated surface under atmospheric pressure; a) volume (solid line) and vertical position of the bubble (dashed line); b) deformation parameter a_2.

Deformation parameter a_2 is determined in the momentary description of the bubble surface by Legendre polynomials:

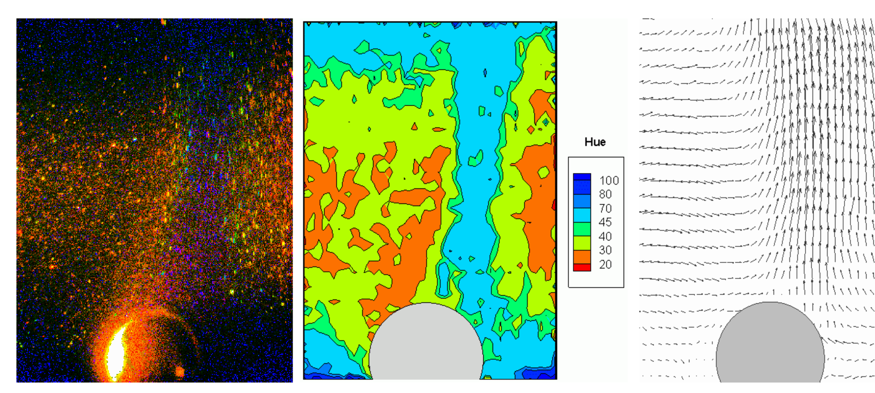
$$R(\theta,t) \approx R_o\left[1+\sum_{l=2}^{\infty} a_l(t)\cdot P_l(\cos\theta)\right]$$

where R – radius of the bubble, R_O – unperturbed radius of the bubble, a_l – instantaneous amplitude of the *l* – th mode of oscillations, θ – polar angle of the spherical coordinate, $P_l(\cos\theta)$ – Legendre polynomials. Fundamental mode a_2 describes elongation and contraction, that is prolate and oblate bubble form.

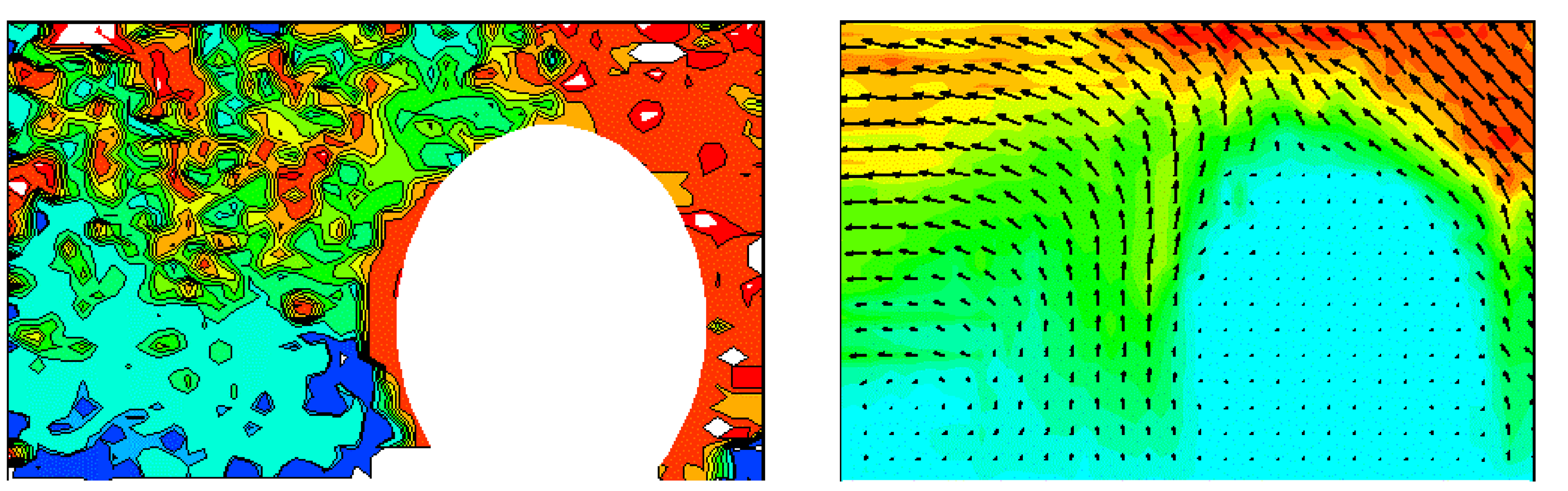
PARTICLE IMAGE VELOCIMETRY & THERMOMETRY



Flow field associated with departure and implosion of the vapour bubble. Long illumination time (20 ms) is used to visualize complexity of the flow structure. Variation of the tracer colour demonstrates non-uniformity of the instantaneous temperature field. After implosion few remaining tiny satellite bubbles moving away with a velocity of few m/s can be see.



Flow field surrounding the steady vapour bubble visualized with liquid crystal tracers, the evaluated temperature field, and the corresponding velocity field. The experimental condition are: pressure: 6.1 kPa, liquid temperature: 35.7 °C, heated wall temperature: 57 °C.



Vapour bubble of water growing at the heated surface; P = 3.5 kPa, Tl = 35.5 °C, Tb = 66.5 °C. Evaluated temperature field (left) varies from 35 – 37.5 °C, PIV evaluated velocity (right) has maximum magnitude 3 mm/s