Holographic Interferometry Studies of the Temperature Field near a Condensing Bubble

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Abstract

For a better understanding of the mechanism of bubble collapse, holographic interferometry combined with high-speed cinematography was used as measuring technique to study the temperature field near a condensing bubble.

To ensure well-defined reproducible conditions, experiments have been carried out by injecting single vapour bubbles into subcooled liquid through a nozzle. The experiments were performed for a range of pressure from 0.25 to 4 bar, for subcoolings from 5 to 50 K and for initial bubble diameters of about 2 mm. Freon 113 and Ethanol were used as test fluids.

To evaluate the axisymmetric temperature field around the bubble from the interference fringe field, the methods of Abel-integral are not sufficient. A correction procedure considering the light deflection caused by the local temperature gradient has been developed and applied to calculate the heat transfer coefficient. Calibration tests with a heated solid sphere showed that the experimental results agree with additional thermocouple measurements to ± 10%.
Some interferograms and the experimental results are presented.

1. Introduction

The thermo- and hydrodynamic phenomena during the collapse of vapour bubbles in subcooled liquid are of scientific interest for a better understanding of the instability condition in two-phase flow, e.g. subcooled boiling, cavitation. They are also of great significance for the practical layout of heat generating systems with high-power densities and direct contact type heat exchangers. Prior knowledge of bubble collapse /2-7/ has been largely based on observations of the temporary variation of the bubble volume and surface area. By using holographic interferometry combined with high-speed cinematography in this work, more information - e.g. of the temperature field around

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the bubble - can be deduced. Local heat transfer coefficients can also be calculated.

2. Experimental apparatus and measuring technique

The testsection is shown in Fig. 1. Since each bubble should find a temperature field as homogeneous as possible at its entrance into the liquid, the test chamber is integrated into a liquid loop which produces a vertically downward directed flow of low velocity at the end of the nozzle. This guarantees that the flow doesn't impede the bubble detachment and its rising freely, because the bubble rise velocity is about 10 times the velocity of the counterflowing liquid.

As already mentioned in the introduction, the heat transfer was investigated by holographic interferometry. The principle of this measuring technique /1,8/ shall not be explained in this paper. To perform measurements on bubbles, the real-time method was used. The arrangement of the required optical set-up is shown in Fig. 2.

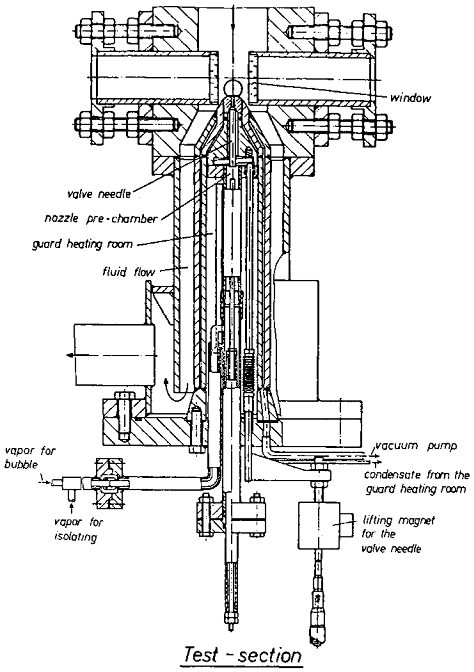


Fig. 1: Test section

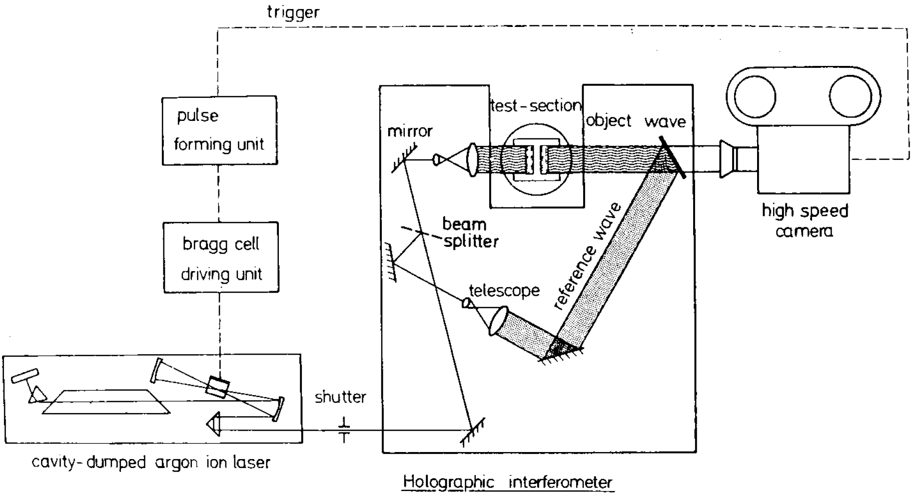


Fig. 2: Optical arrangement of a holographic interferometer

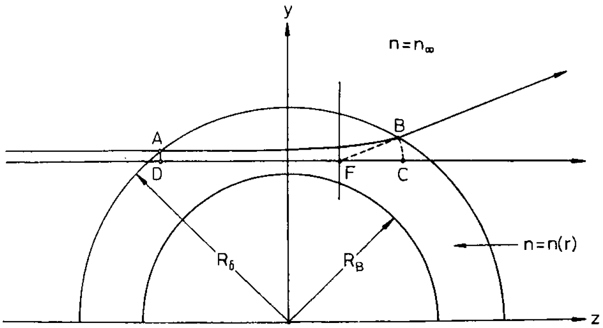
3. Interferogram analysis and calibration test on a heated sphere

To analyse the interferogram, the methods known in the literature - e.g. Abel-integral - are not sufficient. Here one must take into account that the beam which passes through the temperature field around the bubble suffers a non-neglectable deflection, caused by the large local temperature gradient. Therefore, the following correction procedure has been developed.

A first analysis of the interferogram is performed without regard to the deflection of the light beam.

$$\varepsilon(y)\,\lambda_0 = \int_{-z_0}^{z_0} \left[n(r) - n_\infty \right] dz \qquad r_B \leq y \qquad (1)$$

With the above equation the phase shift between the measuring and reference waves is calculated by means of the order of fringes $\varepsilon(y)$ and the wavelength λ_0 of the applied light. Considering the light beam deflection, the analysis of the interferogram is much more complicated then discussed above. Fig. 3 shows, as an example, the deflection of a beam which runs through the liquid boundary layer in the middle section of a bubble. Due to the continuously changing temperature in the boundary layer and the resulting change of the refractive index, this beam has a curved trajectory. For an observer beyond the image plan it seems to come from the projected point F on the focussing plan. In the image plan (not shown in Fig. 3) the object beam interferes with the reference beam, which was not deflected.



$$\varepsilon(y)\lambda_0 = \int_A^B n(s)\,ds - n_\infty \overline{DC}$$

Fig. 3: Formation of an interferogram

Both beams - object beam and reference beam - have the same phase relationship up to point A and D. Assuming we have ideal lenses, the optical path length of the two beams behind the points B and C to the image plan is equal. Therefore, the interference only originates from the optical phase shift difference of the object beam running through the bubble boundary layer.

$$\varepsilon(y)\lambda_0 = \int_A^B n\,ds - n_\infty \overline{DC} \tag{2}$$

The path of the beam in the boundary layer is described by the following differential equation

$$\ddot{y} = \frac{1}{n}(1+\dot{y}^2)\left(\frac{\partial n}{\partial y} - \dot{y}\,\frac{\partial n}{\partial z}\right) \tag{3}$$

where dots refer to differentiation with respect to z.
From equations (2) and (3) a new distribution of the interference frings ε(y) can then be numerically evaluated /9/. The refractive index field can now be easily connected into a tem-

perature field, if the dependence of the refractive index on the temperature dn/dT is known. The heat transfer coefficient can then be calculated with the following equation.

$$\alpha = \frac{-\lambda\left(\frac{\partial T}{\partial y}\right)_W}{T_W - T_\infty} \tag{4}$$

Calibration tests of forced convection on a heated sphere were made to check the correction procedure mentioned above. It was found that the experimental results agree with additional thermocouple measurements to ± 10%. An enlarged interferogram of the thermal boundary layer on a heated sphere is shown in Fig. 4.

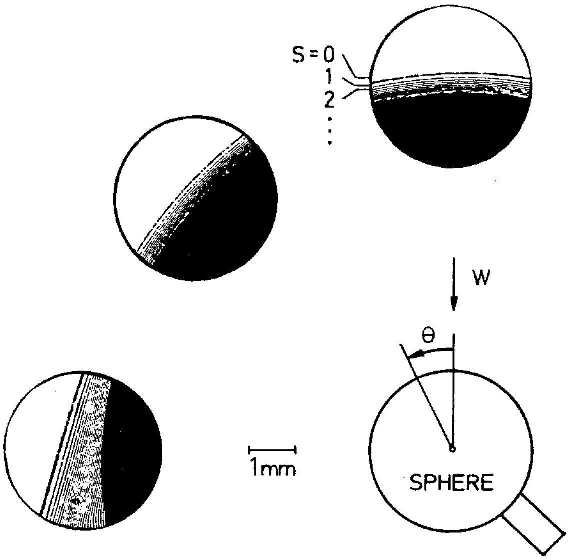


Fig. 4: Interferogram of a heated sphere in Ethanol.
Sphere radius: 1 cm
T_∞ = 23.8 °C T_W = 28.2 °C Re = 350

4. Experimental Results

In Fig. 5 the bubble growth, detachment and collapse are demonstrated by a sequence of interferometric pictures.

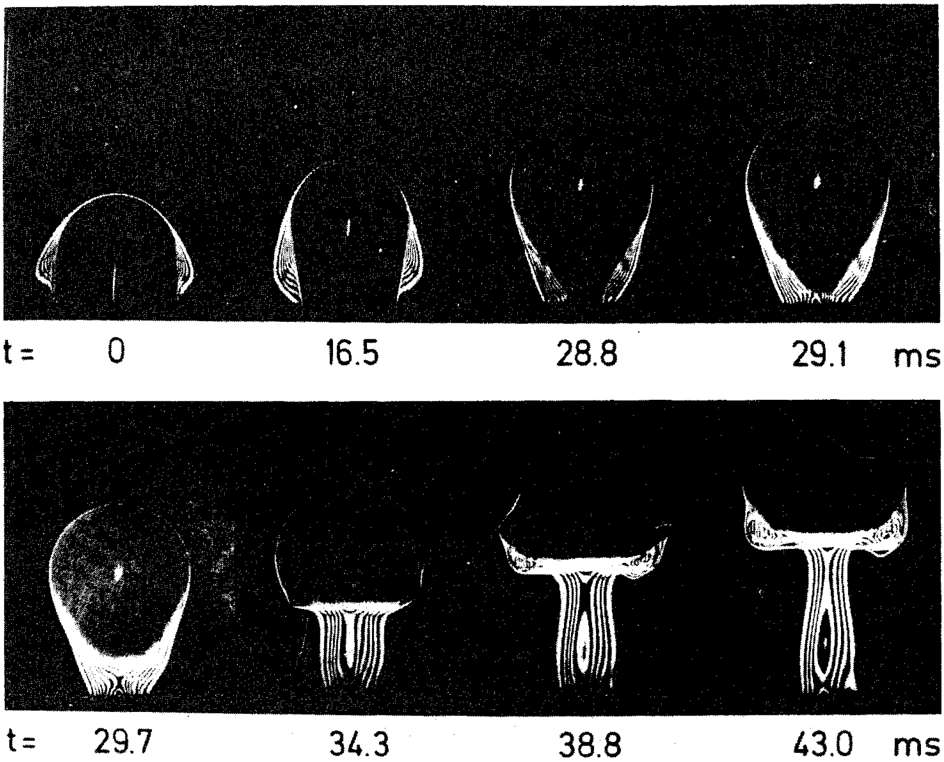


Fig. 5: Interference pictures of growing and collapsing bubbles. Bubble radius at detachment: 1 mm
p = 2.0 bar ΔT = 10 K Freon 113

Enlarged interferograms of a condensing bubble are shown in Fig. 6. The temperature profiles obtained from Fig. 6 (left) are plotted in Fig. 7.

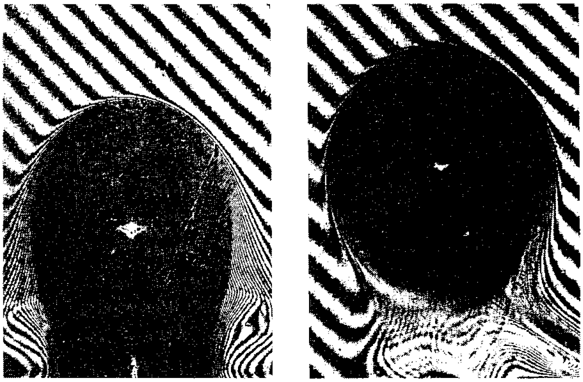


Fig. 6: Interferogram of a condensing bubble
Ethanol p = 2.1 bar ΔT = 14.0 K
left: before detachment right: after detachment

In a series of experiments the effect of the relative velocity between the adhering bubble at the nozzle and the liquid on the temperature field was investigated. Fig. 8 shows this effect.

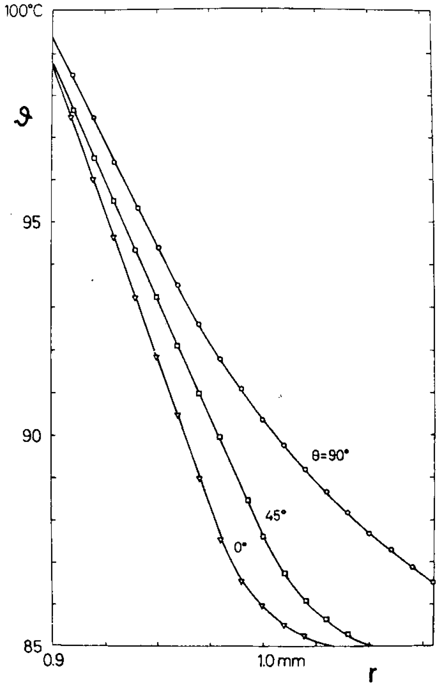


Fig. 7: Temperature profile obtained from Fig. 6 (left)

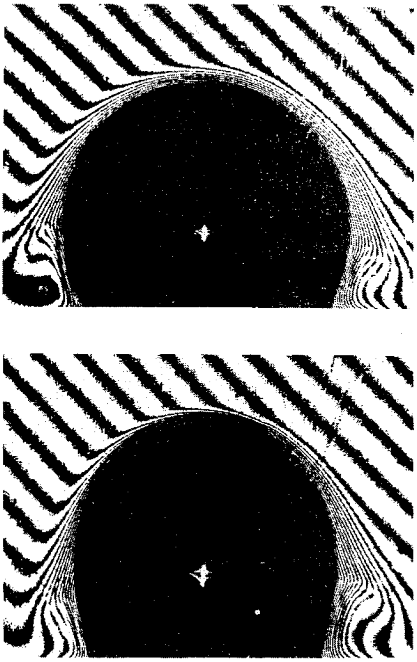


Fig. 8: Effect of the relative velocity on the temperature field Ethanol
p = 1.0 bar
ΔT = 13.0 K
above: w = 2.5 cm/s
below: w = 6 cm/s

5. Conclusion

By investigation with holographic interferometry it was possible to obtain improved understanding of the heat transfer during bubble collapse.

Using a computer program which takes the light beam deflection into consideration, temperature profile and reliable heat transfer coefficients around the bubble could be calculated.

Acknowledgement

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