Int. J. Multiphase Flow Vol. 17, No. 1, pp. 153–158, 1991
Printed in Great Britain. All rights reserved

0301-9322/91 $3.00 + 0.00
Copyright © 1991 Pergamon Press/Elsevier

BRIEF COMMUNICATION

THE DEPARTURE SIZE OF POOL-BOILING BUBBLES FROM ARTIFICIAL CAVITIES AT MODERATE AND HIGH PRESSURES

W. M. SLUYTER, P. C. SLOOTEN, C. A. COPRAIJ and A. K. CHESTERS
Laboratory of Fluid Dynamics and Heat Transfer, Eindhoven University of Technology, Eindhoven, The Netherlands

(Received 16 April 1990; in revised form 21 September 1990)

1. INTRODUCTION

The growth and departure of boiling bubbles is determined by so many factors—hydrodynamic, thermal and physicochemical—that a general description is out of the question at the present time. Under certain circumstances, however, many of these factors are of only secondary importance and the situation simplifies sufficiently to permit the construction of viable first-order models. An attempt at such modelling has been undertaken previously by one of the authors [Chesters (1978), henceforth referred to as paper I] in the context of nucleate pool boiling under conditions of "slow" growth—a situation expected to prevail in most cases at atmospheric and high pressures. While the observations available at the time appeared to support this model, their interpretation was complicated by the fact that in most cases a population of active nuclei was present whose identity changed throughout the experiments concerned.

The present contribution, based in particular on the results of Slooten (1983), concerns bubbles formed on well-defined artificial cavities at atmospheric and higher pressures, which provide an unambiguous basis for evaluating the slow-growth model. The considerations begin with a brief review of the principal elements and regime of validity of the model, adapted where necessary to the interpretation of the results which follow. The experimental results—growth rates and departure radii as a function of boiling conditions, cavity size and liquid concerned (water or ethanol)—are then presented and compared with expectations based on the model.

2. THE SLOW-GROWTH MODEL

As demonstrated in paper I, of the various forces acting on a vapour bubble attached to a solid surface only those due to buoyancy and surface tension are significant at sufficiently slow growth rates. Since, furthermore, the bubble inertia is negligible, the total force acting on the bubble must be zero, indicating a balance between surface tension and buoyancy forces. The bubble departure radius, R, is then the largest radius at which this balance is attainable. For "confined" bubbles—for which the three-phase contact line between vapour, liquid and solid remains confined to the cavity on which the bubble originated—the maximum size attainable is given by

$$R = (3r\sigma/2\rho g)^{1/3}, \qquad [1]$$

where r denotes the cavity radius, σ is the surface tension, ρ is the liquid density and g is the acceleration due to gravity.

At sufficiently high growth rates other forces in addition to buoyancy and surface tension become important, the most significant for low viscosity liquids being that due to the inertia of the surrounding liquid. This retards the upward motion of the bubble—which is required for its detachment—resulting in longer growth times and thus larger bubbles. Bubble growth rates are governed by thermal diffusion (except initially or at low pressures) and accordingly vary during the growth process;

$$R = \mathrm{B}t^{1/2}, \qquad [2]$$

where the constant B is given by

$$\mathrm{B} = (\Delta T / i\rho_G)(12k\rho c/\pi)^{1/2} \qquad [3]$$

(k, c, i and ΔT are, respectively, thermal conductivity, specific heat, latent heat of vaporization and superheat of the liquid, and ρ_G is the density of the gas/vapour). The transition from slow to rapid growth was shown in paper I to be given by

$$(6/\pi)^{1/5} G_{\mathrm{trans}} / g^{3/5} = 2\pi r\sigma/\rho g, \qquad [4]$$

where G_{trans}, the volumetric growth rate at departure, is given by

$$G_{\mathrm{trans}} = 2\pi \mathrm{B}^2 (3r\sigma/2\rho g)^{1/3}. \qquad [5]$$

Accordingly,

$$\mathrm{B}_{\mathrm{trans}} = (r\sigma/3\rho)^{1/4}. \qquad [6]$$

We note that if the rapid-growth model is revised to incorporate the time dependence of G implied by [2], the transition point shifts only marginally.

In paper I the order of magnitude of B was related to the cavity radius via the approximation that the level of superheat present is that required to activate the cavity:

$$\Delta T \cong 2T\sigma/i\rho_G r. \qquad [7]$$

Under the special conditions created in the present experiments this approximation is not a good one and the transition criterion [6] cannot be reduced further.

3. EXPERIMENTS

Experimental set-up

The set-up used is shown schematically in figure 1. A stainless-steel vessel, filled either with degassed, demineralized water or ethanol contains two windows, the artificial cavities being

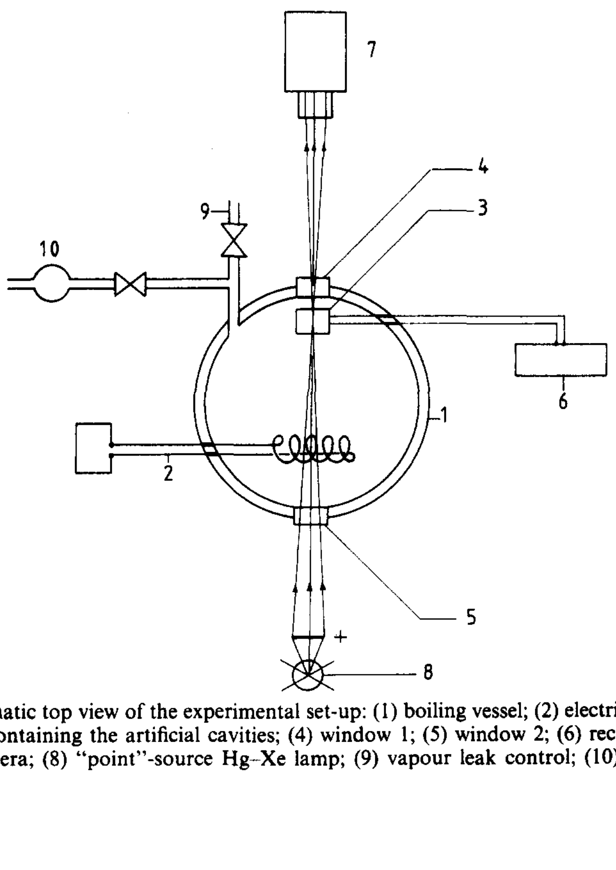

Figure 1. A schematic top view of the experimental set-up: (1) boiling vessel; (2) electric heating; (3) small horizontal plate containing the artificial cavities; (4) window 1; (5) window 2; (6) recording of p and T; high-speed camera; (8) "point"-source Hg–Xe lamp; (9) vapour leak control; (10) vacuum pump.

contained in a stainless-steel plate behind window 1. The light from a "point-source" Hg–Xe lamp, entering through window 2, was focused on the cavities and a high-speed camera (up to 1000 frames/s) used to record the process of bubble growth. Each series of observations was initiated by heating the liquid electrically with the vessel closed until a pressure of 45 bar was attained, when the heater was disconnected. After the free-convection flow had ceased a vapour leak was introduced, as a result of which the pressure slowly decreased, inducing a moderate superheat leading to boiling on the artificial cavities (figure 2). Since the magnitude of this superheat (typically a few degrees—see the following section) was determined by the characteristics of the vessel, rather than those of the cavities, approximation [7] is clearly not applicable. Further as [7] indicates, the superheat required to activate a given cavity increases with decreasing pressure, becoming of the order of that available (for the cavities concerned) at pressures around atmospheric. The result was that the cavities typically became inactive at these pressures, though their activity could be extended somewhat by the application of moderate electrical heating to the surface containing the cavity; this extra degree of freedom also enabled more than one level of superheat to be examined at a given pressure. Probably due to the removal of all permanent gas, the cavities generally became inactive after a series of experiments.

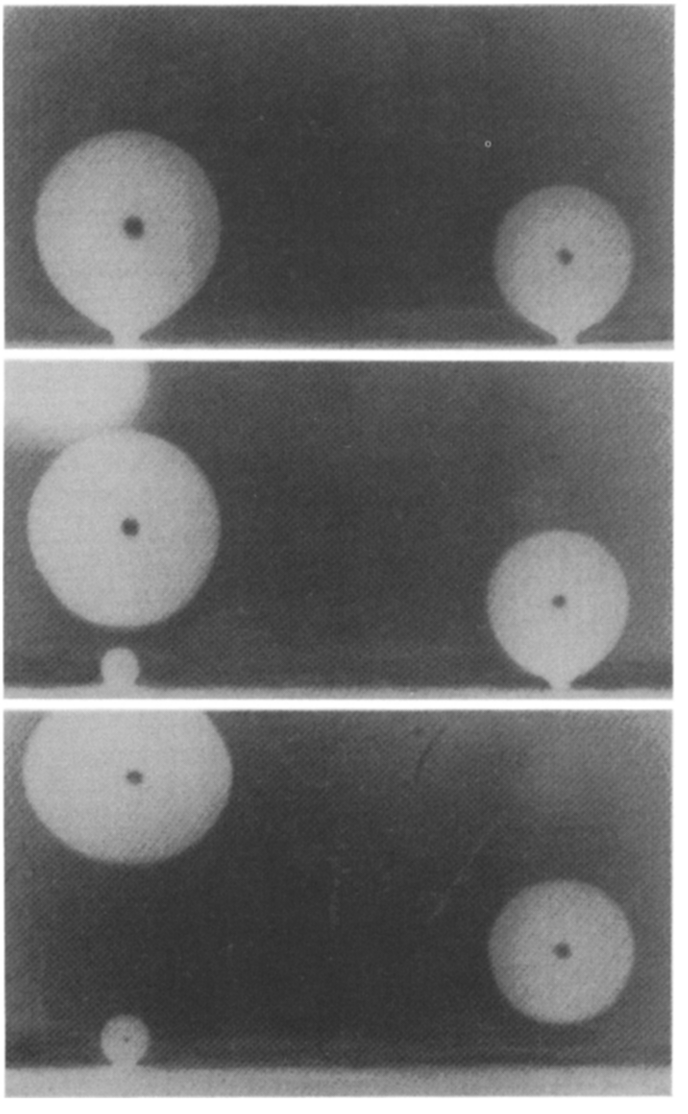

Figure 2. Three subsequent pictures of static bubble departure in water at two different artificial cavities, $p = 19.7$ bar. $R(50\ \mu m) = 0.647$ mm, $R(25\ \mu m) = 0.494$ mm. The camera speed was 152 frames/s.

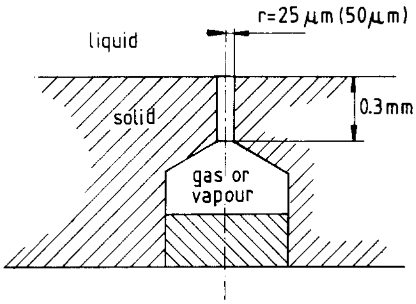

Figure 3. Reservoir-type cavity.

As a result of the leak, the pressure in the vessel slowly dropped and a series of high-speed observations (10–30 bubble cycles/situation) could be made at various pressures.

The resulting pictures were analyzed frame by frame to obtain the bubble radius as a function of time and the corresponding values of B, which proved to be approximately constant during a given growth cycle. Within a sequence of bubble growth cycles the values of the bubble departure time and radius exhibited a variance of about 10 and 5%, respectively.

Two cavities were contained in a stainless-steel plate, of radii 25 and 50 μm, about 3 mm apart. Both cavities were of the reservoir type shown in figure 3. The reservoir was made by drilling a hole of 0.35 mm in the lower side of the plate and then closing it with a tightly-fitting plug. The cavity hole was then drilled from the upper side of the plate into the reservoir.

Experimental results

All bubbles observed were of the confined rather than the spreading type. Figure 4 depicts the variation of the departure radius, R, with the absolute pressure, p, for three series of observations using water and the plate with adjacent cavities. Before considering the agreement of these results with the slow-growth model, some comments are in order regarding the growth rates concerned. In two of the runs wall heating was applied which, as expected, increased the growth rate (typically by a factor of about 2). Since both cavities may be expected to experience very nearly the same superheat, the value of B should not, according to [3], depend on the cavity radius and this was

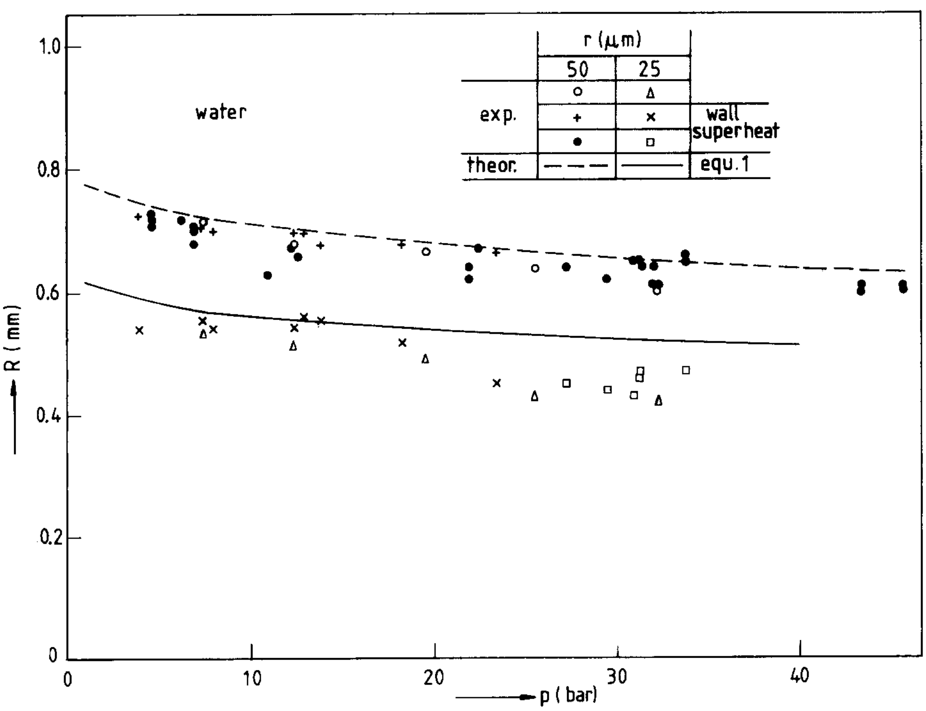

Figure 4. Pressure dependence of departure radius R for water.

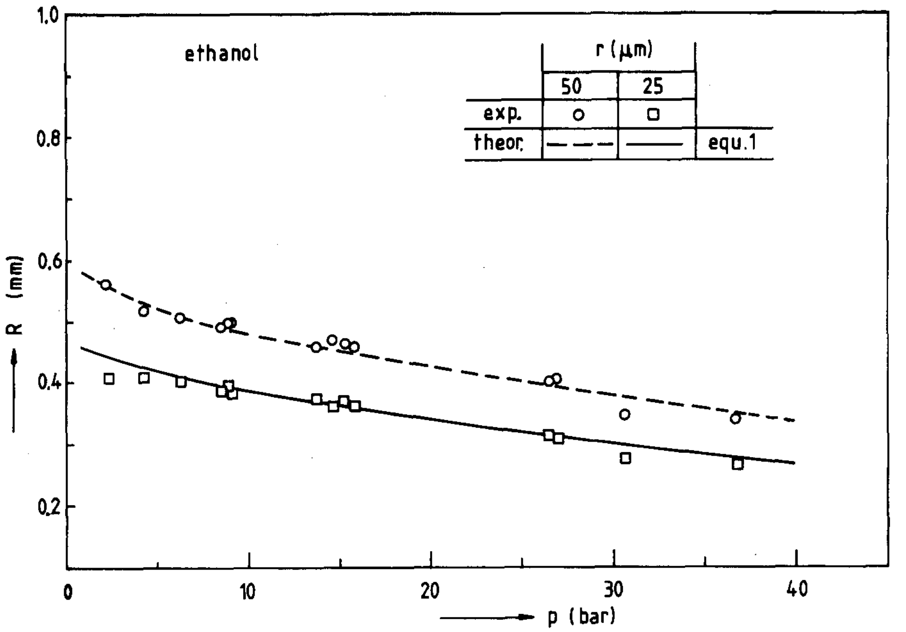

Figure 5. Pressure dependence of departure radius R for ethanol.

confirmed by the measured growth rates. In these and other series, the values of B concerned ranged between 1.4×10^{-3} and $2.8 \times 10^{-4}\,ms^{-1/2}$ (corresponding, via [7], to a superheat between 1 – 4°C). Since the value of B_{trans} given by [6] is about 4.7×10^{-3} for the smaller cavity and 5.6×10^{-3} for the larger, the slow-growth model would be expected to apply to a good approximation in all cases.

The results seem to bear this out, though the predicted values of R are generally too high, particularly in the case of the smaller cavity. The explanation of this discrepancy was found to lie in the deposition of small quantities of minerals (visible under the microscope) at the cavity edge. This explanation was confirmed by the excellent agreement with the slow-gwoth theory obtained using ethanol after cleaning the cavities (figure 5). Consistent too with the slow-growth model was the fact that at a given pressure the departure radius was independent of the degree of wall heating applied and hence of the growth rate.

4. FINAL DISCUSSION AND CONCLUSIONS

The results obtained on well-defined, sharp-edged cavities confirm the expectation that at "slow" growth rates ($B \ll B_{trans}$) bubble departure sizes are determined to a good first approximation by a balance between surface tension and buoyancy forces, the departure radius in the case of confined growth being given by [1]. As noted in paper I, this slow-growth model should apply to most situations of pool boiling at atmospheric or high pressures.

Relation [1] predicts only a slight diminution of the departure radius with increasing pressure (confirmed by the present observations), whereas various investigations of pool boiling on natural cavities (Semeria 1962; Tolubinsky & Ostrovsky 1966) have indicated a more rapid diminution. As concluded tentatively in paper I, this must therefore be attributed to the shifting of the distribution of active cavities to smaller sizes. A factor to be borne in mind in this connection is the possible reduction of cavity sizes due to mineral deposition there.

Finally, the results provide further evidence that the growth of bubbles on cavities in metal surface occurs according to the *confined*, rather than the spreading mode.

REFERENCES

CHESTERS, A. K. 1977 An analytical solution for the profile and volume of a small drop or bubble symmetrical about a vertical axis. *J. Fluid Mech.* **81,** 609–624.

CHESTERS, A. K. 1978 Models of bubble growth in the slow-formation regime of pool boiling. *Int. J. Multiphase Flow* **4,** 279–302.

SEMERIA, R. L. 1962. An experimental study of the characteristics of vapour bubbles. Presented at the *Symp. on Two-phase Fluid Flow*, Inst. Mech. Engrs, London, Paper 7.

SLOOTEN, P. C. 1983 Departure of vapor and gas bubbles in a wide pressure range. Ph.D. Thesis, Eindhoven Univ. of Technology, The Netherlands.

TOLUBINSKY, V. I. & OSTROVSKY, J. N. 1966 On the mechanism of boiling heat transfer (vapour bubbles growth in the process of boiling of liquids, solutions and binary mixture). *Int. J. Heat Mass Transfer* **9,** 1463–1470.