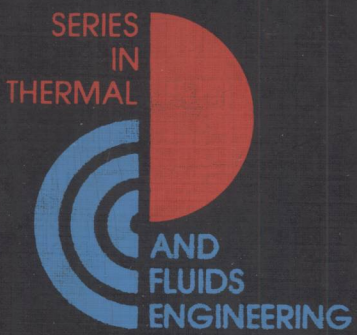
SJOERD VAN STRALEN
ROBERT COLE

Boiling Phenomena

VOLUME 2



BOILING PHENOMENA

Physicochemical and Engineering Fundamentals and Applications

Volume 2

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With Invited Contributions

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This book is dedicated to the memory of my beloved wife Alida Leijerweert, who encouraged and inspired me in close harmony during two happy decades. (SvS)

BOILING PHENOMENA: Physicochemical and Engineering Fundamentals and Applications

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Preface

In 1973, the editorial board of the Dutch journal *Polytechnisch Tijdschrift*, edition *Procestechniek* (editors H.J. Meemeling and Ir. F.J.G. Kwanten) kindly invited one of us (S) to write a contribution on film boiling. Ultimately, this invitation resulted in a series of 16 papers entitled "Kookverschijnselen" (Boiling Phenomena), which appeared during 1974–1979. This series formed the basis for the present book.

During a sabbatical stay (1971–1972) at Eindhoven University of Technology, one of us (C) presented a series of lectures on boiling nucleation and nucleate-boiling heat transfer. Revised and extended versions of these lectures have been incorporated into the present book.

While preparing the manuscript, we became aware of the desirability of including a number of chapters on additional (but related) topics by invited specialists. Their contributions increase the versatility of the book and, in some instances, present differing but complementary opinions. Also, we have included a number of recent developments and results that have not yet appeared in the published literature.

We confess that the preparation of a book on the physical basis of boiling phenomena is (at this time) still a precarious enterprise. Nevertheless, we hope that the book may be a reliable guide to both research workers and graduate students, and may inspire them to establish a further understanding of the fundamental phenomena and their applications to complex engineering systems.

Sjoerd van Stralen
Robert Cole

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We are indebted to Professor D.A. de Vries for continued friendly cooperation, support, and encouragement over a period of many years. Thanks are due to W.M. Sluyter, C.A. Copray, J.G.M. Niessen, A.G.M. Linssen, W.A.M. Aarnink, Mrs. H. Weise-Bornebroek, and the "Reproduction Service" (all of Eindhoven University), Mrs. Marlene Wright (Clarkson College), and many others for assistance in the preparation of the manuscript, the artwork, and the index.

We also acknowledge the enjoyable cooperation of the invited contributors, and that of the president (Mr. W. Begell) and the editors of Hemisphere Publishing Corporation. Further, we wish to acknowledge the kind invitation of Professors J.P. Hartnett, T.F. Irvine, and J.P. Holman to include the book in the Series in Thermal and Fluids Engineering.

Permission has been granted to one of us (S) by the editorial board of the *Polytechnisch Tijdschrift*, edition *Procestechniek*, and by the Pergamon Press, Ltd., to translate or reprint material from his published papers; reprinted material originally appeared in the *International Journal of Heat and Mass Transfer*, volumes 9–22 (1966–1979).

Sjoerd van Stralen
Robert Cole

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VII

BUBBLE GROWTH RATES IN NUCLEATE BOILING AT SUBATMOSPHERIC PRESSURES

14

The Evaporation Microlayer in Pure Systems

Sjoerd van Stralen

1 INTRODUCTION

1.1 Nucleation

In Chap. 5, it was stressed that initial vapor-bubble generation during boiling occurs on so-called nuclei at a superheated wall. Preferably, poorly wetted and partly gas- or vapor-filled cavities serve as nuclei. These are activated at moderate wall superheating.

According to the homogeneous nucleation theories for initial uniform liquid superheating θ_0 (Chap. 3), only vapor clusters with a certain radius R_0 are in metastable equilibrium with the surrounding liquid:

$$R_0 = \frac{2\sigma T}{\rho_2 l \theta_0} \tag{1}$$

Under the condition of an initially uniform system superheating (i.e., the wall superheating equals the liquid superheating; Chaps. 3 and 5) in heterogenous nucleation, Eq. (1) is valid in a certain range of contact angles. The contact angle characterizes the wetting of the surface and influences the bubble shape. The radius R_0 denotes the radius of the cavity at the heating surface. In the derivation of Eq. (1), the pressure of inert gas in the cavity is neglected.

In the more complicated case of heterogenous nucleation at nonuniform system superheating (in which the wall superheating exceeds the liquid superheating), Eq. (1) is still basic; θ_0 then denotes the wall superheating.

For homogeneous nucleation, which occurs generally at $\theta_0 \approx 100$ K, the nucleus radius R_0 is of the order of 1–10 nm. For heterogenous nucleation on commonly used heating surfaces, R_0 (the cavity radius) is of the order of 1–10 μm at a wall superheating $\theta_0 \approx 10$ K. Generally, R_0 is small in comparison with the thickness of the thermal boundary layer at the heating surface, the latter being of the order of 100 μm. As a

consequence, the initial superheating at the entire bubble wall equals $\theta_R(0) = \theta_{R_0} = \theta_0$.

1.2 Growth Rates of Vapor Bubbles

The course of the growth of a vapor bubble in nucleate boiling is complicated by the nonuniformity of the initial temperature field surrounding the bubble. The bubble originates in a superheated thermal boundary layer and pushes it locally away from the heating surface. According to van Stralen, this layer is denoted as a "relaxation microlayer" that surrounds the lower part of the bubble wall. The relaxation microlayer cools during bubble growth, as a consequence of the requirement of latent heat of vaporization at the bubble boundary (Chaps. 9 and 21).

During the advanced (diffusion-controlled) mode of growth, the instantaneous superheating $\theta_R(t)$ at the bubble interface has already been diminished from $\theta_{R_0}(0) = \theta_0$ to zero. Initial bubble growth is governed by hydrodynamics: The bubble is "blown up" due to an excess pressure, which corresponds to a superheating $\theta_R(t) > 0$. In the case $\theta_R(t) \equiv \theta_0$, early bubble growth is an isothermal process. Advanced (asymptotic) bubble growth, which is characterized by $\theta_R(\infty) = 0$, is isobaric, and has been reduced to a heat-conduction process.

Decreasing ambient pressure extends the initial stage of growth. Consequently, bubble growth is most complicated at subatmospheric pressure. An additional complication arises from the formation of a thin liquid layer ("evaporation microlayer" according to Mesler) beneath the hemispherical bubble (Fig. 1). During bubble growth, this layer (which has an initial thickness of 1–10 μm) evaporates, starting at the center, where a "dry spot" occurs at the heating surface. Also, the behavior of vapor bubbles during local boiling must be described by a suitable combination of isothermal and isobaric modes.

2 INITIAL ISOTHERMAL BUBBLE GROWTH

2.1 The Rayleigh Equation of Motion

Rayleigh [1] derived a nonlinear differential equation of the second order for the radius $R(t)$ of a spherical cavity (with initial radius R_0 and a constant excess pressure Δp) in an inviscid, incompressible, infinitely extended liquid that is initially at rest. The derivation, given in Sect. 2.2.2 of Chap. 7, results in the following equation of motion:

$$\frac{1}{2R^2\dot{R}}\frac{d}{dt}(R^3\dot{R}^2) = R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{\Delta p}{\rho_1} \tag{2}$$

In the asymptotic case ($R/R_0 \to \infty$), the radius increases with time:

$$R(t) \cong \left(\frac{2\Delta p}{3\rho_1}\right)^{1/2} t \tag{3}$$

i.e., the radial growth rate $\dot{R} = \text{const}$.

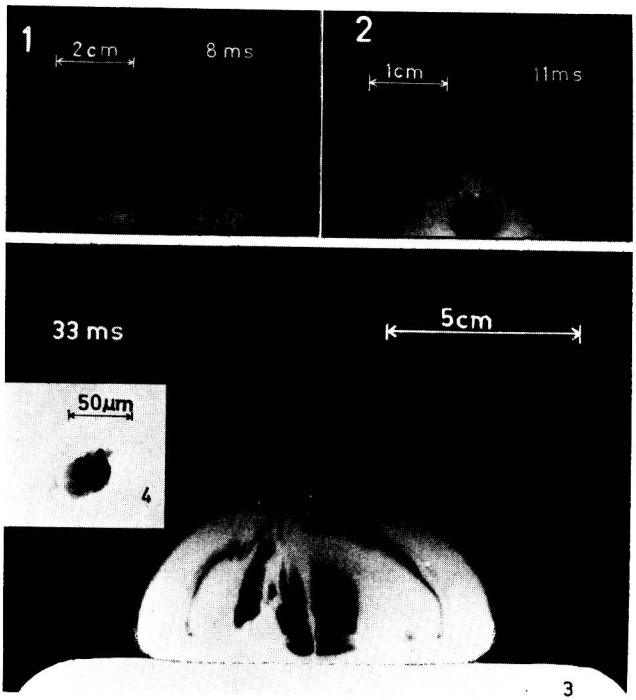

Fig. 1 Water boiling at 26.72 kPa (1) and at 2.04 kPa (2, 3). (1–3) Initial mode of hemispheric growth of adhering vapor bubble. (4) Artificial nucleus.

2.2 The Extended Rayleigh Equation

Forster and Zuber [2], Plesset and Zwick [3], and Scriven [4] extended Eq. (2) to the case of a spherical vapor bubble in an initially uniformly superheated, viscous, infinite liquid:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{\Delta p(t)}{\rho_1} - \frac{2\sigma}{\rho_1 R} - 4\nu\frac{\dot{R}}{R} = \frac{2\sigma}{\rho_1 R_0}\frac{\theta_R(t)}{\theta_0} - \frac{2\sigma}{\rho_1 R} - 4\nu\frac{\dot{R}}{R} \tag{4}$$

The derivation of Eq. (4) is based on the assumption of thermodynamic equilibrium at the bubble boundary: The initial excess pressure is $\Delta p(0) = 2\sigma/R_0$, as $\theta_{R_0}(0) = \theta_0$; $\Delta p(t)/\Delta p(0) = \theta_R(t)/\theta_0$ follows, as in the derivation of Eq. (1), from the Clapeyron equation: $\Delta p(t) = (\rho_2 l/T)\theta_R(t)$ (cf. Chap. 7). A negative surface-tension term [expressing the fact that the required excess pressure $p(t) = 2\sigma/R(t)$ is not available for bubble growth] and a negative viscosity term are added to the right side of Eq. (4). Both terms can be neglected for $\theta_R(t)/\theta_0 \gg R_0/R$, and for liquids (e.g., water) with a relatively small kinematic viscosity. Obviously, the right side of Eq. (4) is approximately zero as $t \to 0$ because $R(0) = R_0$ and $\theta_R(0) = \theta_0$, that is, $\ddot{R}(0) = \dot{R}(0) = 0$, which expresses metastable equilibrium [cf. Eq. (1)].

Generally, Eq. (4) is simplified by inserting Eq. (1), which yields the following

equation of motion for $R \gg R_0$:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{\rho_2 l}{\rho_1 T}\theta_R(t) \tag{5}$$

The Rayleigh solution of Eq. (5) is in the *initially isothermal* case, for which $\theta_R(t) \equiv \theta_0 = \text{const}$ and R_0 is neglected:

$$R_1(t) \cong \left(\frac{2\rho_2 l\theta_0}{3\rho_1 T}\right)^{1/2} t = Bt \tag{6}$$

Apparently, Eq. (6) can also be derived by inserting $\Delta p(t) \equiv \Delta p(0) = (\rho_2 l/T)\theta_0$, the Clapeyron equation, into Eq. (3).

2.3 The Decrease in Superheating at the Bubble Boundary

In Eq. (86) of Chap. 7, the following expression for the instantaneous superheating of the bubble boundary was derived:

$$\theta_R(t) = \theta_0 \left[1 - \frac{2}{(\pi a)^{1/2}} \frac{\dot{R}t^{1/2}}{\text{Ja}}\right] \tag{7}$$

Actually, Eq. (7) is based on the concept of a constant heat flux density $\rho_2 l\dot{R}$ toward the bubble boundary. Substitution of the (after a short initial stage) valid Rayleigh solution (6) yields the following expression for the instantaneous superheating at the bubble boundary:

$$\theta_R(t) = \theta_0 - \frac{2}{\pi^{1/2}} \frac{a^{1/2}}{k} \rho_2 l \left(\frac{2\rho_2 l\theta_0}{3\rho_1 T}\right)^{1/2} t^{1/2} \tag{8}$$

Substitution of $\theta_R(t)$ into Eq. (5) yields a complicated expression for the bubble radius.

Numerical Example

For water boiling at a pressure of 7.8 kPa, this results in $\theta_R(t) = \theta_0 - 43.8{\theta_0}^{1/2}t^{1/2}$; for a realistic value $\theta_0 = 30$ K, $\theta_R(t) = 30 - 240t^{1/2}$. After $t = 4$ ms, the superheating of the bubble wall has diminished to 15 K, half the original value. The decrease in the superheating at the bubble wall is proportional to ${\rho_2}^{3/2} \sim p^{3/2}$; so as pressure increases, $\theta_R(t)$ decreases rapidly. One calculates a decrease of up to half of 30 K in $t = 80$ μs for water boiling at atmospheric pressure. This implies the minor role of the Rayleigh solution (6) at higher pressures; vapor-bubble growth is then nearly completely governed by heat diffusion.

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