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Boiling Phenomena

VOLUME 1

SERIES IN THERMAL AND FLUIDS ENGINEERING

BOILING PHENOMENA

Physicochemical and Engineering Fundamentals and Applications

Volume 1

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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

Contents

Survey of Boiling Phenomena

Sjoerd van Stralen

1 PHYSICAL AND MATHEMATICAL BACKGROUND

Boiling phenomena occur during the combined transport of energy, momentum, and matter in the two-phase flow of boiling media. Physical transport phenomena are mathematically described by a system of coupled nonlinear partial differential equations expressing the conservation of energy, momentum, and mass.

In general, boiling phenomena are very complicated, owing to the interaction of a number of factors or effects. Because of the nonlinearity of the basic equations, hydrodynamic or thermal instabilities may occur under certain conditions—for instance, the instantaneous transition from laminar flow to turbulence. To avoid difficulties in solving the basic equations, generally the connection between the one-phase heat transfer and the temperature and flow field is expressed in semiempirical relations between characteristic dimensionless numbers. These "correlations" are independent of the applied scale. Although interfaces between the phases are present, as a rule two-phase flow is reduced to the corresponding one-phase flow of the liquid. A recent development is the application of numerical methods to two-phase problems with nonstationary boundary conditions resulting from moving boundaries. Boiling can occur only if at least a part of the available liquid is superheated, i.e., at a temperature exceeding the saturation temperature at ambient pressure. Vapor bubbles are generated on activated nuclei (Fig. 2). Figure 3 shows the regions of metastable superheated liquid and subcooled vapor.

2 INSTRUMENTATION

Apart from the global information, local information on the fluctuating parameters should also be available. For this purpose, the application of very advanced measuring techniques is required—for example, (ultra) high-speed cinematography, holographic interferometry, the laser-Doppler method, the application of pulse lasers, velocity and vapor fraction measuring devices, and fast temperature and pressure recorders.

3 APPLICATIONS

Important fields of technical application are energy supply (nuclear engineering and water electrolysis, or the "hydrogen economy" as a promising alternative to fossil fuels in the future); heat and refrigeration technology (heat exchangers, machines, and pumps); process engineering (distillation, condensation, dairy engineering); and space travel.

Because of the recent "energy crisis," society is aware of the immense social and industrial importance of developing traditional and new alternative primary energy sources (solar energy, wind energy, water energy, coal gasification, methanol production, hydrogen production, nuclear energy, fast breeders, etc.). In the field of boiling phenomena, most attention is paid to practical utilization. There is a gulf between the methods and procedures applied by designers and by research workers; the former

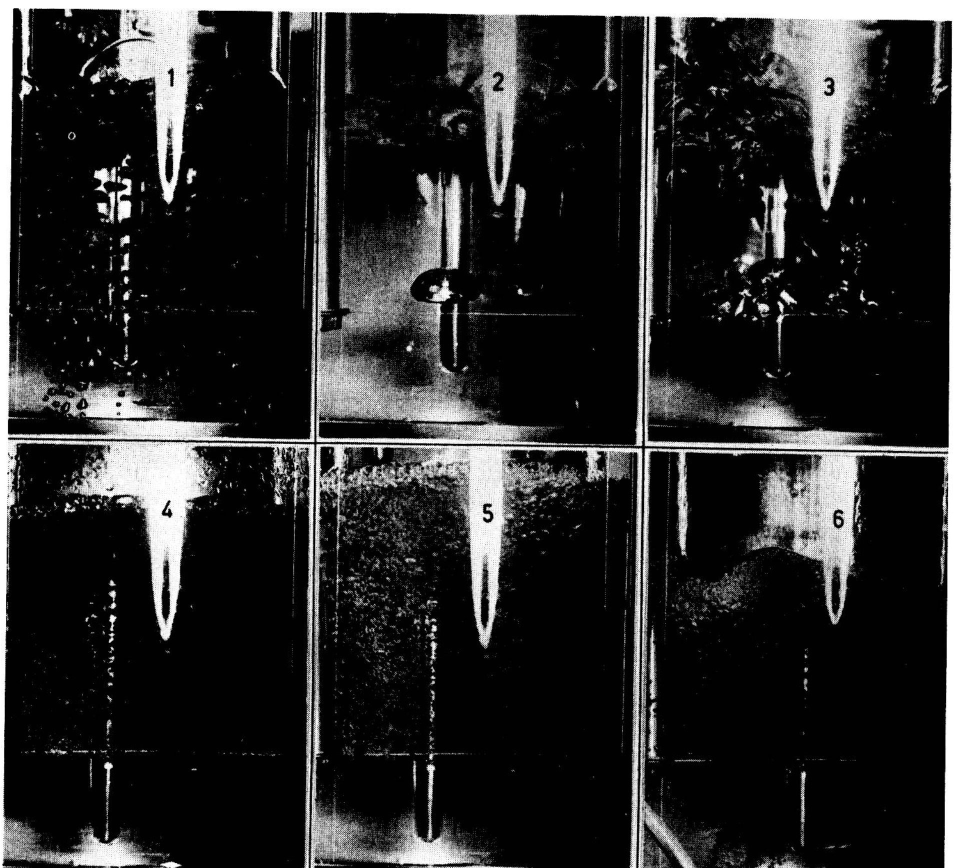

FIG. 1 Behavior of vapor bubbles in boiling liquids. Parts 1–3: water. (1) Nucleate boiling at atmospheric pressure; (2) nucleate boiling at 0.13 bar; (3) film boiling at 0.13 bar. Parts 4–6: aqueous mixtures, nucleate boiling at atmospheric pressure. (4) 4.1 wt% 2-butanone; (5) 12.7 wt% 2-butanone; (6) 6.0 wt% 2-butanone.

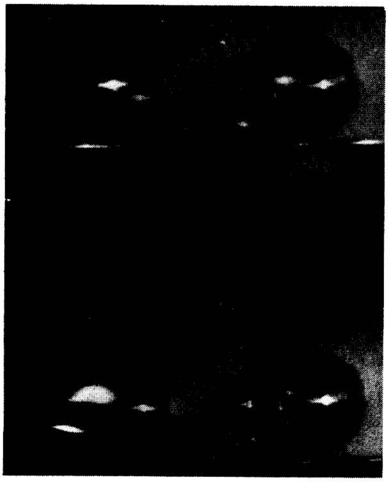

FIG. 2 Water. A series of photos of vapor bubbles generated on an electrically heated wire at atmospheric pressure. The photos were taken at the rate of 3000 frames/s.

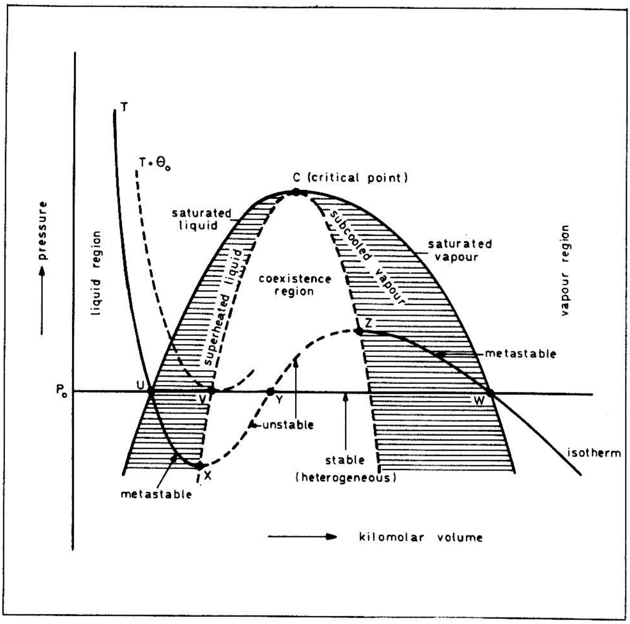

FIG. 3 Schematic graph of van der Waals' equation of state, showing metastable regions of superheated liquid and subcooled vapor. θ_0 denotes the maximum superheating of a liquid with usual boiling point T at pressure p.

are mainly interested in systems, the latter in phenomena. Although essential progress has been made during the last decades in understanding the basic mechanisms governing boiling heat transfer, much effort will have to be directed to the study of complicated systems in which a number of basic phenomena interact. In this regard, investigations on phenomena occurring during transitional processes are indispensable. On the other hand, comparisons of theoretical models with careful experiments require the further development of refined instruments that give exact information on the local conditions in fluctuating flow and temperature fields. Obviously, a natural restriction on insights into boiling phenomena results from the present state of knowledge of stochastic processes and its applicability to physical phenomena such as turbulence.

4 EXAMPLES

Some illustrative examples of research results on boiling phenomena are given below.

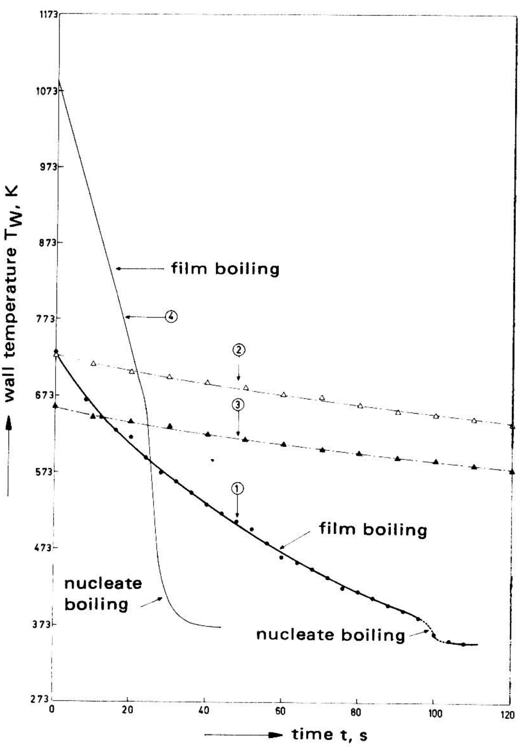

FIG. 4 Cooling of: (1) A copper cylinder in boiling ethanol mixture (atmospheric boiling point: 351 K). (2) The same cylinder in air at room temperature (295 K). (3) The same cylinder with black surface in air at room temperature. The cooling rate is increased because of radiant transport. (4) A nickel-alloy rod in slightly subcooled water at 371 K. The quenching of hot bodies in liquids is initially governed by film boiling. The body is surrounded with a coherent vapor film. At sufficiently low wall superheating, a transition occurs to nucleate boiling with high heat fluxes.

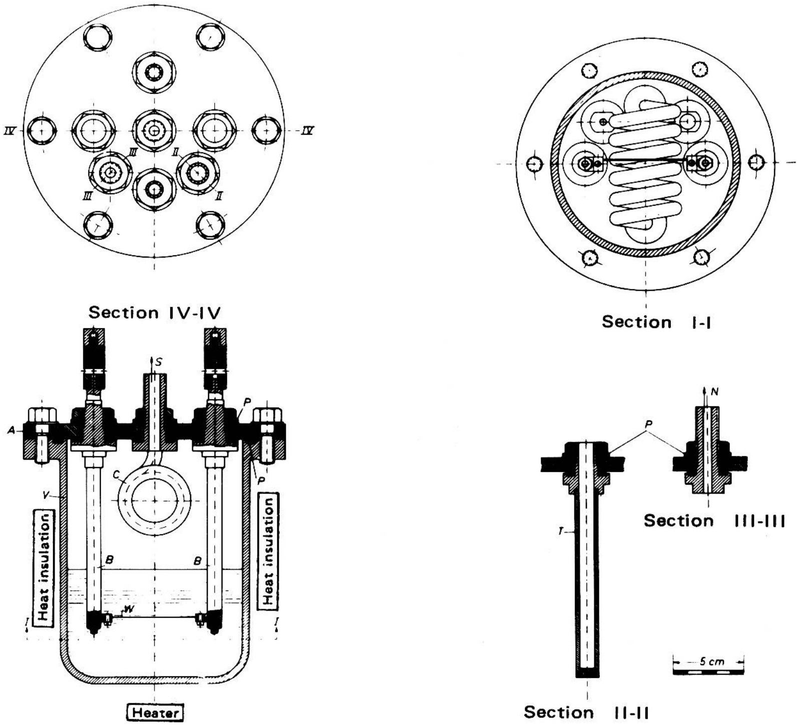

FIG. 5 Stainless-steel boiling vessel for the determination of boiling curves (see Fig. 6). A = stainless steel (ss) cover; B = ss bars; C = ss water-cooled total reflux condenser; N = ss pressure gauge, nitrogen cylinder, and ss Cartesian manostat (at pressures below 5 bar); p = packing; S = ss safety valve; T = ss thermometer tube; V = ss vessel; W = heating wire.

4.1 High Heat Fluxes

In a large number of applications, boiling liquids are used for the storage of thermal energy or as coolants (Fig. 4), the latter especially at elevated pressures (Figs. 5–8), in forced convection (Fig. 9), in subcooling (Fig. 10), or preferably with combinations of these effects.

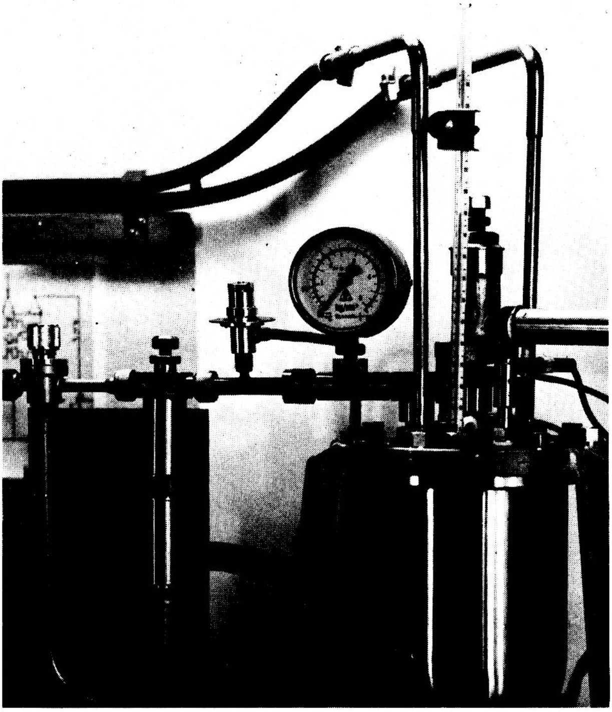

FIG. 6 Boiling vessel with pressure regulator up to 10 bar (see Fig. 5).

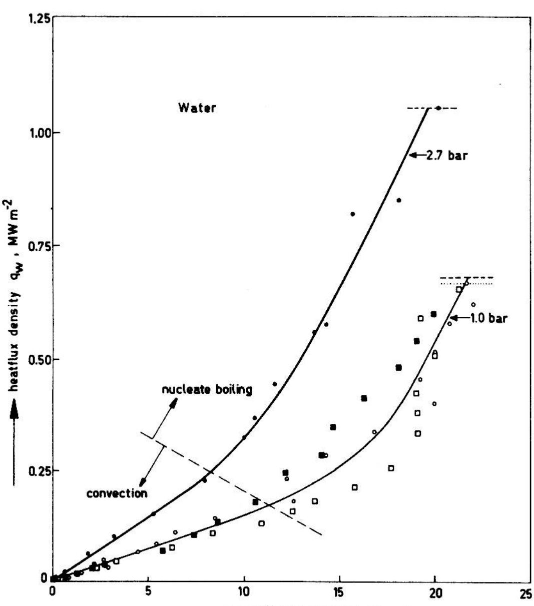

FIG. 7 Water. Regions of convection and nucleate boiling of boiling curve at atmospheric and a higher pressure.