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Micro Transport Phenomena During Boiling

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内 容 简 介

作为热流体工程科学中最具挑战性的研究课题之一，沸腾现象在微型能源系统、微电子和发光二极管冷却、高密度紧凑式装置或系统、高热流密度散热和热管理等方面的应用，以及沸腾现象的复杂性和多样性一直受到高度关注，其物理本质的研究因而成为一大热点。本书从微细尺度沸腾研究基础理论、沸腾的微尺度特征和理论、微尺度沸腾与传递现象的描述、微尺度沸腾传递的应用几个侧面分析这一领域的最新进展，系统地描述了这一现象并给出了基础理论的框架。

本书可供大学和研究院所力学、热物理、能源、微电子等专业的研究人员和本科高年级学生、研究生阅读参考。

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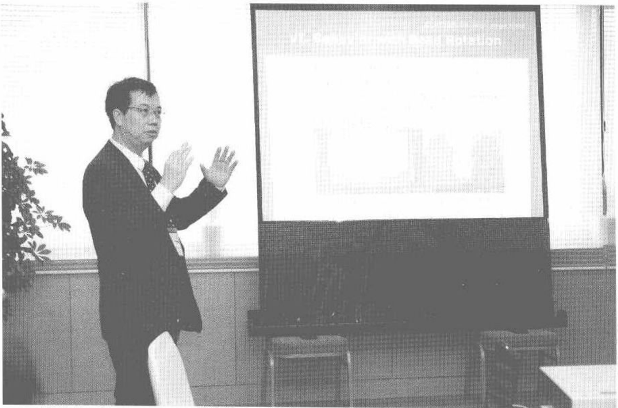

Prof. Xiaofeng Peng making a speech on heat transfer at Tsinghua Univ. on Oct. 2008.

Prof. Peng with his students July, 2006.

About Author

Dr. X. F. Peng (Xiao-Feng Peng, May 6, 1961—September 10, 2009) was a renowned scholar and professor of the Thermal Engineering Department at Tsinghua University. He received his B.S. and Ph.D degrees from Tsinghua University in 1983 and 1987, respectively. He worked at Tsinghua University all through his career, as Lecturer (1987 – 1991), Associate Professor (1991 – 1995) and Professor (1995 – 2009). He served as Department Head from 1997 to 2002 and received the Cheung Kong Endowed Chair in 2001. He held multiple visiting professorships, and engaged in active collaborations with numerous research institutions in China, USA, France and Korea. His research activities cover the fundamentals of phase-change heat transfer and two-phase flows, interfacial transport phenomena, convective flow boiling, heat and mass transport in porous media, microscale heat transfer, heat transfer under microgravity conditions, cooling technology for thermal management, and micro energy systems. His outstanding research accomplishments won him many prestigious national honors, such as the Science and Technology Research Award (1989), National Natural Science Award (1990), Award for Research Achievement (1996), and the First Prize Award for Natural Scientific Research Achievement (2005). Also Professor Peng was invited to deliver plenary presentations at many international conferences, including the 10th and 11th International Heat Transfer Conferences (1994, 1998) and the 18th International Symposium on Transport Phenomena (2007). He had over 600 publications and presented papers and several contributions to different English books. He also served on the editorial boards of various international and regional scientific journals, including the International Journal of Heat and Mass Transfer and International Communications in Heat and Mass Transfer, International Journal of Transport Phenomena, Experimental Heat Transfer, Heat Transfer Asian Research, and a number of Chinese journals including the Chinese Journal of Engineering Thermophysics. He also served on numerous Chinese and international technical committees.

Preface

This book is based on the excellent fundamental research of Prof. X. F. Peng. Many unique micro transport phenomena during boiling with their corresponding mechanisms have been investigated. This will serve as a special reference for researchers interested in the field of microscale boiling.

Boiling exists widely in the natural world, with boiling heat transfer has been employed in many practical applications. However, due to the highly nonequilibrium and coupled driven effects of the various physical potential, boiling heat and mass transfer is extremely complicated and many interesting phenomena are triggered under different specified conditions. Nowadays, the rapid development of practical engineering applications of boiling in cooling of electronic devices, thermal management of aerospace and micro energy systems, and micro-manufacturing, promote a strong demand for better understanding of microscale transport phenomena and create a notable shift of thermal science and heat transfer research from macroscale to microscale. Consequently, in recent decades, more and more investigations have been conducted to explore the micro transport phenomena during boiling. This book reviews and summarizes the new achievements and contributions of recent investigations, including the outstanding fundamental research conducted by the writer and his co-authors. The fundamentals for conducting investigations on micro boiling, microscale boiling and transport phenomena, boiling characteristics at microscale, and some important applications of micro boiling transport phenomena are introduced and discussed.

Chapter 1 introduces the background and industrial applications, as well as the research history of boiling, and then, the critical concept of "micro boiling" is described. In Chapter 2, some important thermal physics concepts and principles involved in boiling phenomena, such as phase and phase equilibrium, phase transition, interfacial aspects, contact angle and dynamical contact behavior, and cluster dynamics are described in detail. Chapter 3 introduces new understandings of boiling nucleation and achievements in the latest 20 years. Cluster theory is used to analyze the dynamic characteristics of nucleus formation, with theories for the characteristics of liquid-to-vapor phase change heterogeneous nucleation, and bubble evolution. In Chapter 4, the phase change and interfacial behavior of subcooled pool boiling on ultrathin wires are investigated experimentally and numerically, and a series of interesting phenomena is observed visually and analyzed. In Chapter 5, the complex subcooled boiling phenomena on fine wires is investigated under weakened gravity, and a bubble dynamics equation incorporating the thermocapillary effect is proposed to investigate various kinds of bubble motion such as slippage, separation, collision, oscillation and leaping, indicating that the thermocapillary effect on the bubble interface is very important for the bubble motion. Chapter 6 describes experimental investigations on phase-change transition, bubble nucleation, and bubble dynamics in microchannels conducted by the author and co-workers, including the new concepts of "evaporating space" and "fictitious boiling". Furthermore, the nucleation criterion in microchannels is derived by utilizing thermodynamics and cluster dynamics. Chapter 7 describes experimental investigations conducted to visualize the boiling phenomena, covering nucleate, transition and film boiling regimes and for individual water droplets on the heating surfaces. The oscillation of sessile droplets is investigated experimentally and numerically. Chapter 8 describes the boiling phenomena in micro structures and porous media; the dynamic behavior of bubble interfaces in a confined space, replenishment of liquid during boiling, interfacial heat and mass transfer in pores and occurrence of dryout are analyzed further. Chapter 9 presents visualizations of explosive boiling nucleation phenomena in micro capillary tubes, and liquid exploding emissions, with a correlation for the critical heat flux derived from a scaling analysis.

Prof. Xiaofeng Peng passed away suddenly on Sept. 10^{th}, 2009. As the supervisor of his Ph. D work before 1987 and his research co-worker for a long time, I write this preface with great sadness as a permanent memory to him. I hope this book is helpful and provides inspiration for many researchers and students.

I want to express my appreciation to my colleagues, particularly Prof. Qiang Yao and Prof. Yuanyuan Duan, for their great support and many helpful suggestions. I also thank his research group for their help in preparing the manuscript for publication.

Bu-Xuan Wang
Tsinghua University, Dec., 2009

Contents

1 Introduction

Abstract This chapter describes the importance of boiling research and its applications in modern industry. The history and trends of boiling are also reviewed, and then the scope and definition of "micro boiling", which is the key topic in this book, are described in detail.

Keywords boiling dynamics, micro boiling

1.1 Critical Technology

Boiling phenomena and the associated heat transfer, characterized by small temperature differences and high heat fluxes, are encountered in various energy conversion and utilization systems. The boiling process has been widely employed to improve the heat transfer performance of heating and cooling devices and to meet the increasing demand of high heat removal in various practical applications covering thermal and nuclear power engineering, space, aviation, cryogenic, refrigeration, chemical, food and bioengineering, and other technologies. In the latest 20 years, high-technology applications, such as spacecraft thermal control, aerospace systems, electronic devices and light emitting diodes (LED) cooling systems, micro-electro-mechanical systems (MEMS), and biological and medical systems, have further promoted more comprehensive investigations into boiling and other phase change phenomena.

Recent trends in science and technology have indicated an increasing emphasis on miniaturization of engineering systems with/without extremely fast processes and study of micro- and nano-scale phenomena [1 – 3]. Actually modern technologies and industrial developments have brought a drastic reduction in size of computers, electronic chips/components, laser devices, micro energy systems, compact heat exchangers and employed in various kinds of the micro-sensors and micro-actuators. In these systems and devices having characteristic lengths of several microns to 500 microns, mass and energy transport are always important and play critical roles in their performance and/or their safe operation. Apparently, the reduced characteristic size strongly affects the thermal fluid flow and transport processes, particularly suppressing boiling nucleation, vapor bubble formation, phase distribution and two phase flow development, and associated boiling heat transfer for micro boiling systems. As one important topic for microscale transport phenomena, the micro boiling has attracted great attention of investigators all over the world [2, 4 – 10].

Of the variety of innovative and high performance micro cooling technologies, the highly potential one is microchanneled sink technology of metal and silicone substrates in which flow boiling and two phase flow heat transfer occurs, and it is widely recognized that this kind of heat sinks can reach a high heat removal rate of 300 W/cm^2 [11]. Actually, various micro boiling and evaporation phenomena are critical transport processes encountered in many innovative technologies and practical applications, such as micro heat pipes, fuel cells, impinging and spreading cooling devices, ultra-compact heat exchangers, micro bio-systems/devices, micro mixers and separators, micro reactors, and other micro thermal devices/systems.

1.2 History and Trends of Boiling

As a normal recognition, the earliest work of boiling is the Leidenfrost's experiment in which the Leidenfrost phenomenon was observed and described [12], while the practical application where boiling was first encountered can be traced back to the alchemy [13]. However, boiling was recognized as a way having enormous potential for transferring heat at low temperature differences only in the 1930s, and this time has been known as the beginning of modern boiling research. In 1934 Nukiyama firstly described the basic characteristics of pool boiling on a wire, particularly the boiling regimes and associated heat transfer modes, normally termed as the boiling curve. Later, many researchers focused their research on understanding macroscopic phenomena and determining heat transfer performance, such as boiling nucleation, different boiling modes and transition, boiling heat transfer and associated heat transfer enhancement [3 – 4]. In more recent literature, the attention has shifted to explore new phenomena associated with microscale effects, micro gravity effects, electromagnetism effects, and so on [5 – 7]. Some high technological applications of boiling phenomena, like thermal ink jet printer and MEMS, bubble and nucleation driving or propulsion, have made researchers pay more attention to understand bubble dynamical behavior [8].

The boiling investigation mainly includes nucleation theory, bubble dynamics, and boiling mode and associated heat transfer characteristics [9]. In the boiling systems, the bubbles occur through a nucleation process. The nucleation is usually a nanoscale/microscale process, and it can be described by statistical mechanics and kinetic theory. The bubble dynamics is one of the critical problems in boiling research [10], and it directly affects the boiling heat transfer performance. The bubbling phenomena are very complex, because there are various forces and special structures in the boiling fluid systems. The boiling usually has three modes: nucleate boiling, transition boiling, and film boiling. The heat transfer performance of different modes is critical important to the equipments with boiling processes, so various empirical correlations and physical models have been proposed to describe and predict the boiling heat transfer. '

In general, two main reasons including practical and scientific requirements continuously improve the boiling investigation. Firstly, boiling is a very efficient mode of heat transfer and is employed in various energy systems and other practical applications. Secondly, boiling is a very complex process and understanding its physical nature is a very challenging work closely associated with many fundamental disciplines, or interdisciplinary nature is a critical aspect in the research. Since fewer studiers have focused on the physics of the boiling systems, it focused on the boiling physical nature especially its dynamics. The nucleation process was mainly investigated in three aspects: inception phenomena, evolution process, and microscale effect. Experimental investigation, theoretical analyses, and numerical method were conducted to study the dynamics of immobile and moving bubble during the subcooled boiling of water on heating wires. Additionally, the heat transfer performance of different boiling modes during the abrupt cooling was described, and the boiling stability was also theoretically analyzed.

A brief review of the boiling dynamics and an introduction to current studies were presented in this chapter. Because of the practical and scientific requirements, the boiling investigation is a very challenging work, and it can be mainly divided into three sections: nucleation theory, bubble dynamics, and boiling mode. Available literature is cited to introduce the boiling dynamics and associated research, and some problems are further pointed out. The boiling physical nature especially various dynamic behaviors are focused on, and its objective and content are also described in detail.

1.3 Micro Boiling

So far, the available investigations of micro boiling have almost been conducted in microchannels, especially the evaporation in microchannels. Although the great number of publications and research work was contributed to understand microscale thermal-fluid science and transport phenomena, mostly in microchannels, there is still no generally accepted definition of the word, "microscale". As a simple and generally used word, it means that the hydraulic diameter of a microchannel is in the micrometer range, or the very large size range of 1 – 1000 μm. However, it is expected that the definition will be significantly different for boiling in microchannels due to the process of nucleation or bubble formation. For example, boling and two phase flow in channels having hydraulic diameters up to several millimeters can not be described using classical theories [6]. Thome et al. [14] discussed these different definitions appeared in the literature under different situations. They suggested that a threshold is chosen to define bubble flow as the criterion of microchannel size, below which macroscale theories become unreliable for predicting flow boiling heat transfer coefficients, two phase flow pattern transitions, two phase pressure drops and critical heat flux (CHF).

In this book, the similar considerations are adapted. The term of the micro boiling dedicates that the boiling characteristics are significantly influenced by and/or dependent of the size at which boiling occurs, or greatly deviated from the classical boiling theory. This is to say, an emphasis is addressed on the boiling phenomena closely associated with size effects, rather than trying to reach a general conclusion on a popularly accepted definition of the micro boiling. For a more comprehensive consideration not only in micro-tubes/channnels, attention is also paid to explore new micro boiling phenomena in microstructure (or porous pores) and during any practical boiling processes, and re-recognize classical boiling phenomena and theories at microscale level.

Complexity of boiling phenomenon is connected with combination of phase conversion and turbulence in an area with irregular internal structure.

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