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Preface

On the Advancements in Boiling, Two-Phase Flow Heat Transfer, and Interfacial Phenomena

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Introduction

Phase change by boiling or evaporation is a highly efficient heat transport mechanism, which accommodates large heat fluxes with relatively small driving temperature differences. This mode of heat transfer is in fact encountered in a wide spectrum of engineering systems that include, among others, energy conversion, refrigeration and air-conditioning, chemical thermal processing, heat treatment and manufacturing, microelectronic cooling, and numerous microscale devices (microelectromechanical systems (MEMS), MTMS, μ-TAS, sensors, microheat pipes, biochips or lab-on-chips, etc.) that are emerging in the current wave of new developments and changing applications. The consequent research interest, spanning more than two centuries of work with an ever-increasing literature database, is therefore not surprising [1–10]. The energy crunch with attendant needs for higher thermal efficiencies and demands for mitigation of environmental degradation in recent years have further led to efforts to enhance boiling heat transfer [11–15].

The explosive growth in research and its technical literature generation in the last six decades or so [8–10,14,16,17] has considered a variety of fundamental and applied aspects of this intrinsically complex heat transport process in order to advance our basic understanding as well as provide design tools. The continued interest in the field is further articulated in the set of papers appearing in this special issue of the *Journal of Heat Transfer*, and they address the many technical challenges that are still presented by the intricacies of heat transfer by means of boiling and forced-convective two-phase flow, and the concomitant interfacial phenomena. In its evolutionary essence, this field of scientific and engineering engagement is at once quite ancient in its simplicity and elegance of application, and yet complexly modern in its experimental investigations, theoretical modeling, and computational simulations [16,18–20].

Historical Antecedents

Given the present-day advancements in our understanding of boiling, two-phase flow heat transfer, and interfacial phenomena, and the many yet to be resolved issues with the fundamental physics and optimal applications, it is instructive to reflect briefly upon the historical antecedents of the field. An excellent and insightful review of the work up to 1981, with exhaustive annotations that characterize both fundamental and applications-driven developments in the multifacetted unfolding of phase-change heat transfer, has been provided by Bergles [16]. This is further supplemented by the 1987 review by Nishikawa [18], providing a good commentary to link the evolution of basic understanding of boiling with engineering practice as well as the development of enhancement techniques.

The quest to develop mechanical devices based on two-phase processes in ancient western traditions, and as recounted by Bergles [16], can be traced to Archimedes (~287–212 B.C.E.) [21] and the whirling aeolipile of Heron of Alexandria (~60 C.E.) [22]. It was more than 1650 years later that phase-change machines became the prime movers of the Industrial Revolution (~1750–1850), epitomized by the development of a single-acting steam engine by Watt and the subsequent steam-engine-powered locomotives [16,23]. An understanding of the phase-change process represented by film boiling also appeared in this period, when in 1756 the German medical doctor Leidenfrost recorded the evaporation behavior of distilled water droplets on a hot iron spoon and the application of this phenomena (distillation or separation by boiling) to determine the quality or proof of wine or brandy [24]. An advanced and elaborate knowledge of distillation and its practical applications, however, predate this in the ancient eastern traditions [19,25–27]. The classical Indian text *Rasarnavam Rastantram* (~500 B.C.E.), and subsequently Nagarjuna's *Rasratnakar* and *Rasaratna Samuchchaya* (~2nd century C.E.) describe the attendant boiling and condensation processes, and a rather intricately refined distillation technology and apparatus were used in ancient India for the distillation of water, wine, mercury, and zinc, among others [26,28]. Also, quite remarkably, a sophisticated understanding of liquid wetting, surface-tension-driven liquid motion, and capillary forces was available in ancient India [25,27]. In the present-day context, these phenomena form an essential part of the interfacial behavior associated with phase-change heat transfer, and are a basis for developing techniques for enhancing boiling and two-phase flow as well as newer microchannel heat exchangers and microfluidic devices [7,13,29,30].

The beginnings of modern day advancements can perhaps be ascribed to the pioneering work in the 1930s by Jakob and Fritz [31,32], and Nukiyama [33]. Jakob and Fritz [31,32] explored effects of boiling history (or nonreproducibility), heater surface roughness, bubble dynamics, and increase in nucleation sites with heat flux. Nukiyama [33] essentially established the complete boiling curve (as measured by heat transfer from an electrically heated platinum wire) and which has become the cornerstone of representing virtually all nucleate boiling results. In the subsequent decade, McAdams [34] reported the subcooled fully devel-

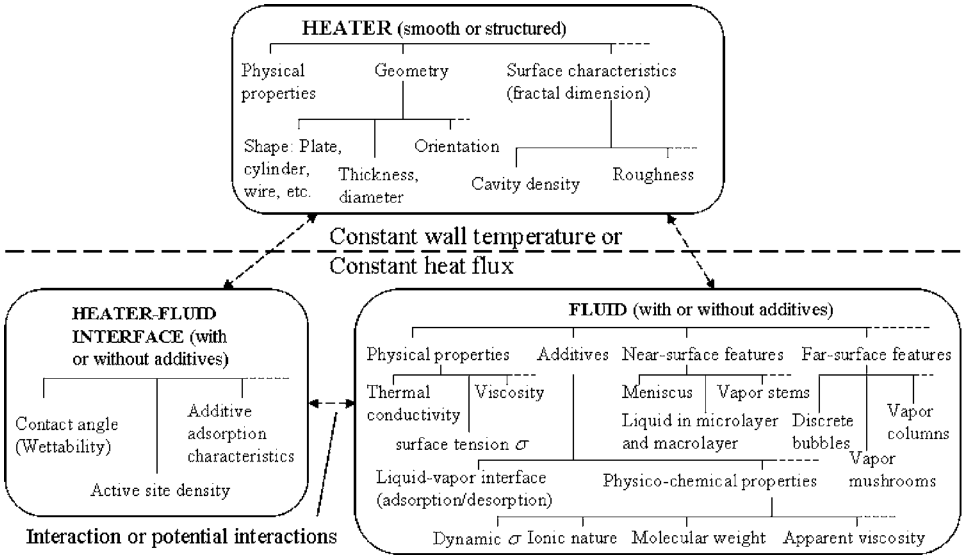


Fig. 1 Schematic statement of the conjugate problem in modeling nucleate boiling heat transfer and attendant interfacial processes (Ref. [43] adapted from Ref. [40])

oped nucleate boiling curve, and Lockhart and Martinelli [35] considered separated two-phase flow pressure drop to develop the classical multiplier function. With rapid developments in nuclear power and aerospace industries in the 1950s, there was an exponential growth in the research literature [16,18]. Notable advancements included the classical nucleate pool boiling correlation proposed by Rohsenow [36], which endures to this day [1–6]. Theoretical models for various mechanistic aspects of the phase-change process (bubble dynamics, microlayer evaporation, nucleation site density and stability, burnout, etc.) were attempted, and they continue to provide the framework for current research. The growing demands for energy and improved process heat transfer efficiencies in the 1960s brought efforts to augment or enhance heat transfer to the fore [12,13,37]. This exploded as a major field of study in the 1970s, driven in part by the space and energy programs and later by the Mid-Eastern countries' "oil embargo." The present-day energy crisis, which is compounded by pressures for mitigating environmental degradation due to excessive energy consumption and imperatives for sustainable development, warrants a generational growth in enhancement science and technology [13,14,38].

In this unfolding, there has been ever growing interest over the last two decades in addressing the problems of two-phase flow and boiling heat transfer, and the concomitant interfacial phenomena. Some of the issues that baffled early research still engage continued activity, as more refined experiments are conducted and theoretical models developed to advance our fundamental as well as applications-oriented understanding [7,12,39–42]. The primary determinants of the general nucleate boiling problem in pure or additive-laden liquids, which has been referred to as a conjugate problem [40,43] that can be essentially classified under three broad categories (heater, fluid, and heater-fluid interface), and the associated potential mechanisms are depicted in Fig. 1. This broad description includes two more prominently employed passive enhancement techniques, by either structuring the heater surface or adding reagents, electrolytes, and/or nanoparticles to the liquid [13,14,44–46]. A direct correlation of the heat transfer with suitable descriptive parameters for all possible phenomenological effects, however, remains elusive because of the intricate nature of the problem.

Current Research

While the complex phase-change heat transfer process in nucleate and/or flow boiling has many parametric determinants, a major part can be considered to be associated with the local heat transfer and hydrodynamics phenomena in the vicinity of ebullience and governed by the solid-liquid-vapor interfacial activity. Schematic illustrations of the primary flow-boiling and CHF regime map, and the interfacial mechanisms that affect liquid-vapor bubble dynamics are given in Fig. 2. In essence, liquid-solid interface wetting and the consequent "film" behavior, along with the transient liquid-vapor interface dynamics and the attendant bubbling characteristics significantly influence boiling performance. The set of papers in this special issue of *Journal of Heat Transfer* address some basic aspects of these processes, as well as issues of heat transfer enhancement and applications of surface-tension driven flow phenomenon.

An extended review of both empirical correlations and mechanistic heat transfer models for predicting the wall heat flux in subcooled flow nucleate boiling is given by Warrier and Dhir [47]. Recognizing the importance of interfacial and microscale effects to the basic boiling and phase-change processes, Fuchs et al. [48], Panchamgam et al. [49], Carey and Wemhoff [50], and Mukherjee and Kandlikar [51] have considered different aspects of thin-film evaporation. Computational simulation, theoretical modeling, and microscale experimentation results are presented to inform the mechanisms that fundamentally govern heat and mass transfer in nucleate pool boiling of pure liquids, binary mixture evaporation, and thin-film phase-change in micropassages. As would be expected in current research [13,14,52], enhancement of heat transfer is the focus of papers by Schneider et al. [53], Ghiu and Joshi [54], and Ahn et al. [55], which explore microchannel flows, performance characteristics of structured surfaces, and novel techniques. Li et al. [56,57] and Cai et al. [58], respectively, have investigated evaporation and CHF in thin capillary wicks, and thermal characteristics of a pulsating heat pipe. Finally, in the best traditions of technical debate and scientific dissemination that bodes well for the vibrancy of heat transfer research, a discussion and its response consider some aspects of the motion of bubbles emanating from a microwire heater.

In his eloquent recounting of the early modern history of boiling and two-phase flow heat transfer, Bergles [16] had predicted that "Looking into the future, there will be much more emphasis on computer solutions of two-phase phenomena." There was also a caveat ("We must remember, however, that the computer codes are only as good as the basic thermal-hydraulic input") with a reminder that experimentation, along with mechanistic modeling, would continue to occupy center stage in scientific and techno-

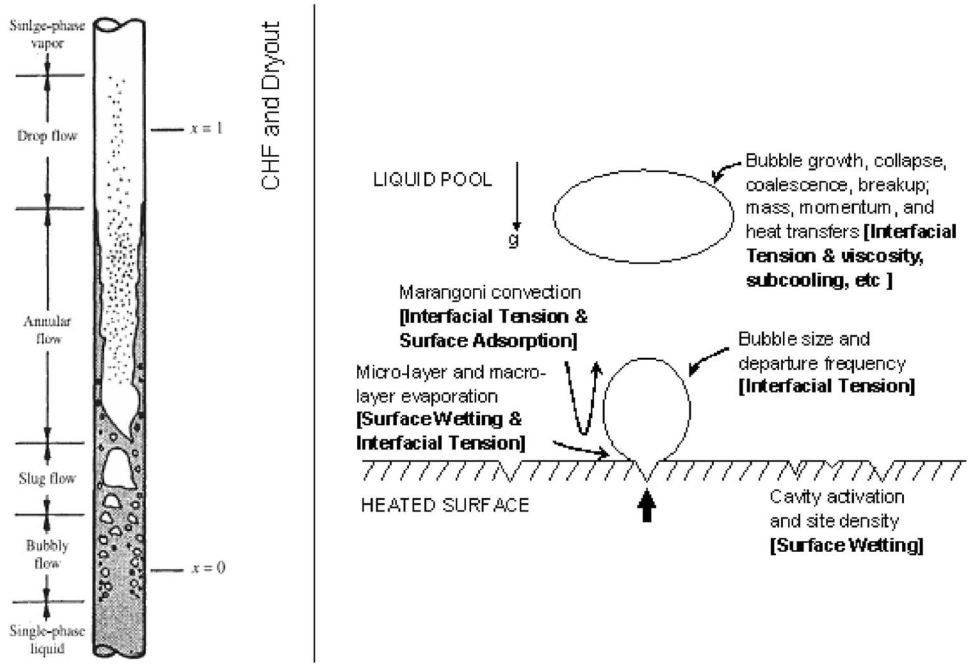


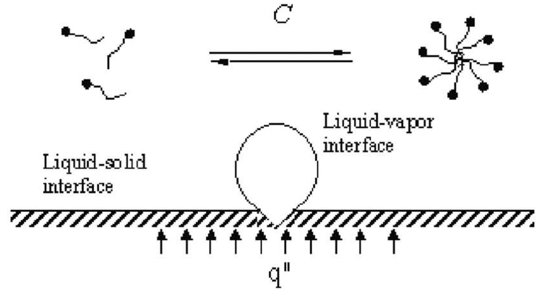
Fig. 2 Flow boiling regimes and CHF in a vertical tube, and the influence of interfacial properties on the nucleation and dynamics of a boiling bubble

logical discoveries. This foresight is indeed reflected in the ensuing articles, and they represent critical efforts in ameliorating imperfections in our understanding of many areas of boiling, two-phase flow heat transfer, and interfacial phenomena, as well as extending the exploitation of these processes to novel and emerging applications.

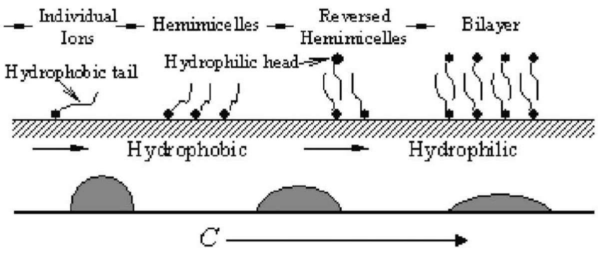
Future Prospects and Directions

One can safely surmise a vibrant and challenging future of this field of study, which can perhaps be predicted to be marked by many more fundamental studies (both experimental and theoretical or computational) that resolve the gaps in our phenomenological understanding, as well as expand the development of application-oriented performance evaluation and design tools. For the latter, as an example, the scrutiny of diminishing length and time scales (mili-, micro-, and nanoscale) has generated various novel devices (MEMS, MTMS, μ-TAS, microsensors, and lab-on-chips, among others) that in many cases exploit boiling and interfacial phenomena. This has attracted considerable attention to issues relating to microchannel flows [7,59,60], particularly for sustaining very high heat fluxes and thermal management of microelectronic devices, and some enterprising sensor and actuator development. Regardless of the scales of applications, nevertheless, the problems in ebullient phase change and interfacial heat and mass transfer abound [16,18,20,38,40] to provide opportunities for exploring hitherto uncharted dimensions as well as advancing our basic understanding.

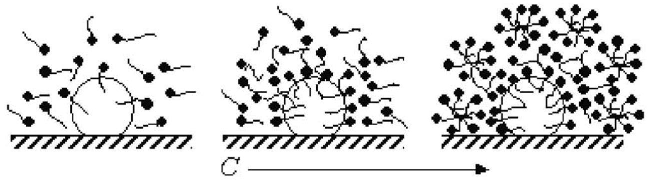
An especially vital component of future research, given the growing problems of diminishing energy availability, environmental damage, and thermal management in new technologies, is enhancement of boiling heat transfer. A variety of techniques and schemes have been proposed, developed, and transferred into every-day use [13,15,38]. Prominent among these is to either structure the heated surface to provide pre-existing nucleation sites that tend to be active and stable, or to treat the surface so as to change wetting. A few novel passive and/or active schemes have been proposed in some recent studies [29,30,45,61,62] that exploit surface adsorption and electrokinetics of surface-active molecular additives in solvents in different ways, along with some



(*a*) Schematic of a nucleated bubble



(*b*) Adsorption at the solid-liquid interface



(*c*) Adsorption at the liquid-vapor interface

Fig. 3 Representation of the modification of interfacial phenomena in nucleate boiling in aqueous surfactant solutions (not to scale) Ref. [45]

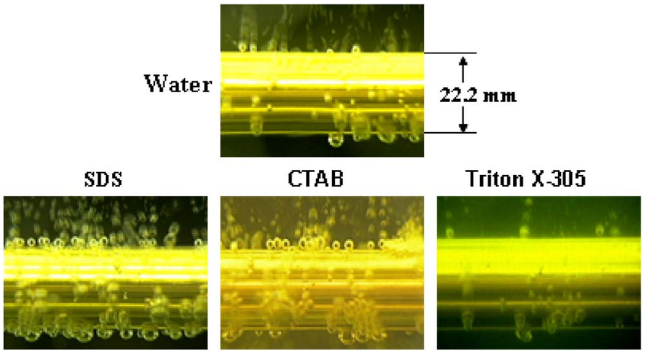
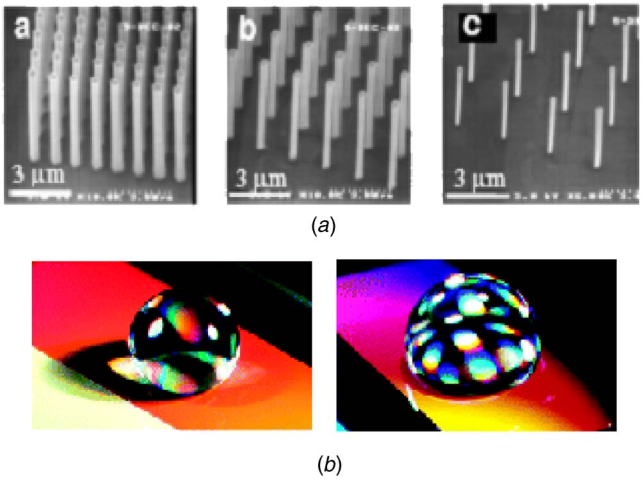


Fig. 4 Boiling behavior in distilled water, and aqueous surfactant (SDS, CTAB, and Triton X-305) solutions in their respective half-micellar concentrations (or C=0.5CMC) and at a heater wall heat flux of $q''_w=20$ kW/m^2



(*a*)

(*b*)

Fig. 6 Dynamic tuning of surface wetting on a nanostructured hydrophobic surface with application of electrical potential Ref. [30] (*a*) surface structure produced on a silicon substrate and (*b*) change in droplet contact angle when an electrical potential is applied

external stimulus in some cases, to produce self-assembled monolayers or micellar layers on the surface and thereby doctoring interfacial properties and wetting.

In a recent set of studies [43–46,63], it has been shown that by adding small quantities of surface-active soluble agents (polymers and surfactants, for example) the liquid-vapor interfacial tension (surface tension) and liquid-solid interfacial tension (wetting) can be altered and decoupled. The additives have a unique long-chain molecular structure composed of a hydrophilic head and a hydrophobic tail, with a natural tendency to adsorb at surfaces and interfaces when added in low concentrations in water. The interfacial changes are caused by their molecular mobility at interfaces, which manifests in a dynamic surface tension behavior (adsorption-desportion at the liquid-vapor interface) and varying surface wetting (physisorption and electrokinetics at the solid-liquid interface). A conceptualization of the molecular dynamics and altered surface tension and wetting is depicted in Fig. 3. These molecular-scale phenomena, modulated by the monomer and/or micellar structure of reagent, distinguishably alter the boiling bubble dynamics, as seen in the typical boiling signatures in three different reagent solutions given in Fig. 4 [45], thereby providing an attractive passive technique for changing (enhancing or degrading, and controlling) "on demand" the nucleate boiling behavior.

A similar theme of controlling surface wettability by using self-assembled monolayers of polymers, or other long-chain molecules that have a hydrophilic head and a hydrophobic tail, but coupling it with the application of an electric potential to tune the surface charge is documented by Lahann et al. [62]. By altering its charge, a surface can be "reversibly" switched from a hydrophobic to hydrophilic state, and vice versa, as schematically depicted in Fig. 5. Another method [30] considers the application of an electrical field to a nanostructured superhydrophobic surface to alter the contact angle of pure liquids. A typical set of surfaces used in this study [30], produced by etching arrays of cylindrical nanosized pins or posts on a silicon wafer, and the changed droplet contact angle when an electrical potential is applied between the droplet and substrate are shown, respectively, in Figs. 6(*a*) and 6(*b*). In yet another scheme, light-induced modification of liquid wetting on a photoresponsive surface (produced by a photoirradiated cover of photoisomerizable monolayer), shown by the droplet motion in Fig. 7, has been reported by Ichimura et al. [61]. All of these techniques, it may be noted, represent what would be termed as compound techniques and require external input of active energy (electric charge or light) along with some form of passive surface modification, and they are a part of growing trend in the enhancement literature [13,38].

In closing, it is perhaps appropriate to reiterate that the challenges of advancing the science and engineering of boiling and two-phase flow heat transfer, and the concomitant interfacial phenomena would expand considerably in the foreseeable future. These would undoubtedly be driven by both large-scale (given our globe's ever increasing energy needs for domestic, commercial,

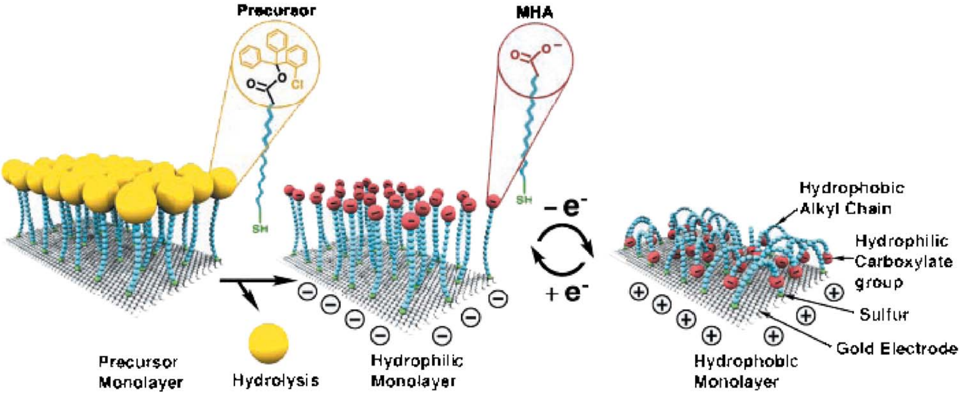


Fig. 5 Conceptual representation of a "reversibly switching surface" by applying an electrical charge to dynamically tune the orientation of self-assembled molecular monolayers and render the surface hydrophilic or hydrophobic Ref. [62]

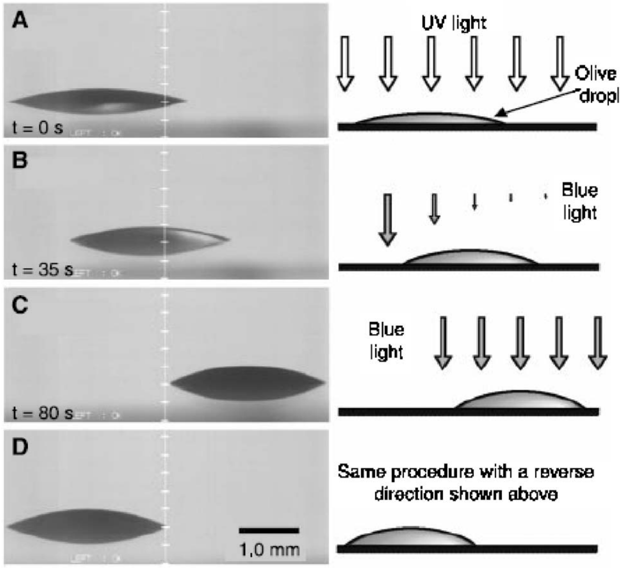


Fig. 7 Light-driven droplet motion on a surface that is photoirradiated with a coating of a photoisomerizable monolayer Ref. [61]

and industrial consumption) and small-scale (emerging applications in sensors, microactuators, and electromechanical-thermal machines, among others) applications and their design needs. This special issue of *the Journal of Heat Transfer* and its collection of technical contributions certainly reflect this direction.

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