Enhanced Boiling Heat Transfer

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PREFACE

Enhanced boiling is one of the most exciting and dynamic areas of thermal engineering. Although single-phase heat transfer provides only a marginal opportunity for improvement above and beyond the addition of extended surface area, some enhanced boiling surfaces produce up to 100 times the performance of a conventional, plain surface under certain conditions. Thus in this sense enhanced boiling surfaces can be thought of as "superconductors" of heat. Enhanced boiling is a subject still ripe for significant advances, such as in innovative development of new enhancement geometries and their manufacture. Key fundamental problems regarding the physical processes and phenomena remain to be solved, providing an incentive to the creative investigator to explore and then to explain how and why these enhancement geometries work as outstandingly as they do. Thus enhanced boiling is still an emerging science and technology.

In the past 20 years there has been extensive research and development in enhanced boiling heat transfer. The application of enhanced boiling surfaces in heat exchangers has become widely, although not extensively, established, and their use in other services, such as in heat pipes and for cooling electronic chips in the electronics industry, is widening. Therefore, it is the right time for an extensive survey of the subject, first to bring organization to the massive and exponentially growing amount of literature available and second to provide thermal design information for the application of enhanced boiling surfaces in practice.

The book is organized as follows. After a short introduction to the subject in Chapter One, Chapter Two provides a brief, basic review of conventional boiling heat transfer for nonspecialists. The historical development of enhanced boiling surfaces together with the corresponding advancements in nucleation theory influencing their invention are presented in Chapter Three. In Chapter Four, many types of commercially available enhanced boiling tubes are described. Boiling nucleation on enhanced boiling surfaces is surveyed in Chapter Five, and in Chapter Six the thermal mechanisms responsible for the tremendous heat transfer coefficients of enhanced boiling surfaces and the geometric factors affecting their performance are discussed. In Chapter Seven, the boiling performances of many enhancement geometries are compared for a wide range of fluids to help in the selection of suitable surfaces for a particular application and to use as a "yardstick" for the evaluation of new enhancement geometries. A complete survey of correlations available for predicting enhanced nucleate pool boiling coefficients is presented in Chapter Eight. Chapter Nine surveys the enhanced boiling of mixtures. Section 10-1 of Chapter Ten reviews the experimental studies on enhanced boiling inside tubes and includes an extensive review of the thermal design correlations available. Enhanced shell-side boiling is treated in Section 10-2 of Chapter Ten, and practical application guidelines and case histories are covered in Chapters Eleven and Twelve. Evaporation in plate-fin heat exchangers is an important form of enhanced boiling, and thus two-phase flow patterns and heat transfer in these units are reviewed in Chapter Thirteen.

One novel feature presented for the first time is an enhanced boiling surface selection aid for heat exchangers. Utilizing a specially developed graph together with boiling data available throughout the book, one can quickly determine the merits of using plain, low-finned, highly enhanced, or doubly augmented tubes in a particular application. In addition, photographs never previously published of the boiling nucleation and liquid film formation processes, inside boiling enhancements are shown. Other highlights are an extensive survey of special thermal design considerations and constraints involving enhanced boiling heat exchangers; a review of energy conservation interventions that use enhanced boiling tubes in ethylene plants, refineries, and the like; a survey of the effects of oil on both intube and shell-side boiling of refrigerants; a photographic sequence of the fouling and cleaning of a reboiler's low-finned tube bundle together with a review of the benefits of using low-finned tubes in highly fouling boiling services; and a survey of the thermal design correlations for plate-fin heat exchangers.

Efficient utilization of energy is still an elusive goal of the engineering community and humankind as a whole. Enhanced boiling should play a principal role in our efforts because of the ability of these special geometries to transfer megawatts of heat at boiling temperature differences on the order of only 1.0 K. One should consider that every industrialized country in the world has a "renewable" and incredibly large natural resource in the form of nonpolluting energy that can be extracted from petrochemical facilities, refineries, fertilizer plants, and so forth by use of enhanced boiling technology in conjunction with "pinch" technology, vapor recompression cycles, and the like. Consequently, another goal of this book is to stimulate further the application of enhanced boiling surfaces in the refrigeration, petroleum, and chemical processing industries by presentation of special thermal guidelines for the design and operation of enhanced boiling heat exchangers, a survey of possible process interventions, and a description of several case histories of actual operating units. In summary, it is my goal to provide a useful treatise for both the research engineer and the heat transfer practitioner.

I would like especially to thank my wife, Carla, and my two sons, Luca and Alessandro, for their moral support and sacrifice, which made the writing of this book possible. I am grateful to the many friends and acquaintances who provided photographs for the book. I would also like to thank William Begell and Florence Padgett of Hemisphere Publishing Corporation for their encouragement and assistance.

John R. Thome

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CHAPTER
ONE

INTRODUCTION

Enhanced boiling is one of the *high-technology* areas of heat transfer. In single-phase heat transfer the augmentation of performance is incremental, depending almost exclusively on the provision of additional heat transfer surface area with fins, corrugations, and the like. In contrast, enhanced boiling surfaces can in some instances produce heat transfer coefficients as much as 100 times larger than those of a comparable plain, smooth surface that is boiling at the same wall superheat. Thus a significant leap forward in technology has been achieved that may change many conventional practices in heat transfer design and heat exchange equipment for years to come.

Enhanced boiling heat transfer is of great importance to evaporation processes in the refrigeration and air-conditioning industries, the hydrocarbon and chemical industries, the microelectronics industries, the growing heat pipe industry, and others. In refrigeration systems, for instance, enhanced boiling tubes are widely used to augment performance of flooded evaporators. In refineries and chemical processing plants, enhanced boiling tubes can be utilized for reboilers on distillation towers in nonfouling services and in evaporators of cascade refrigeration systems. In the electronics industry, enhanced boiling is a promising new technology for cooling high–power density components. In the air separation and gas processing industries, plate-fin geometries are utilized to augment boiling heat transfer and to obtain compact designs. In heat pipes, enhanced boiling surfaces improve performance in the evaporation zone.

The principal economic benefits derived from the application of enhanced boiling technology in heat exchangers are a reduction in size and cost of new units and a decrease in energy-related operating costs when retubing existing units with enhanced boiling tubes. The primary advantage to electronic components is the augmentation of cooling rates, which lowers the start-up and operational temperatures of the power-dissipating components and in turn increases their service life and reliability.

Numerous ways to augment boiling heat transfer coefficients have been developed. Active techniques include rotation or vibration of the heated surface, periodic wiping of the heated surface or suction at its surface, ultrasonic vibration of the evaporating fluid, application of electrostatic fields to the fluid, and the introduction of trace additives to the fluid. Most of these active methods are difficult to implement outside the laboratory or to justify economically. Passive techniques include roughening the heat transfer surface; placing tiny nonwetting spots (such as Teflon or epoxy) on the heated surface; pitting a surface with a corrosive chemical; using integral fins or rolling, splitting, or knurling integral finned tubes to form complex geometries; and coating the heated surface with a porous layer. Also, dendritic types of scaling have been used to augment boiling performance. Only several of these methods are practical on a large scale and economically advantageous compared to conventional, unmodified surfaces such as ordinary drawn tubing. Various other passive techniques have also been developed that do not require modification of the heated surface. These include twisted metallic tapes, coiled wire inserts, and inlet vortex generators, all of which are primarily installed inside conventional shell-and-tube heat exchangers to improve below-design boiling performances. Also, tubes have been externally wrapped with various materials such as wire and wire screens.

As can be expected for any new technology, further developments in enhancement techniques, boiling performances, and manufacturing methods and novel applications to thermal processes are forthcoming. This area of heat transfer is especially exciting for the heat transfer specialist in that he or she has the opportunity to significantly improve the thermal performance of a heat transfer process by utilizing his or her own creativity rather than following standard, ordinary design procedures.

The ultimate goal of enhanced boiling research and development is to obtain the optimal combination of surface and boiling performance for each general area of application together with accurate and reliable thermal design methodology. The optimal surface, in this case, does not necessarily mean the one with the best boiling performance but rather the best surface when such factors as unit cost, quality of manufacture, uniformity in performance, and service life are taken into account. The biggest impediment to widespread application of enhanced boiling surfaces is the scarcity of well-documented thermal design methods for use by the engineering practitioner. This is one aspect of enhanced boiling heat transfer in which extensive research and development are urgently required to obtain the necessary correlating equations and then to implement them in widely used design software. The principal design parameters that are needed for enhanced boiling surfaces are:

1. the nucleation superheat, which denotes the minimum operational wall superheating permissible to sustain boiling;
2. the maximum or critical heat flux, which is the largest heat flux that can be applied while remaining in the nucleate boiling or wetted wall regime; and
3. the boiling heat transfer coefficient as a function of wall superheat or heat flux for the particular operating conditions of the enhanced boiling surface.

Each of these parameters is a function of numerous geometric factors, the type of fluid, and the flow conditions. These include the particular type of boiling enhancement being used, the operating pressure, whether there is subcooling of the bulk liquid, the local vapor quality (in flow boiling), and mass diffusion effects (in mixtures).

Chapter Two treats boiling heat transfer on plain surfaces. Chapters Three to Nine deal primarily with the fundamentals of enhanced nucleate pool boiling. Chapters Ten to Thirteen cover flow boiling inside tubes, outside tube bundles, and inside plate-fin heat exchangers. Practical design and operation information and a survey of applications of enhanced boiling heat exchangers are addressed principally in Chapters Eleven and Twelve.

CHAPTER
TWO

FUNDAMENTALS OF BOILING HEAT TRANSFER ON PLAIN SURFACES

2-1 INTRODUCTION

The thermal design of conventional evaporators is based on our knowledge of boiling on plain, smooth surfaces. Plain, drawn tubing is the typical surface in heat exchangers, with boiling either on its inside or outside surface. Because conventionally designed evaporators with drawn tubing are the reference against which enhanced boiling tube evaporators are compared, a review of the fundamentals of boiling heat transfer on plain, smooth surfaces is presented.

The general topics covered in this chapter are nucleate pool boiling, intube boiling, and boiling on the outside of tube bundles. The aim is to provide some background on these processes for nonspecialists in boiling heat transfer. Another objective is to furnish some of the heat transfer correlations for conventional boiling that are used later in the text to determine the relative augmentation in heat transfer performances obtained by enhanced boiling surfaces under various circumstances.

Boiling heat transfer is distinct from single-phase forced convection in that the boiling heat transfer coefficient is a strong function of the temperature difference between the heated wall and the bulk liquid. During boiling, a large quantity of the heat is transported from the heated wall as latent heat in vapor bubbles in addition to the sensible heat added to the liquid. Another distinguishing characteristic of boiling heat transfer is the effect of the microsurface geometry on the boiling process. Therefore, boiling heat transfer is a much more complex process than the more widely studied single-phase forced convection process, and hence much more effort is required to obtain a basic understanding of the involved phenomena, heat transfer mechanisms, and predictive methods.

The subject of boiling heat transfer is traditionally divided into two parts: pool boiling and flow boiling. Pool boiling represents the situation in which boiling occurs on a single heated surface, usually a tube or a disk, in a large pool of otherwise quiescent liquid (the only motion is caused by the boiling process itself). As its name implies, flow boiling refers to the situation in which there is bulk motion of the liquid past the heated surface (or surfaces) either by natural circulation of the liquid or by the driving action of a pump. Flow in the natural circulation regime is provided by the driving head produced by a column of liquid in the inlet piping. Pool boiling by itself is of limited practical significance as a process, but it is studied extensively to gain insight into the more complex problem of flow boiling.

The reader who requires further information about conventional boiling heat transfer is referred to Rohsenow (1973) for a review of the general principles of boiling, Van Stralen and Cole (1979) for an exhaustive survey of the fundamentals of nucleate boiling, and Collier (1981) for an extensive review of flow boiling inside tubes. For boiling on the outside of horizontal tube bundles, the reader is referred to the article by Palen, Yarden, and Taborek (1972).

2-2 POOL BOILING

Pool Boiling Curve

Pool boiling heat transfer is most easily explained with reference to the pool boiling curve, which represents the functional dependence of the heat flux leaving the heated wall on the temperature difference between the surface of the heated wall and the surrounding bulk liquid. Figure 2-1 depicts the pool boiling curve and delineates the various boiling regimes occurring when the wall temperature is the independently controlled variable. The wall superheat is plotted along the abscissa and is defined as the difference between the surface temperature of the wall and the saturation temperature of the liquid (when the bulk liquid is not at saturation but is subcooled, the bulk temperature is used in place of the saturation temperature). The heat flux passing from the heated wall into the fluid is plotted along the ordinate.

The pool boiling curve in Fig. 2-1 for boiling on the outside of a typical plain, smooth tube in water is divided into four distinct heat transfer regimes: single-phase natural convection, nucleate pool boiling, transition boiling, and film boiling. As the wall superheat is raised from an initial value of zero, the regime of single-phase natural convection is in effect until nucleation occurs and the first vapor bubbles form on the heated wall. The wall temperature must reach a minimum value (point A) above the saturation temperature of the liquid for boiling to initiate. Hence natural convection can occur up to this point, even though the temperature of the liquid in the thermal boundary layer at the heated wall is higher than the saturation temperature. Liquid in this state is said to be superheated.

Once boiling nucleation occurs and bubbles begin to grow and depart from various sites on the heated wall, the mechanism of heat transfer is augmented by the boiling process, and the heat flux passing through the heated wall increases to the higher value at point B. The regime of nucleate pool boiling has now been attained. This regime is

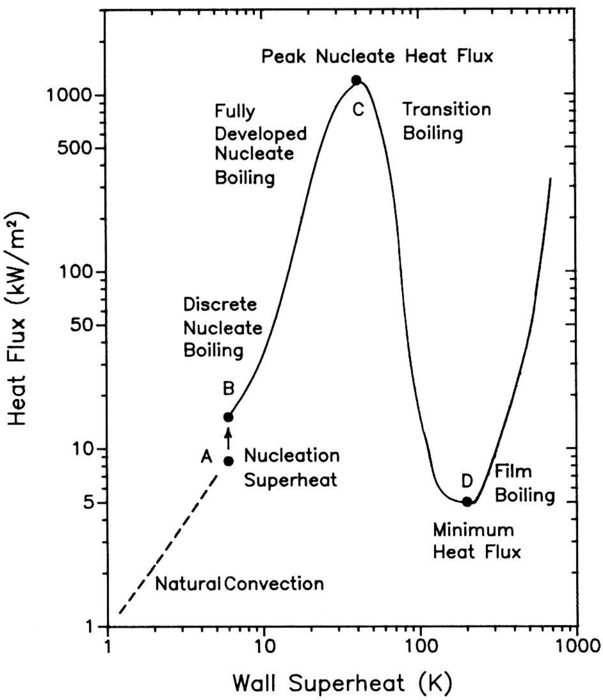

Figure 2-1 Boiling curve and boiling regimes for a horizontal, steam-heated tube.

characterized by discrete bubbles growing and departing from the heated wall at numerous nucleation sites at low heat fluxes, often called the discrete boiling region, and by large patches and slugs of vapor leaving the surface at medium and high heat fluxes, the latter of which is commonly referred to as fully developed nucleate pool boiling. These boiling regimes are depicted schematically in Fig. 2-2. Heat can leave the surface either as sensible heat in the form of superheated liquid or as latent heat in vapor bubbles. Here the principal mechanisms of heat transfer are (1) liquid-phase convection, augmented by the agitating action of the vapor bubbles and the cyclic stripping of the thermal boundary layer by departing bubbles (the later process is

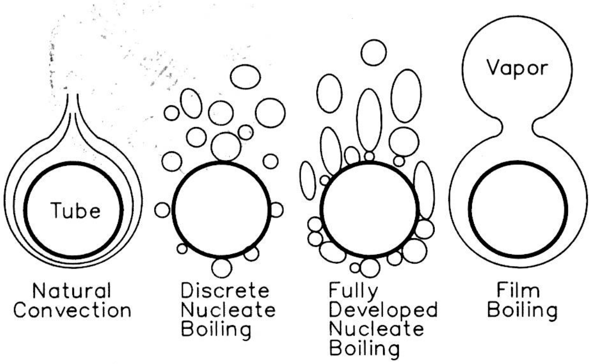

Figure 2-2 Depiction of the nucleate pool boiling regimes.