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Review of boiling heat transfer enhancement on micro/nanostructured surfaces

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ABSTRACT

In the recent decades, the rapid growth of surface modification and fabrication technologies has facilitated the achievement of boiling heat transfer enhancement on micro/nanostructured surfaces. In this paper, several researches on the micro/nanostructured surfaces that have been designed to enhance boiling heat transfer are introduced and closely reviewed. Firstly, theoretical and experimental researches on nucleate boiling heat transfer (NBHT) and critical heat flux (CHF) are introduced in the outline. The fabrication techniques for achieving these engineered surfaces, which are technically classified into machining, coating, chemical process, and micro/nanoelectromechanical systems, are described in detail in the paper. Explanations and analysis of the results of boiling heat transfer enhancement tests are presented in view of NBHT and CHF. Finally, the special features of the existing surfaces capable of enhancing boiling heat transfer are summarized, and the need for future research is also presented.

1. Introduction

Boiling heat transfer is an effective mechanism that can remove a large amount of thermal energy from a surface owing to the high heat transfer coefficient of water ($O[h] \sim 10^3$–10^5 W/m^2 K), thus maintaining relatively lower surface temperature. The boiling heat transfer phenomenon has been applied to several engineering and industrial fields requiring the removal of high heat flux, such as power plants, electronic chip cooling, and marine ship power generation. The features of boiling heat transfer can be readily understood using the well-known boiling curve (Fig. 1), primally presented by researchers such as Nukiyama [1], Jacob and Linke [2], and Drew and Mueller [3]. In the boiling state, the most effective heat transfer region of a surface is the nucleate boiling heat transfer (NBHT) region, where bubble generation, and its growth on and detachment from a heating surface repeatedly occur, resulting in lower surface temperature. Beyond this NBHT region, the critical heat flux (CHF) phenomenon suddenly causes a significant decrease in the heat transfer coefficient and a drastic rise in surface temperature (called burn-out) occurs. As the NBHT and CHF phenomena are the key mechanisms dominating boiling heat transfer and significantly influencing thermal and economic efficiency and safety, several trials and related studies to enhance them have been conducted to date. In the recent decades, rapid growth in surface modification and fabrication technologies has facilitated the enhancement of NBHT and CHF through the fabrication of micro/nanostructures (with sizes between hundreds of nanometers and several micrometers) on a heating surface. Related studies include those on heating surface modification methods, which are classified as follows:

- Surface mechanical machining technique.
- Surface coating technique (homogeneous/heterogeneous coating of special materials).
- Chemical process (oxidation, chemical etching, and so on).
- Micro/nano electro mechanical system (MEMS/NEMS) technique (photolithography technique, reactive ion etching (RIE)/deep reactive ion etching (DRIE) for developing micro/nanoporous surfaces).

The research outcomes for boiling heat transfer enhancement constitute results from theoretical and experimental investigations of boiling heat transfer, studied since the 1930s. And recently, several review articles on the enhancement of boiling heat transfer on the micro/nano-structured surfaces had been reported [4–7]. In

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Nomenclature

A	area
C_{sf}	surface constant
c_p	specific heat capacity
D_b	bubble departure diameter
f_b	bubble departure frequency
g	gravitational acceleration
h_{fg}	latent heat
k	thermal conductivity
N_a	active nucleation site density
P	pressure
Pr	Prandtl number
q''	heat flux
R_c	critical cavity radius
T	temperature
t_w	bubble waiting time

Greek symbols

α	thermal diffusivity
μ	dynamic viscosity
θ	static contact angle
ρ	density
σ	surface tension

Subscripts

f	fluid
g	gas
l	liquid
NB	nucleate boiling
sat	saturated
v	vapor
w	wall

this paper, the theoretical and experimental researches on NBHT and CHF are first introduced as an outline, based on which the results of boiling heat transfer enhancement using micro/nanostructured surfaces are analyzed. Furthermore, the researches on NBHT and CHF enhancement utilizing surface modification techniques are thoroughly reviewed based on the technical classification presented above, and the analysis of the research outcomes is presented. For these objectives, the surface modification techniques used on the micro/nanostructured surfaces are introduced along with the fabrication methods. Next, the NBHT and CHF characteristics of the surfaces are explained and analyzed. In conclusion, the boiling heat transfer characteristics of micro/nanostructured surfaces are comprehensively described and the need for future research is presented.

1.1. Nucleate boiling heat transfer (NBHT)

In the NBHT region, a large amount of heat is transferred from the heating surface to the cooling fluid owing to vigorous bubble behavior. The most classical models and correlations for predicting the NBHT coefficient (NBHTC) explain the relationship between heat flux and wall superheat on the heating surface, as seen in Eqs. (1)–(3).

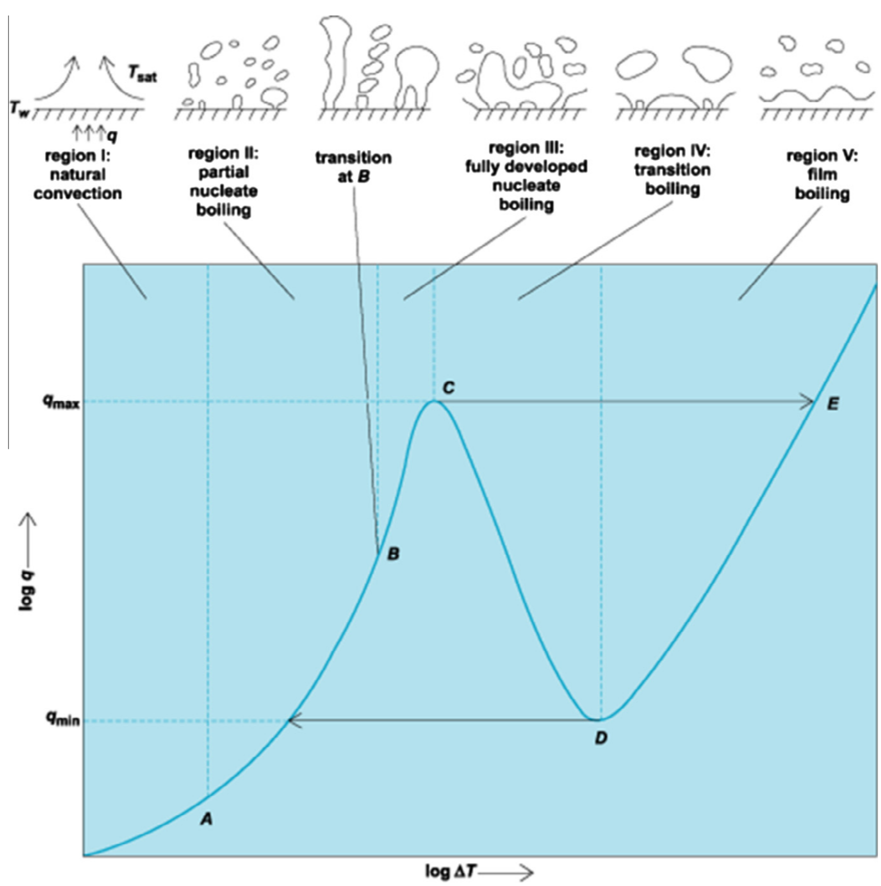

Fig. 1. Pool boiling curve.