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Enhanced boiling heat transfer on nanowire-forested surfaces under subcooling conditions

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ABSTRACT

In boiling heat transfer, the emerging issues are the improvement of both the critical heat flux (CHF) and the thermal stability. Nanowire-forested (NF) surfaces and subcooled environments are favorable for improving CHF as well as the thermal stability owing to their distinctive morphology and consequential convection expedition, respectively. In this study, the improvement of CHF and temperature uniformity/stability are evaluated on NF surfaces immersed in de-ionized water with subcooling from 0 to 30 K using a resistance temperature detector (RTD) sensor with five measuring points. NF surfaces catalyze dispersed, confined and fast bubble ebullitions under subcooling conditions, resulting in the delayed bubble coalescences. This lead to the enhancement of CHF accompanying stabilized spatial/temporal temperature variations. We demonstrate that NF surfaces applying 30 K subcooled condition not only significantly improve the thermal stability by reducing spatial/temporal temperature variations to less than 1/5 but also enhance CHF by 4.3 folds, compared to the plain surfaces under the saturated condition. These remarkable enhancements show that NF surfaces can be effective solutions to secure the thermal stability under vigorous boiling conditions.

1. Introduction

Over the past several decades, boiling heat transfer phenomena have attracted a great deal of attention from researchers, prompting widespread application in various industries ranging from large-scale power plants to small-scale electronics. Boiling heat transfer, in which the working fluid undergoes a phase-change from liquid to vapor, has greater heat-transfer capabilities than single-phase convection schemes [1]. Many recent studies have focused on developing practical cooling configurations capable of sustaining harsh thermal loads, namely maximizing the heat-dissipation capacity under stable operating conditions, i.e., increasing the critical heat flux (CHF) and heat transfer uniformity/stability [2–8].

Functional interfacial structures have intrinsic merits in the context of boiling applications; fine structures can attain high surface roughness and increase the heat-transfer area for heat dissipation. Nanoscale or nano-micro-hierarchical structures exhibit strong interfacial hemi-wicking with consequential superhydrophilic wetting, which directly enhances the surface rewetting against surface dry-out. As heterogeneous phase change and sequential two-phase convection are strongly dependent on solid–liquid interfacial characteristics such as roughness and wettability [9–15], researchers have focused on the manipulation of their functionalities for favorable nucleation and hydrodynamic balance against surface dry-out. Recent studies reported CHF can be dramatically improved by employing nanostructures on a boiling surface [10–16]. Because surface wettability and morphology can be controlled by nanoscale surface design, numerous studies have focused on the invention and characterization of novel nanostructures to enhance the heat and mass transfer for practical application [12–20].

The distinctive morphology of nanowire-forested (NF) surfaces, in particular, have shown promising results in their ability to improve CHF and enhance heat transfer stability. As shown in Fig. 1, on the basis of distinctive near-field characteristics of interfacial benefits for boiling concomitant with morphological aspects, we have confirmed that the merits of NF surfaces extend to subcooled boiling. In this regime, NF surfaces readily enhance CHF by suppressing bubble coalescence. As subcooling is a far-field

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Nomenclature

A	heating area (m^2)
D	diameter (m)
I	current (A)
Ja	Jakob number
k	thermal conductivity (W/mK)
l	latent heat (J/g)
P	pressure (Pa)
q	heat flux (W/cm^2)
r	radius (m)
T	temperature (°C)
t	thickness (m)
V	voltage (V)

Greek letters

γ	surface tension (J/m^2)
Δ	difference
δ	thermal boundary layer thickness (m)
θ	contact angle (°)
ρ	density (kg/m^3)
σ	standard deviation

Subscripts

avg	average
b	bubble
c	critical
eff	effective
f	fluid
r	resistance temperature detector
Si	silicon
sat	saturated
sub	subcooled
T	temperature
w	wall

hydrodynamic property of boiling, the subcooling of working fluids confines the behavior of nucleated bubbles [21]. Specifically, NF surfaces contain submicron nucleation sites [10–12,18] that are compatible with heterogeneous ebullition under subcooling conditions, resulting in discrete nucleation and suppressed bubble development.

Although many researches into enhancing boiling heat transfer via nanoscale morphology control have been conducted [10–16],

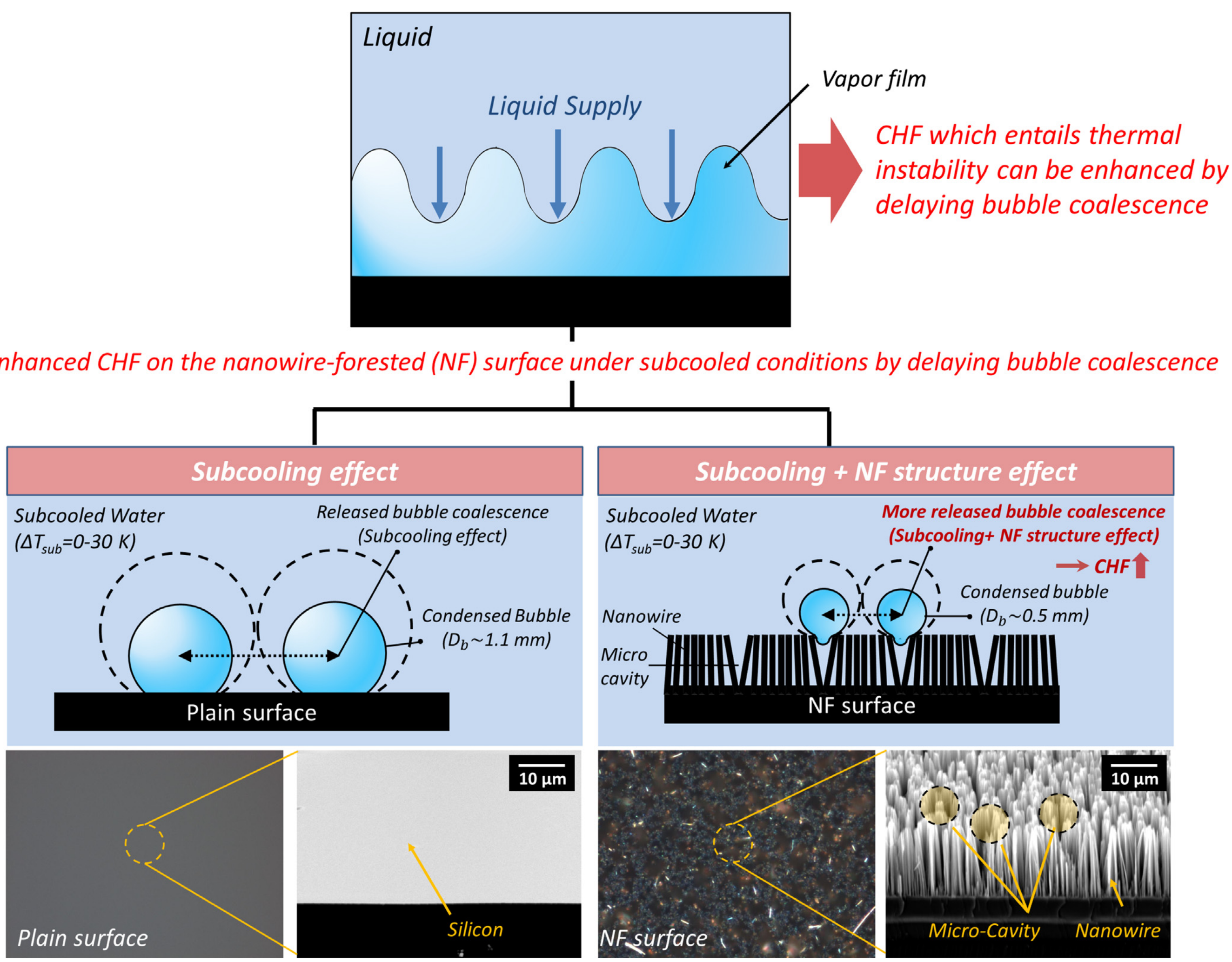

Fig. 1. Schematic diagram showing the effects of nanowire-forested (NF) structures and subcooling conditions on critical heat flux (CHF) enhancement during pool boiling heat transfer.