Pool boiling heat transfer performance of water on thin film coated micro/nano textured surfaces

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By

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I, **Nitish Kumar,** certify that the work embodied in this thesis is my own bona fide work carried out by me under the supervision of **Prof. Pradyumna Ghosh** and **Prof. P. Shukla** for a period of 6 years from January 2018 to December 2023 at IIT (BHU) Varanasi. The material contained in this thesis has not been submitted for the award of any other degree. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any others' work, paragraphs, text, data, results etc. reported in journals, books, magazines, reports, dissertations, theses, etc. or available at websites and have not included them in this thesis and have not cited as my own work.

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Nomenclature

h	Heat transfer coefficient (W/m^2 K)
h_c	Planck constant
h_{fg}	Latent heat of vaporization (J/kg)
k	Boltzmann constant
k_{cu}	Thermal conductivity of copper (W/m-K)
c_{pf}	Specific heat of fluid at liquid phase (J/kg-K)
D	Bubble diameter (m)
f_b	Bubble frequency (Hz)
$\boldsymbol{q''}$	Heat flux (kW/m^2)
T	Temperature (° C)
ΔT	(T_w - T_{sat}) Wall superheat temperature (K)
n_a	Active nucleation site density (sites/m^2)
T_1	Temperature of thermocouple location first (° C)
T_2	Temperature of thermocouple location second (°C)
T_3	Temperature of thermocouple location third (°C)
v	Volume (cm^3)
SiO_2	Silica dioxide
TiO_2	Titanium dioxide
Al_2O_3	Aluminum oxide
CS	Coated surface

Greek symbols

σ	Surface tension of liquid (N/m)
ρ_v	Vapor density(g/cm^3)
ρ_l	Liquid density (g/cm^3)
θ	Contact angle (˚)
Δ	Difference
$\emptyset$	Volume concentration

Subscripts

bf	Base fluid
np	Nanoparticle
d	Departure
f	fluid
w	wall
sat	saturation

Abbreviations

CHF	Critical heat flux
MaCE	Metal assisted chemical etching
LbL	Layer -by-layer
EPD	Electrophoretic deposition
ECD	Electrochemical deposition
CVD	Chemical vapour deposition
LPCVD	Low pressure chemical vapour deposition
PECVD	Plasma-enhanced chemical vapour deposition

MOCVD	Metal organic chemical vapour deposition
HFCVD	Hot filament chemical vapour deposition
ALD	Atomic layer deposition
DRIE	Deep reactive ion etching
BDA	Break down anodization
BIT	Boiling inception temperatures
PVD	Physical vapour deposition
GLAD	Glancing angle deposition
EBPVD	Electron beam physical vapour deposition
ONB	Onset of nucleate boiling
HTC	Heat transfer coefficient
BHTC	Boiling heat transfer coefficient
NBHT	Nucleate boiling heat transfer
DI	Deionised water
HF	Hydrofluoric
CCD	Charge-coupled device
CNT	Carbon nanotubes
ENM	Engineered nanomaterials
AFM	Atomic force microscopy
SEM	Scanning electron microscopy
FESEM	Field emission scanning electron microscopy
EDX	Energy dispersive X-ray spectroscopy
EDM	Electric discharge machining
NWs	Nanowires
RMS	Root mean square

CNTs	Carbon nanotubes
HFE	Hydrofluoroether
AAO	Anodised alumina oxide
PPA	Porous alumina
PTFE	Polytetrafluoroethylene
ITO	Indium tin oxide
SWCNT	Single-walled carbon nanotubes
MWCNT	Multi-walled carbon nanotubes
MEMS	Microelectromechanical systems
MPF	Micro-pin-fin

ABSTRACT

Boiling is a natural phenomenon that is observed in everyday life. It occurs at the interface of a heated surface and a hot liquid. Nucleate boiling is the most desirable regime of boiling where the heat transfer coefficient is very high. That is why it is used in many industrial applications such as steam generation in power plants, preventing overheating in electronic cooling, and thermal desalination in chemical process industries, etc. It enables high heat dissipation at a relatively low wall superheat temperature, a process dominated by rapid bubble formation and intense liquid vaporization. In this case, a large portion of heat energy is transferred to the bulk liquid, which is carried by the bubbles. Therefore, most researchers have focused on understanding the bubble formation mechanism and scope to improve the boiling performance characteristics. There are two basic parameters usually considered by which nucleate boiling performance is evaluated: one is the boiling heat transfer coefficient (BHTC) and the other is the critical heat flux (CHF). The present work mainly focuses on the enhancement of BHTC on a hydrophobic surface. The BHTC can be enhanced by promoting either active nucleation sites or bubbles start forming at a low wall superheat temperature (low ONB).

In this study, pool boiling performances, such as the boiling curve, onset of nucleate boiling (ONB), and nucleate boiling heat transfer coefficient, have been examined on various coated texture surfaces. A thin film coating layer of three different binary oxide nanoparticle combinations (SiO_2/TiO_2, TiO_2/Al_2O_3 and Al_2O_3/SiO_2) has been created via electrophoretic deposition on a copper substrate in a water-based binary hybrid nanofluid. For each combination, four different surfaces were prepared by varying the coating duration. As the coating duration changes, surface characteristics such as morphology, roughness, coating layer thickness, and wettability also change. The morphology and texture of the coated surface depend on the coating materials as well as the coating duration. Surface roughness (Ra) and coating layer thickness increase as the coating duration increases. All coated textured surfaces are hydrophobic in nature, whereas polished copper is hydrophilic.

A series of pool boiling experiments were performed on twelve different textured and polished copper (bare) surfaces in demineralised water at nearly saturation temperature and atmospheric pressure conditions. Experimental results show that bubbles start forming relatively early on hydrophobic textured surfaces, causing the ONB temperature to reduce. On hydrophobic surfaces, the adhesion force is comparatively less, hence less buoyancy force is required at the departure stage, subsequently, and the bubbles' size is smaller than on the hydrophilic (bare) surface. Also, due to increased surface roughness and changes in the textured pattern, nucleation sites increase on the coated surface. Initially, pool boiling characteristics are influenced by wettability, surface roughness, and surface morphology, and enhancement in BHTC is caused by an increase in nucleation sites and departure frequency. When the coating duration increases, roughness and coating layer thickness also increase, which causes a heat transfer deterioration. Due to increased surface roughness, bubble formation starts at a very low wall superheat and starts interacting with the surrounding bubbles, consequently, large bubbles form before the departure, which causes an increase in wall superheat. Also, due to high coating layer thickness, the thermal resistance of the surface increases and heat transfer decreases, consequently, the wall temperature increases.

Experimental investigation revealed that the boiling heat transfer performance of hydrophobic textured coated surfaces increased if the coating thickness was maintained below an optimum range. If the coating layer thickness is kept higher than the optimum range, BHTC may deteriorate, which will increase the surface temperature, and in some cases, thermal damage may occur due to it. The optimum coating layer thickness in the case of TiO_2/SiO_2, TiO_2/Al_2O_3, and SiO_2/Al_2O_3 are ~10µm, ~16µm, and ~27µm, respectively, whereas the maximum enhancements in BHTC are 62%, 63%, and 75%, respectively.