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Behavior of pool boiling heat transfer and critical heat flux on high aspect-ratio microchannels

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ABSTRACT

We conducted pool-boiling experiments and investigated the physical mechanism of boiling heat transfer and critical heat flux (CHF) on heating surfaces with top-opened rectangular microchannels. Through capillary wicking experiments for the boiling samples, it was revealed that, as the microchannel heights increase, the liquid-wicking capability is enhanced significantly for the same capillary pressure gradient, i.e., for the same channel width. This result can be explained by considering the balance between the capillary-pressure potential and the viscous friction by the channel walls. The pool boiling experiments showed that the higher aspect-ratio channel sample has a higher CHF and boiling heat transfer coefficient (BHTC), and it provides evidence that on the microchannel surfaces, additional liquid supply to the dry spot that is formed on the boiling surface by capillary wicking can lead to an enhancement of CHF and BHTC under pool boiling conditions. Expressions for the liquid mass-flow rate and the liquid-occupied region by capillary wicking were derived by the mathematical procedure with a one-dimensional, steady-state fluid momentum equation for liquid flow inside a single microchannel, and the parameters increased monotonically with an increase in channel height. Through numerical analysis, a simple relationship between the average boiling surface temperature ($T_{s,avg}$), the surface heat flux (q_s), and the dry-spot diameter (D_{dry}) was derived as $T_{s,avg} \propto D_{dry}^2 q_s$. Hence, an exact solution to predict CHF on the boiling surface with microchannels was obtained, and it supports the strong relationship between the CHF and the capillary wicking capability on a boiling surface.

1. Introduction

Boiling is a highly effective way to remove or cool large-scale and high-density thermal energy in several applications, such as electric power plants, highly-integrated electronic chip devices, and refrigeration and air conditioning [1,2]. However, in the boiling state, a burnout phenomenon, which is termed the critical heat flux (CHF), exists, and it determines an inherent and physical upper-limitation to the removable or coolable amount of thermal energy from a boiling surface. During past decades, researchers have tried to enhance the CHF, mainly by boiling-surface-modification techniques, which contain physical or chemical hydrophilic material coatings [3–7], nanoparticle coatings on the surface [8–12], and micro-/nanostructure fabrication [13–18]. As the main underlying mechanism for the CHF enhancement by surface modification, most studies presented the improvement in liquid supply capability into the hot surface by the induction of a capillary pressure gradient from the existence of micro-sized roughness (1–100 μm) [19–26] and the intensification of a liquid adhesion force on the surface from an increase in the liquid-vapor-solid contact line length by nano/micro-sized roughness [27–30]. For the optimal design of a boiling surface, a clear understanding and explanation of the direct precursor that triggers the burnout phenomenon are essential. Recently, with the help of high-speed total internal reflection [31,32] and infrared thermometry [33–36] measurement techniques, it has been clarified that the burnout phenomenon is related closely to dry-spot behavior under a boiling vapor bubble and the related heat transfer characteristics. A burnout triggering mechanism by dry spot behavior has been proposed by several researchers [26,32,36–41] since 1970s. According to this mechanism, the burnout phenomenon in boiling is triggered when the area of a dry spot on the boiling surface becomes larger than a critical magnitude, which is determined as a maximum area value to which the amount heat that is transferred to the dry spot can be transported to the surrounding liquid region. A dry spot that is larger than the critical area value may expand irreversibly. The formation and behavior of the dry

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Nomenclature

A_{eff}	effective heating area (m^2)
A_{flat}	flat base surface area (m^2)
A_l	liquid cross-sectional area (m^2)
A_{MC}	Microchannel fin surface area (m^2)
D_b	large vapor bubble diameter (m)
D_{dry}	dry spot diameter (m)
D_h	hydraulic diameter (m)
f	friction factor
g	gravity acceleration (m/s^2)
H	channel height (m)
h_{fg}	latent heat (kJ/kg)
h_{film}	film boiling heat transfer coefficient (W/m^2K)
h_v	vapor bubble height (m)
I_{heater}	electric current to heater (A)
k	thermal conductivity (W/mK)
K	Darcy-Weisbach friction factor coefficient
L_c	length of capillary pumping region (m)
L_{liq}	length of liquid-occupied region (m)
L_{wet}	wetted perimeter (m)
P	pressure (Pa)
ΔP_c	capillary pressure gradient (Pa)
ΔP_v	viscous pressure loss of vapor flow (Pa)
q_{CHF}	critical heat flux (kW/m^2)
q_f	heat transfer rate from fin surface (W)
q_{flat}	heat transfer rate from flat surface (W)
q_{max}	maximum heat transfer rate (W)
q_s	surface heat flux (kW/m^2)
Re	Reynolds number
R_{pt}	electrical resistance of Pt heater (Ω)
T_{cr}	critical temperature (°C)
T_{LF}	Leidenfrost temperature (°C)
$T_{s,avg}$	average surface temperature (°C)
T_{sat}	saturation temperature (°C)
T_{sup}	wall superheat (K or °C)
V_{heater}	electrical voltage to heater (V)
W	channel width (m)
W_s	channel wall width (m)
x	x coordinate

Greek symbols

σ	surface tension (N/m)
δ_l	liquid film thickness (m)
η_f	fin efficiency
θ	contact angle (°)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

i	inlet
l	liquid
o	outlet
r	receding
s	static or surface
Si	silicon
v	vapor
w	wall or water

spot can be controlled by liquid and vapor hydrodynamics and interfacial behaviors near the boiling surface and the heating material characteristics.

We investigate the relationship between CHF enhancement and dry spot behavior based on a comprehensive consideration of capillary-induced liquid flow and viscous frictional resistance to the flow. We fabricated boiling surfaces with various aspect-ratio rectangular microchannels and conducted pool boiling experiments with saturated water under atmospheric conditions. In our experimental cases, the CHF values were enhanced significantly with an increase in channel height and, on a surface with the highest channel height (channel height: 100 μm, and width: 30 μm), the CHF recorded an approximately 1000 kW/m^2 higher value than that on the flat surface. These results demonstrate that the size of a dry spot area on a boiling surface is determined by liquid supply capability to the spot, which can be induced mainly by capillary pressure gradient. For surfaces with microchannels, through the higher height of the channel side walls broadens the liquid-occupied area on the surface and contracts the dry spot size, the CHF and the boiling heat transfer coefficient can be largely promoted.

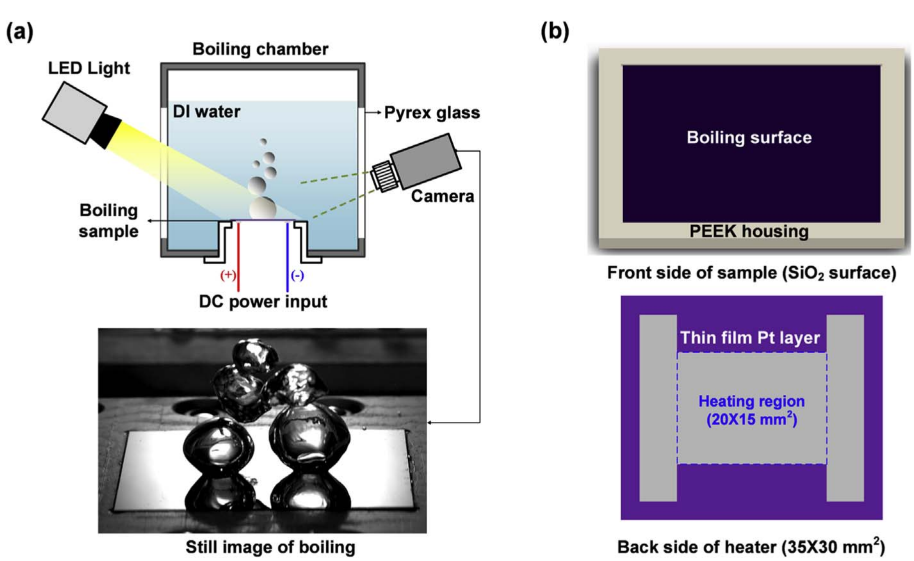

Fig. 1. (a) Schematic diagram of pool boiling experimental facility. (b) Boiling sample geometry and configurations.