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Effect of surface roughness on pool boiling heat transfer at a heated surface having moderate wettability

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The effect of surface roughness on pool boiling heat transfer coefficient and critical heat flux (CHF) at a copper surface having moderate wettability was studied in saturated water. Copper surfaces were polished with sandpapers of different average surface roughness (R_a), ranging from 0.041 μm to 2.36 μm. Test measurements included static and dynamic contact angles for each of the nine surfaces tested. Although the surface roughness, R_a, moderately influenced the contact angles, pool boiling test results successfully correlated with the coefficient, C_{sf}, in the well-known Rohsenow correlation. The CHF showed noticeably strong dependence and an enhanced performance on the surface roughness as well. The CHF at the roughest surface (R_a = 2.36 μm) was 1625 kW/m^2, which is approximately twice as much of that at the smoothest surface (R_a = 0.041 μm). The large increase in CHF with increasing surface roughness is considered to be a consequence of the capillary wicking from the surrounding liquid to the dry spot. A model for the CHF is obtained by modifying an existing correlation for pool boiling with the inclusion of the capillary wicking effect, and a comparison of the results with the experimental data shows good agreement when the wicking effect is included in the correlation.

1. Introduction

Surface characteristics of heated surfaces are considered one of the most dominant factors affecting boiling heat transfer. Many researchers have studied the effect of surface roughness on the pool boiling heat transfer since Jakob's study of its effects on pool boiling [1]. Using rigorous experiments, Rohsenow [2] included the surface effects in his boiling correlation by matching the surface–fluid combination to the proper coefficient, C_{sf}. Subsequently, many studies have revealed the relationship between roughened surfaces and an increase in the number of nucleation sites, resulting in augmented boiling heat transfer [3–6]. Recent research efforts are focused on boiling heat transfer with a more complex surface exhibiting multiscale roughness [7], surface roughness accompanying a wettability change [8], and roughness in complex geometries [9]. A few attempts have been made to develop more accurate correlations between heat transfer coefficient h and roughness parameters [10–12]; these correlations were tabulated and compared with experimental data by Jones et al. [13]. Even though there are many correlations available, based on extensive experimentation with a variety of fluids over a range of pressures, they do not all have a simple physical reasoning, unlike the Rohsenow correlation. Therefore, the first objective of the present study is to understand the nucleate boiling heat transfer enhancement due to surface roughness by establishing the relationship between the average roughness R_a and the coefficient C_{sf} in the conventional Rohsenow correlation.

In contrast to the clear relation between heat transfer coefficient and surface roughness [13], the effect of surface roughness on the critical heat flux (CHF) is still obscure. Many researchers believed that the CHF is triggered by the hydrodynamic instability [14] and does not include the effect of the surface condition, viz. surface roughness and wettability. The surface conditions were overlooked for a long time until Ramilison et al. [15] reported that they are important and concluded that the wettability effect on CHF is more prominent than the roughness effect. Many other studies related to the effect of surface roughness on the CHF were performed [16–18] and their data showed varying augmentation of CHF with increasing surface roughness. However, the extent of the augmentation was no more than ±20%. Although surface roughness shows somewhat limited enhancement of CHF for typical metal surfaces, recent studies on the effect of surface roughness on hydrophilic silicon surfaces exhibited a much larger augmentation of CHF, unlike metal surfaces. Some researchers have focused on the combined effect of wettability and surface micro/nanostructures on silicon surfaces.

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Nomenclature

a	exponent in the Rohsenow correlation
A	constant
C	constant
C_p	specific heat [J/kg K]
C_{sf}	coefficient in the Rohsenow correlation
D_b	bubble diameter [m]
F	force [N]
g	gravity [m/s^2]
h	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat [J/kg]
H_b	bubble height [m]
m	exponent for surface roughness
n	exponent for heat flux
N	number of capillary tubes
P	pressure [Pa]
Pr	Prandtl number
q''	heat flux [W/m^2]
r	roughness factor
R	radius [m]
R_a	average roughness [m]
R_q	root mean squared roughness [m]
R_z	ten-point average roughness [m]
S	accommodation factor
S_m	mean spacing [m]
T	temperature [K]

Greek symbols

ΔT	wall superheat (=$T_w - T_{sat}$) [K]
θ	contact angle [°]
λ_T	Taylor unstable wavelength [m]
μ	viscosity [N s/m^2]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

0	reference
C	capillary
CHF	critical heat flux
G	gravity
I	interface
l	liquid
M	momentum
sat	saturation
S	surface tension
v	vapor
w	wall

They have treated super-hydrophilic coating on well-designed artificial microstructures. These types of microstructures were fabricated on silicon wafer surfaces because micro-fabrication on silicon surfaces is fully developed as an accurate and mature technique. Some of these studies reported a surprisingly large increase in CHF on super-hydrophilic structured surfaces [7,19,20]. Rahman et al. [20] attained the CHF of as high as 2570 kW/m^2 on their hierarchically-structured silicon surface using the bio-template of the tobacco mosaic virus. The increase seems to be beyond the limit that can be attained by wettability alone. It is hypothesized that the capillary wicking effect prevents dry-out of the heated surface, thus resulting in augmented CHF. From the studies on silicon surfaces, it is optimistic to anticipate similar results on metal surfaces provided they are hydrophilic. O'Hanley et al. [8] pointed out that surface conditions including wettability, roughness, and porosity should be considered as separate parameters for precisely estimating the effect of each parameter on CHF. The present study is intended to start from roughened copper surfaces having moderate wettability, which means normal copper surfaces with contact angles of approximately 60–70°. Because it is not super-hydrophilic but still hydrophilic, it is expected that the wettability effect is relatively small, but capillary wicking due to the roughness change is still effective. Simultaneously, the static and dynamic contact angles are also measured in order to investigate the variation of contact angles with increasing surface roughness. On the basis of the experimental data, a CHF correlation including the capillary wicking is proposed that is appropriate for metal surfaces by using roughness parameter R_a.

2. Experimental setup

2.1. Surface preparation and characterization

Copper blocks of size 10 mm × 10 mm × 3 mm were prepared to serve as test surfaces. The top and bottom surfaces were polished with a 600 grit sandpaper and cleaned by sonicating in an isopropyl alcohol (IPA) solution, after which a 20-Ω heating element was soldered to the bottom side of the copper block. In order to measure the temperature, a 30 AWG type T thermocouple was inserted into a hole drilled at the center of the copper block, where the hole is located at the 1.5 mm below the boiling surface. The top surfaces were polished again with various sandpapers having 2000, 600, 220, and 80 grit, and a compound that was a mixture of alumina and silicon oxide nanoparticles and tallow. The compound produced a smoother surface than that obtained by the sandpaper polishing process. The polishing was performed in one direction, which naturally made unidirectional scratches on the copper surfaces. The number of strokes for polishing was increased with increasing sandpaper grit because more strokes were required for making smoother surfaces. Although the number of strokes was 50 for the 220 and 80 grit sandpapers, it was 100 for the 600 grit sandpaper and approximately 300 for the 2000 grit sandpaper. A total of nine samples were prepared, two samples for each sandpaper and one for the compound.

The polished surfaces were characterized in two ways: wettability measurement and roughness measurement. Before the boiling test, the static and dynamic contact angles for each surface were measured using a goniometer (KRUSS, DSA30). The volume of the sessile droplet was 11.5 μl for static contact angles. For advancing contact angles, the initial droplet of 30 μl was set up on the surface and the volume was increased to 50 μl by feeding water at a rate of 20 μl/min. For receding contact angles, the droplet of 50 μl at the end of the advancing process shrank to zero volume at a rate of 20 μl/min. After the boiling test, the static and dynamic contact angles were measured again to see how much the angles were changed during the test. The surface roughness was measured using the surface roughness tester (Mitutoyo, SJ-210). The tip radius of the probe was 2 μm, the measuring force was 0.75 mN, and the evaluation length was 4 mm. Each sample was scanned at six different points to obtain the representative roughness. The roughness definition and the measurement technique follows standard ISO 4287-1997 practices.