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Nucleate boiling from smooth and rough surfaces – Part 2: Analysis of surface roughness effects on nucleate boiling

John P. McHale, Suresh V. Garimella *

Cooling Technologies Research Center, An NSF IUCRC, School of Mechanical Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907-2088, USA

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ABSTRACT

The effect of surface roughness on nucleate boiling heat transfer is not clearly understood. This study is devised to conduct detailed heat transfer and bubble measurements during boiling on a heater surface with controlled roughness. This second of two companion papers presents an analysis of heat transfer and bubble ebullition in nucleate boiling with new measures of surface roughness: area ratio, surface mean normal angle, and maximum idealized surface curvature. An additional length scale of importance, the maximum base diameter of an emergent bubble, is identified. Measurements of bubble departure diameters, growth periods, ebullition periods, and void fraction above the surface are obtained from high-speed videographic visualizations by an automated procedure. Correlations of heat transfer coefficient and bubble ebullition characteristics with different measures of surface roughness are compared in terms of relative uncertainty. The data set of results for pool boiling in the perfluorinated dielectric liquid, FC-72, are found to correlate best with a length-scale filtered value of average roughness $R_{a,\ filt}$. Over a larger database with three different data sets including FC-72, FC-77, and water at atmospheric pressure, the most reliable correlations were obtained with the appropriately filtered area ratio. FC-72 bubble growth curves are well correlated for all test conditions with the normalized relationship $D^* \sim (t^*)^{1/3}$. Finally, the maximum void fraction in the region above the surface is correlated with normalized heat flux for these data and for water as the two-thirds power of heat flux.

1. Introduction

In Part 1 of this work [1], it was shown through a review of the literature that the effects of surface roughness on boiling heat transfer are not completely understood. Novel indium tin oxide (ITO) heater/sensor substrates with controllable surface roughness were therefore developed in order to measure boiling curves accurately and to exhaustively visualize bubble ebullition characteristics for surfaces with different roughness features. Quantitative and qualitative differences in boiling from smooth and rough surfaces were demonstrated. Boiling curves revealed that similar boiling curves do not imply similar R_a values, and similar R_a values do not imply similar boiling curves. Visualizations revealed that there is a marked difference in the bubble ebullition characteristics of smooth and rough surfaces. The inconsistent effect of R_a on the boiling curves and bubble behaviors suggests that the relative "roughness" of a surface should be quantified in a manner different from existing approaches to date in the literature.

Several recent studies have reported attempts to develop surface characterization methods that relate more directly to boiling physics. Qi et al. [2] applied a digital "filtering" operation on 2-D surface scan data to examine potential nucleation sites in terms of cavity mouth radius and cone angle. They did not elaborate on the details of the algorithm; predictions of nucleation site density based on their analysis produced mixed results.

Methods of determining cavity sizes and locations directly from 2-D [3] and 3-D [4] surface scans using a rolling ball technique have also been proposed. In the latter, theoretical nucleation site locations were compared to those identified experimentally for pool boiling of propane from a copper tube. Results for number and distribution of active nucleation sites agreed qualitatively, but specific theoretical nucleation site locations did not match the experimental ones well.

Fractal analysis has been used to explain or reproduce surface roughness characteristics and nucleate boiling characteristics. Majumdar and Tien [5] first developed a fractal method for characterization of different machined stainless steel surfaces, achieving statistical similarity between real and simulated surfaces. Fong et al. [6] showed a correlation between the fractally derived surface roughness measure of a boiling surface and the critical heat flux (CHF). Yang et al. [7] achieved relatively good agreement between their simple fractal surface characterization and observed nucleation site densities in pool boiling of water on a stainless steel surface. Yu and Cheng [8] utilized nucleation site densities and

* Corresponding author. Tel.: +1 765 494 5621.
E-mail address: sureshg@purdue.edu (S.V. Garimella).

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Nomenclature

A	vertical surface amplitude (m) Eqs. (7)–(9) planar area of bubble object in video (m^2)
A_b	planar base area (m^2)
A_r	area ratio (unitless)
A_s	true surface area (m^2)
a	unknown constant
b	unknown constant
c	unknown constant
C_h	heat transfer correlation constant, $h = C_h \cdot q^n$
D	bubble diameter (m)
g	acceleration due to body force (m/s^2)
h	boiling heat transfer coefficient (W/m^2 K)
i	vertical counting index, Eq. (6)
j	horizontal counting index, Eq. (6)
L_0	Laplace length scale (m) $\sqrt{\sigma/g\Delta\rho}$
N	sample size (unitless)
m	maximum vertical grid index, Eq. (6) surface roughness exponent, $h \sim R^m$
n	maximum horizontal grid index, Eq. (6) boiling curve exponent, $h \sim q^n$
p	probability of Type-I error (unitless)
q	heat flux (W/cm^2)
R_a	average roughness (μm or m)
R_p	peak roughness (μm or m)
R_q	root-mean-square roughness (μm or m)
R^2	statistical coefficient of determination
T	temperature (K) (unless °C is specified)
ΔT	temperature difference with respect to saturation (K or °C)
t	time coordinate in bubble growth (s)
V	arbitrary variable, units by context
x	lateral length coordinate (m)
y	lateral width coordinate (surface analysis) (m) video height coordinate (bubble measurements) (m)
z	vertical height coordinate (surface analysis) (m)

Greek

α	void fraction (unitless)
ϕ_m	surface mean normal angle, °, Eq. (5) or (6)
κ_{max}	idealized surface maximum curvature (m^{-1}), Eq. (10)
λ	surface wavelength
θ, θ_r	liquid contact angle (°)
$\Delta\rho$	density difference (liquid density–vapor density) (kg/m^3)
σ	surface tension (N/m)
τ	bubble ebullition period (s)

Subscripts

0	value at intercept
base	value at base of bubble
CHF	value at critical heat flux
cut	cutoff
d	value at departure
eq	equivalent
exp	experimental value
filt	filtered
m	arithmetic mean
max	maximum
min	minimum
ONB	value at onset of nucleate boiling/boiling incipience
pred	predicted value
w	of heated wall

Superscripts

*	normalized quantity, or value for basis of comparison, Tables 3 and 4

bubble departure diameters predicted by fractal theory along with models for individual heat transfer mechanisms [9–14] to reproduce the experimentally observed boiling curves of Wang and Dhir [15] with good accuracy. Most recently, Sathyamurthi et al. [16] noted a similarity between the boiling curve and fractal dimensionality of the void fraction in contact with the surface in pool boiling. However, a widely applicable fractal approach has not been developed to date for the prediction of pool boiling heat transfer.

Prevailing theories of bubble nucleation and growth depend on the shape or at least the horizontal radius of the nucleating cavity. R values (single vertical roughness parameters, e.g., R_a, R_p, R_q) represent a single dimension of variation normal to the boiling surface. Fractal surface characterization depends upon at least two parameters, and the dimensionality of the measurement can be two or higher. The success of fractal surface characterization applied to boiling is probably due to the fact that the correlated parameters are more descriptive of the important features of the surface than conventional single linear measures.

In this paper, surface roughness is varied and carefully characterized and analyzed in terms of its relationship to bubble growth and departure. A new model for scaling surface roughness is proposed, as are alternative roughness measures that incorporate more physical underpinnings in preference to merely using R values. It is shown that the heat transfer results from the present work, as well as those of Jones et al. [17], are linearly correlated by a measurement of surface area ratio A_r obtained at an appropriate length scale. Correlations of measured bubble departure diameters and times with the new length-scaled measure result in improved uncertainty compared to correlations with R_a or unscaled measures. Bubble measurements from the current work also suggest general relationships for bubble growth with time and for void fraction with heat flux in saturated pool boiling of FC-72.

2. Analysis of surface roughness

In the companion paper to this work [1], six borosilicate glass substrates were roughened by abrading with diamond compound to impart microscopic-scale roughness features, then annealed to control roughness characteristics at the nanoscale. One substrate (test piece 1) was not abraded or annealed. All seven substrates were coated conformally with an electrically conductive ITO layer, from which a 400 μm wide × 25 mm long heater/sensor device was patterned on each substrate. Each test piece was fixed at the base of a thermally controlled chamber that allowed saturated nucleate boiling heat transfer to be measured while recording high-speed videographic visualizations from beneath the test surface and from the side simultaneously.

Test pieces 4, 6, and 7 were abraded with the same diamond compound such that R_a values (and therefore microscopic-scale roughness features) would be similar. These three surfaces, however, were exposed to different annealing conditions of temperature and soak period as shown in Table 1 [1] such that the roughness characteristics at the nanoscale are very different. Boiling performance for the three surfaces differed as described