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International Journal of Heat and Mass Transfer 47 (2004) 5033–5044
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Nucleate pool-boiling heat transfer. I: review of parametric effects of boiling surface

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Received 19 August 2003; received in revised form 22 June 2004
Available online 23 August 2004

Abstract

The objective of this paper is to assess the state-of-the-art of heat transfer in nucleate pool-boiling. Therefore, the paper consists of two parts: part I reviews and examines the effects of major boiling surface parameters affecting nucleate-boiling heat transfer, and part II reviews and examines the existing prediction methods to calculate the nucleate pool-boiling heat transfer coefficient (HTC).

A literature review of the parametric trends points out that the major parameters affecting the HTC under nucleate pool-boiling conditions are heat flux, saturation pressure, and thermophysical properties of a working fluid. Therefore, these effects on the HTC under nucleate pool-boiling conditions have been the most investigated and are quite well established.

On the other hand, the effects of surface characteristics such as thermophysical properties of the material, dimensions, thickness, surface finish, microstructure, etc., still cannot be quantified, and further investigations are needed. Particular attention has to be paid to the characteristics of boiling surfaces.

1. Introduction

Over the past 80 years (starting with the works of Jacob, Fritz, Nukiyama and others as early as the 1920s), heat transfer under boiling conditions has been investigated extensively by many scientists worldwide. Many theoretical and empirical correlations have been proposed to estimate the boiling heat transfer coefficient (HTC), as well as critical heat flux under different conditions [1]. The classical boiling process studied was nucleate pool-boiling—boiling on a surface submerged in a liquid pool. Many varieties of boiling surfaces (plates [2–12], strips [13], wires [9,14,15], and single tubes [16]) made of various materials have been investigated over a wide range of boiling conditions.

An analysis of these earlier works shows that the major parameters affecting the HTC under nucleate pool-boiling conditions are heat flux, saturation pressure, and thermophysical properties of a working fluid; therefore, the effects of these parameters on the HTC under nucleate pool-boiling conditions have been the most investigated and are quite well established. On the other hand, the effects of surface characteristics such

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doi:10.1016/j.ijheatmasstransfer.2004.06.019

Nomenclature

A	area [m^2]
C	specific heat [J kg^{-1} K^{-1}]
C_{sf}	coefficient in the Rohsenow correlation [–]
D	diameter [m]
D_b	vapor bubble departure diameter [m]
f_b	frequency of vapour bubble departure [s^{-1}]
g	acceleration due to gravity [m s^{-2}]
G_b	mass velocity of bubbles at their departure [kg^{-2} s^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
h_{fg}	latent heat of vaporization [J kg^{-1}]
H	height [mm]
H_i	absolute deviation of profile from mean line over axis Y [μm]
k	thermal conductivity [W m^{-1} K^{-1}]
l_*	pool-boiling characteristic dimension, $\left[\frac{\sigma}{g(\rho-\rho_g)}\right]^{0.5}$ [m]
n	number of vapor bubble generating centers per unit area [m^{-2}]
p	pressure [Pa]
r	radius of cavity [m] or regression coefficient [–]
R_a	arithmetic-average surface roughness [μm]
R_q	root-mean-square surface roughness [μm]
R_z	mean-total roughness (average value of five highest peaks plus five deepest valleys over evaluation length, $R_z = \frac{1}{5}\left(\sum_{i=1}^{5}\lvert H_i^{\max}\rvert + \sum_{i=1}^{5}\lvert H_i^{\min}\rvert\right)$ [μm]
q	heat flux [W m^{-2}]
T	temperature [K]
$\bar{u}_b$	mean velocity of vapor bubble growth [$D_b f_b$] [m s^{-1}]

Greek symbols

α	thermal diffusivity, $\left[\frac{k}{c_p\rho}\right]$ [m^2 s^{-1}]
Δ	difference [–]
μ	dynamic viscosity [Pa s]
θ	contact (wetting) angle [degrees]
π	reduced pressure, $\left[\frac{p}{p_{cr}}\right]$ [–]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
χ	thermal assimilability of solid, $\sqrt{kc\rho}$

Subscripts

a	arithmetic
b	boiling
c	center
cr	critical
ext	external
f	saturated fluid
g	saturated vapor
l	subcooled liquid
max	maximum
nc	natural convection
p	at constant pressure
s	saturation
sf	surface–fluid
sub	subcooling
w	wall
Note:	physical properties with no subscript refer to saturated liquid

Abbreviations

HTC	heat transfer coefficient
rms	root mean square

as thermophysical properties of the material, dimensions, thickness, surface finish, microstructure, etc., still require further investigation [17].

An analysis of the literature shows that based on their experimental findings, some researchers [9,18–21] concluded that for many practical applications the effects of solid surface/liquid/vapor interaction on the HTC under nucleate pool-boiling conditions are insignificant and can be neglected (except for the boiling of cryogenic fluids). However, others [2–6,8,10,11,22–30] concluded that these effects were significant and proposed different methods to estimate them.

Therefore, several studies were focused on the effects of contact angle, thermophysical properties, dimensions, shape, thickness, orientation in space, roughness (surface finish), and microstructure (including shapes, dimensions, and density of pores that are considered to be vapor bubble generating centers) of the boiling surfaces.

In general, the nucleate pool-boiling process should be described using several internal boiling characteristics (see Table 1), such as the vapor bubble diameter at the moment of departure, D_b (see Fig. 1a), the vapor bubble departure frequency, f_b (see Fig. 1b), and the mean velocity of vapor bubble growth, $\bar{u}_b = D_b f_b$ (see Fig. 1c) [9]. These characteristics best describe the nature of the pool-boiling process. However, in practice, these internal pool-boiling characteristics are not tabulated due to unsolvable difficulties in their accurate estimation (due to the stochastic nature of the boiling process).

The following section discusses the state of knowledge about the effects of various surface characteristics on the nucleate pool-boiling HTC.

Table 1
Internal boiling characteristics of various fluid–surface combinations [9]

Fluid	p_s, MPa	$\pi \times 10^3$	Boiling surface	D_b, mm	f_b, s^{-1}	u_b, mm/s
Water	0.1	4.52	Permalloy	2.5	61	153
			Brass	2.3	67	157
			Copper	2.8	56	157
Freon-12	0.1	23.6	Permalloy	0.7	84	59
			Brass	0.7	99	69
			Copper	0.7	91	64
CCl_4	0.1	22.0	Permalloy	1.1	110	121
			Brass	1.1	108	119
			Copper	1.1	106	117
Ethanol (96.5%)	0.1	15.6	Permalloy	1.0	114	114
			Brass	1.1	112	123
			Copper	1.2	98	118
Methanol	0.1	12.6	Permalloy	1.7	74	124
n-Butanol	0.1	20.2	Permalloy	1.1	106	111
Benzene	0.1	20.3	Permalloy	1.0	99	99

2. Effects of surface characteristics on pool-boiling heat transfer

In general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the surface material (thermal conductivity and thermal absorption), interactions between the solid surface, liquid and vapor (wettability, adhesion, adsorption), surface microgeometry (dimensions and shape of cracks and pores), etc. All these parameters affect the HTC simultaneously and are interlinked. However, there are still not enough data available to solve this complex problem. For this reason, only separate effects are usually considered.

The least known effect is the effect of boiling surface characteristics on the HTC. Some of these characteristics are difficult to assess quantitatively, and are dependent on the presence of surface contamination and oxide films, method of surface treatment, manufacturing process, etc. Therefore, a quantitative estimation of the effect of boiling surface characteristics on the HTC under pool-boiling conditions has not yet been determined.

2.1. Effect of surface microgeometry

A slightly better situation exists as far as the estimation of the heating surface microgeometry effect on the HTC is concerned. The commonly accepted microgeometry characteristic (but not the only one) is the surface roughness, expressed in terms of average (R_a), root-mean-square (rms) (R_q), or mean-total (R_z) surface roughness. Also, in some "old" works [4,5,7,8,16,25], surface treatment is used as a relative characteristic of surface roughness. However, average, rms, or mean-total surface roughness, as well as the method of surface treatment, do not show the real microstructure of the heating surface. For example, for the same value of surface roughness, two extreme cases of microstructures may exist—"plateau with peaks" and "plateau with valleys and cavities". In addition to measuring surface roughness with profilometers [6,15,31,32], the microstructure can be visually determined with microscopes [3,15,33–36]. Nowadays, quite sophisticated equipment—laser profilometers for the evaluation of surface roughness parameters [17,36] and scanning electron microscopes for the evaluation of microstructure [36]—are used.

According to the current understanding of the boiling process, stable vapor bubble generating centers can be only those microgeometry elements that are not filled with liquid after vapor bubble departure. Together with surface wettability, the main parameters that determine this ability of a cavity to preserve a "ready" vapor nucleus, are its shape and size.

The effects of cavity size, shape, and cavity population on nucleation characteristics of a surface were investigated by Singh et al. [37]. Cavity radius and depth (only cylindrical cavities were considered), contact angle of the fluid, and initial fluid penetration velocity are important parameters determining the stability of a cavity in boiling.

In general, relatively large cavities filled with liquid cannot be active vapor bubble centers.

Therefore, the surface roughness may affect the HTC only when surface roughness changes coincide with the appearance of new vapor generation centers, thus

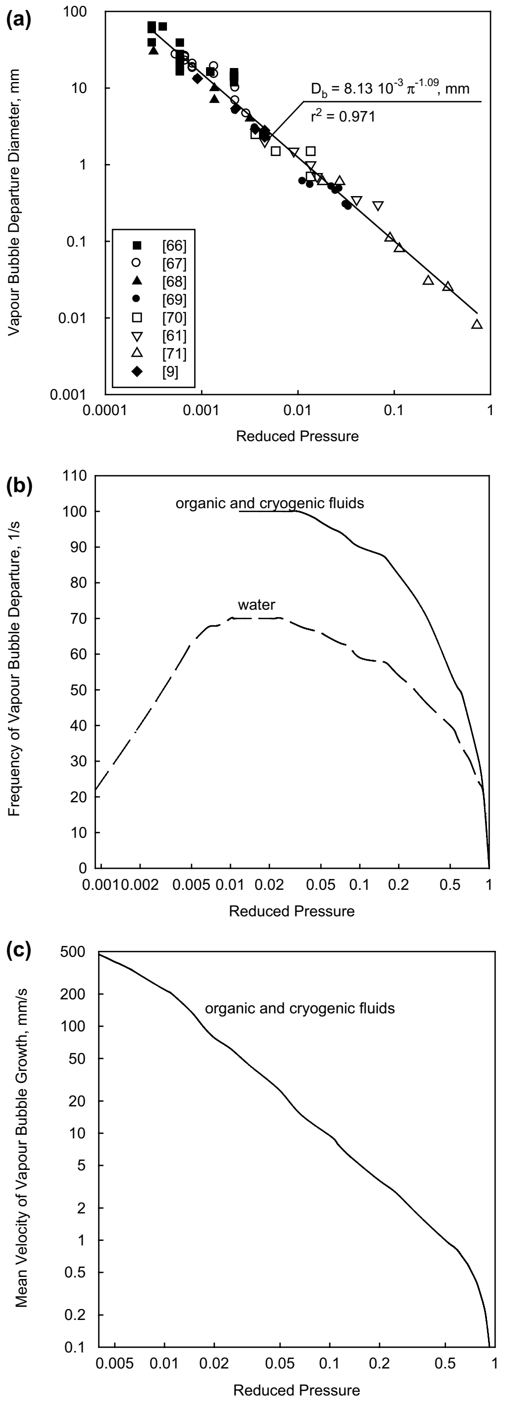

Fig. 1. Effect of reduced pressure on internal boiling characteristics: (a) on vapor bubble departure diameter at water boiling [9,61,66–71]; (b) on frequency of vapor bubble departure [9] and (c) on mean velocity of vapor bubble growth [9].

widening the range of active cavities. If large cavities filled with liquid are created with changing surface roughness, then this change does not affect the HTC [38], suggesting that grooves (which are a more common type of primary roughness elements) are ineffective vapor traps unless they are very poorly wetted or steep walled.

These considerations are supported by experimental results on the effect of roughness on boiling heat transfer. The effect of roughness on HTC is illustrated by the following experimental data obtained during boiling of two very different fluids, water and helium (they are located at opposite extremes as far as critical pressures, contact angles, etc., are concerned).

The experiments [39] showed that with water boiling at $p = 0.4$ MPa and $\Delta T_{\text{sub}} = 20$ K on vertical stainless steel tubes, the HTCs measured on the surfaces of cold-drawn tubes (R_a about 0.8–3.2 μm [40]) and tapered tubes are fairly close (the HTCs on cold-drawn tubes are about 10% higher than those on tapered tubes). However, the HTCs on polished tubes (R_a about 0.1–0.4 μm [40]) are 1.5 times lower than those on cold-drawn tubes within a wide range of heat fluxes ($q = 25$–100 kW m^{-2}).

On the other hand, the HTCs obtained with helium boiling at $p = 0.1$ MPa on the end face of copper rods with various surface roughnesses [41] showed that, with surface roughnesses (R_z) of 5 and 10 μm (R_a roughness [1] according to [42] is about 1 and 2.5 μm, respectively), there is no difference in the HTCs for both surfaces. However, with a surface roughness (R_z) of 1 μm (R_a roughness [2] is about 0.2 μm [42]), the HTCs are lower by up to five times compared with the two previously mentioned surfaces, within a wide range of heat fluxes ($q = 10$–4000 W m^{-2}).

These experiments showed that, with increasing surface roughness, starting from a smooth polished surface (R_a about 0.1–0.4 μm [40]), the boiling HTC increases and reaches some maximum value; after this point, a further increase in surface roughening has no effect on boiling heat transfer. Also, during long-term work a distinctive "pre-treatment" of the boiling surface occurs, thus smoothing primary differences in the conditions of various surfaces. Therefore, for many surfaces without special treatment, i.e., lapping, polishing, etc., the effect of surface roughness within a wide range may not be taken into account.

The population of vapor bubble generating centers can be estimated using [43]

$$\sqrt{n} = 25 \times 10^{-8} \left(\frac{h_{fg} \rho_g \Delta T}{T_s \sigma} \right)^{1.5}. \tag{1}$$

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[1] This range of surface roughness usually corresponds to such production processes as milling, broaching, reaming, boring, turning, extruding, cold rolling, and drawing [40].

[2] This value of surface roughness usually corresponds to such production processes as lapping, polishing, honing, and grinding [40].

Therefore, $n \sim \Delta T^3$, $q \sim \Delta T^3$, and $q_c = \frac{q}{n} \cong \text{const}$, where q_c is the vapor generating capability of a single vapor generating center.

Chowdhury and Winterton [31] investigated surface effects during quenching. They used vertical cylinders ($D_{ext} = 18$ mm and $H = 40$ mm) made of copper and aluminum with different surface roughnesses. These cylinders were heated to 300–450 °C, after which they were submerged into water or methanol. The experiments showed that for the copper cylinder, during nucleate boiling in methanol at atmospheric pressure, the HTC increased with increasing surface roughness from 0.25 to 4.75 μm (contact angles were in the range of 58–72°). For the anodized aluminum cylinder, during nucleate boiling in water at atmospheric pressure, the HTCs were about the same for different surface roughness values (from 1.2 to more than 5 μm and with contact angles in the range of 38–40°). The results were explained by suggesting that roughness itself does not affect nucleate boiling, but rather it affects the number of active nucleation sites on the surface. Scanning electron micrographs showed that the anodized surface had cavities of about 1 μm in size, while the surfaces that had not been anodized had fewer and much larger cavities.

Mikic and Rohsenow [44] developed a model for nucleate pool-boiling heat transfer, which accounted for surface characteristics through cavity size distribution. They showed the effect of cavity size distribution for any surface on the *heat flux vs.* ΔT boiling curve in pool boiling. Their model started with the description of the boiling process assuming that the number of vapor generating centers per unit area with radii greater than r can be expressed as

$$n = C_1 \left(\frac{r_s}{r}\right)^m, \tag{2}$$

where C_1 is the dimensional constant (1/unit area), and r_s is the radius for which n would be one per unit area. C_1, r_s, and m can be determined from cavity size distribution measurements [45]. Mikic and Rohsenow [44] postulated that when a bubble of diameter D_b departs from the surface it pumps superheated liquid away from the surface over a region $2 \cdot D_b$. Colder liquid at saturation temperature replaces this superheated liquid. Between bubble departures, the transient conduction to the liquid in the region $2 \cdot D_b$ would be

$$q = \frac{2k\Delta T\sqrt{f_b}}{\sqrt{\pi\alpha}}, \tag{3}$$

where π is 3.1416.

The fraction of surface covered by n active vapor generating centers per unit area is $n(\frac{\pi}{4})(2D_b)^2$.

Therefore, the heat flux (q) representing the superheating of liquid at these active centers per unit total surface area is

$$q_b = 2\sqrt{\pi k \rho c_p f_b} D_b^2 n \Delta T. \tag{4}$$

This is taken as the heat transfer at the bubble locations that forms the vapor in the pool. Eq. (4) has been verified for many fluid–surface combinations by measuring q_b, ΔT, D_b, f_b and n.

The area between the active vapor bubble generating centers (A_{nc}) per unit total area is

$$\frac{A_{nc}}{A} = 1 - n\pi D_b^2. \tag{5}$$

Postulating that in this region heat is transferred by single-phase natural convection

$$q_{nc} = h_{nc}\Delta T, \tag{6}$$

then the total heat flux is

$$q = (1 - n\pi D_b^2)q_{nc} + q_b. \tag{7}$$

They found that r can be expressed as

$$r = \frac{2T_s\sigma}{h_{fg}\rho_g\Delta T\left(1 - \frac{qr}{k\Delta T}\right)}. \tag{8}$$

For $\frac{qr}{k\Delta T} \ll 1$, combining Eqs. (2) and (8) to eliminate r gives

$$n = C_1 r_s^m \left(\frac{h_{fg}\rho_g}{2T_s\sigma}\right)^m (\Delta T)^m. \tag{9}$$

In general, vapor bubble departure diameter can be expressed as

$$D_b = C_2 \left[\frac{\sigma}{g(\rho - \rho_g)}\right]^{1/2} (Ja^*)^{5/4}, \tag{10}$$

where C_2 is 1.5×10^{-4} for water and 4.65×10^{-4} for other fluids, and $Ja^* = \frac{\rho c_p T_s}{\rho_g h_{fg}}$ is the modified Jakob number.

Vapor bubble departure velocity can be expressed as

$$f_b D_b = C_3 \left[\frac{\sigma g(\rho - \rho_g)}{\rho^2}\right]^{1/4}, \tag{11}$$

where C_3 is 0.6.

Using these relations, Eq. (4) becomes

$$\frac{q_b}{\mu h_{fg}}\sqrt{\frac{\sigma}{g(\rho - \rho_g)}} = B(\phi\Delta T)^{m+1}, \tag{12}$$

where

$$B = \left(\frac{r_s}{2}\right)^m \frac{2\sqrt{\pi}}{g^{9/8}} C_1 C_2^{3/2} C_3^{1/2} \tag{13}$$

and

$$\phi^{m+1} = \frac{k^{1/2}\rho^{17/8}c_p^{19/8}h_{fg}^{m-(23/8)}\rho_g^{m-(15/8)}}{\mu(\rho - \rho_g)^{9/8}\sigma^{m-(11/8)}T_s^{m-(15/8)}}. \tag{14}$$

In general, B is solely a function of cavity size distribution and ϕ is a function of fluid properties and the exponent m.

Mikic and Rohsenow [44] suggested that for a known cavity size distribution, this relation might be predicted. For an unknown distribution it is sufficient to have boiling data at one pressure, in order to predict this relation at other pressures for the same liquid and boiling surface.

Barthau [46] developed a new optical method for estimating the number of nucleation sites on a boiling surface. The proposed method allowed the recording of up to 5,000 active sites per cm^2 during R-114 pool boiling on a horizontal copper tube. He found that the heat transfer contribution of an individual active site decreases with increasing pressure and heat flux.

Berenson [7] found that the nucleate-boiling HTC could vary by up to 600% due to variations in surface finish. A closer look at his experimental work reveals that only high quality surface finishing was used, namely, mirror finishing and lapping. According to Ryffel [47] a typical range of surface roughness produced by these processes is $R_a = 0.05$–0.4 μm. Within this range of surface roughness, small changes in surface finishing may lead to a noticeable increase or decrease in the number of cavities that can be potential centers for vapor bubble generation.

Similar results, in terms of a noticeable surface roughness effect on the HTC, were obtained by Benjamin and Balakrishnan [32]. Also, in their study very smooth boiling surfaces were used (surfaces were polished with 4/0, 3/0, and 2/0 emery papers, which produced R_a values within the range of 0.07–1.17 μm).

Corty and Foust [30] noticed the effect of surface roughness of different polished metal surfaces (copper and nickel) on the HTC for nucleate pool-boiling of various fluids (*n*-pentane, R-113, diethyl ether). Surface roughness (in terms of rms roughness) of these plates was within the range of 0.056–0.58 μm.

Later, Kurihara and Myers [4], based on extensive nucleate pool-boiling experiments with various fluids on different metal surfaces polished with emery papers (4/0–2/0), stated that the surface roughness effect on the HTC was clearly pronounced up to a value of rms surface roughness of about 0.76 μm. Above this limit, the HTC was not affected by further increases in surface roughness (it should be noted here that at some large values of R_a the surface roughness effect on the HTC may reappear, because at a certain surface roughness level (about 50–100 μm and higher), the rough surface may be considered to be a surface with microfins or as an enhanced surface). The effect of surface roughness on the HTC, related to the increased number of active boiling centers with surface roughness, increases.

Nucleate pool-boiling of R-113 on tubes with different surface roughnesses at atmospheric pressure (see Fig. 2) [48] showed that, in general, the HTC increases with increasing roughness. Thus, the HTCs for relatively rough tubes (with surface roughness (R_z) of 19–58 μm (R_a is about 3.8–14.5 μm [42])) are 2.3–3 times higher than those for polished tubes (with surface roughness (R_z) of 0.3–0.45 μm (R_a is about 0.06–0.09 μm [42])) at heat fluxes of 4–40 kW m^{-2}. For tubes without any special surface treatment (with surface roughness (R_z) of 1.9–3.8 μm (R_a is about 0.38–0.95 μm [42])), the HTCs are 1.4–1.9 times higher than those for polished tubes. In the range of surface roughness (R_z) from 1.9 to 3.8 μm (R_a is about 0.38–0.95 μm [42]), the HTCs differ by 14% at $q = 40$ kW m^{-2} and by 25% at $q = 4$ kW m^{-2}. This shows that the effect of surface roughness on the HTC during pool-boiling decreases as the heat flux increases, and is less pronounced for boiling on surfaces without special surface treatment (i.e., lapping, polishing, etc.).

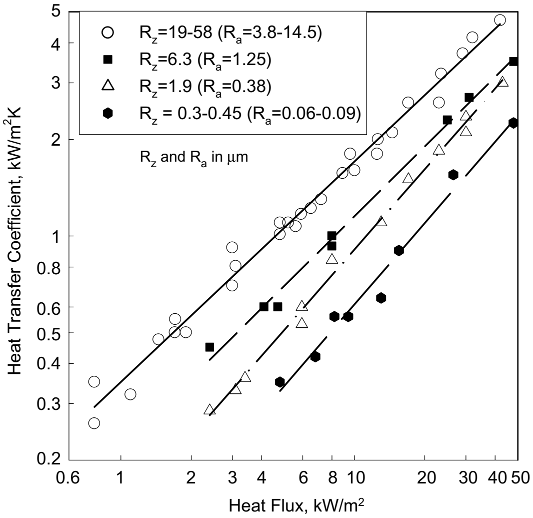

Fig. 2. Effect of heat flux on HTC for boiling of Freon-113 on tubes with various surface roughnesses ($p = 0.1$ MPa) [48].

According to Kutateladze [19], it is impossible to estimate quantitatively the combined effect of various microgeometry parameters on the HTC. Therefore, different values of the constant in a HTC correlation are listed in the literature. However, in his pool-boiling correlations the microgeometry effect was not taken into account.

2.2. Effect of boiling surface material thermophysical properties

The effect of boiling surface material thermophysical properties on the HTC should be considered in terms of two aspects [49]. The first one is related to the spatial discreteness of vapor bubble generating centers, and the second one is related to non-stationary heat transfer between the heated surface and liquid near the vapor bubble generating centers.

Vapor bubble generating centers are places of intensive heat removal, with the local heat flux being much higher than the average value. Due to this situation, the time-average temperature near the active vapor bubble generating center in the surface layer of a heated wall is lower than that on the rest of the surface. This heat flux redistribution inside the surface layer results in a lowering of the entire surface temperature, as compared to the temperature needed for transfer of average heat flux without boiling.

The existence of active vapor generating centers decreases the surface temperature not only near the generating center but also on the free surface, resulted in increasing the HTC. Naturally, the higher the wall material thermal conductivity, the more intense the redistribution of heat fluxes between parts of the free surface and the surface covered with active vapor generating centers. From this statement, a general conclusion regarding the wall thermal conductivity effect on nucleate boiling heat transfer can be drawn. That is, in the case of a "rough" surface that has quite a large number of potential vapor generating centers, the wall thermal conductivity does not significantly affect the boiling heat transfer. This is illustrated in Fig. 3, which shows low values of Prandtl number that correspond to near atmospheric pressure, and therefore, quite a large number of vapor generating centers at these conditions—there is no effect of wall thermal conductivity on the HTC.

At low wall material thermal conductivity, redistribution of local heat fluxes between the free surface and the surface covered with active vapor generating centers would not be so easy as in the case of high wall thermal conductivity. With increasing heat flux the temperature of the free surface would rise. This would lead to the activation of potential vapor generating centers at the free surface and to a decrease in its temperature (i.e., an increase in the boiling HTC). Therefore, it can be expected that at low wall thermal conductivity the heat flux through a single center (i.e., a center that is able to generate vapor) is smaller than for a surface with high wall thermal conductivity, although the number of vapor generating centers will be larger. This is illustrated in Fig. 3, which shows higher values of Prandtl number that correspond to sub-atmospheric pressures, and therefore, a relatively small number of vapor generating centers at these conditions—the HTC will be higher on low conductivity material such as stainless steel, compared to the HTC on aluminum and brass surfaces. This assumption corresponds to the data obtained during the investigation of internal characteristics of boiling water and ethanol on heated surfaces made from different materials [50].

For boiling on "smooth" surfaces (with a significantly limited number of potential vapor generating centers), increasing the heat flux does not result in the appearance of a sufficient number of additional vapor generating centers. Furthermore, at low wall material thermal conductivity, the average temperature (over the surface) increases, i.e., the boiling HTC decreases (see Fig. 4, boiling on plastic surface). This statement is supported by the experimental data obtained for ethanol and benzene boiling on polished tubes made of

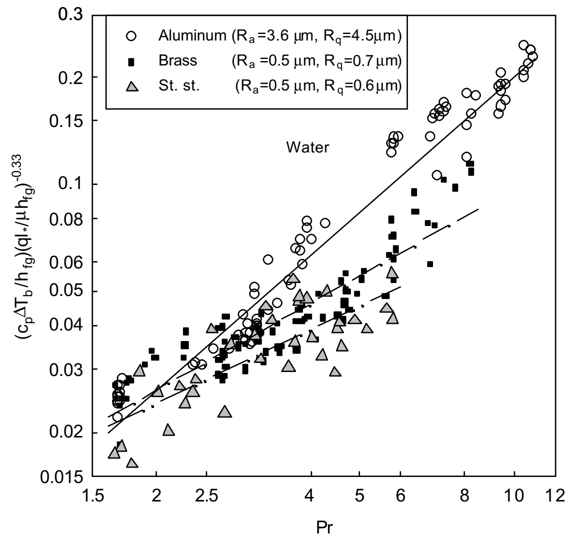

Fig. 3. Comparison of data for various fluid–surface combinations [10–12,17] based on Rohsenow correlation [22,23]: Nucleate pool boiling on thick large-size rectangular plates.

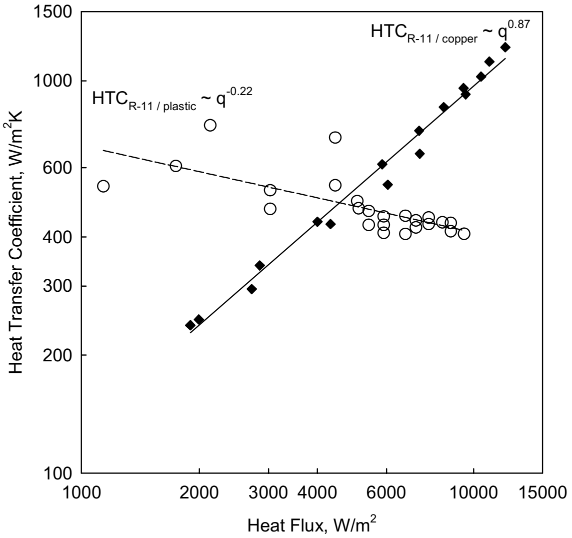

Fig. 4. Effect of heat flux on HTC at nucleate pool boiling of R-11 on copper ($R_a = 1.4$ μm, $R_q = 1.7$ μm) and plastic ($k = 0.48$ W m^{-1}K^{-1}, $R_a = 1.4$ μm, $R_q = 1.7$ μm) large-size surfaces.

silver, nickel, and stainless steel [51]. High quality surface treatment results in a decreasing number of potential vapor generating centers, which leads to a decreasing of the HTC. However, the most interesting part is that the HTC during ethanol and benzene boiling on a silver tube was significantly higher than that on a stainless steel tube [51]. Local redistribution of heat fluxes (due to the high thermal conductivity of silver compared to that of stainless steel) compensated for the decrease in the number of active vapor generating centers (due to the high quality of surface treatment).

For the boiling of cryogenic fluids the wall thermal conductivity affects the HTC even with moderate treatment of the heating surface [52]. Cryogenic fluids wet the heated surface very well, because their contact angles are close to 0. Due to this characteristic, without the special surface treatment (i.e., roughening of the surface) there are not a sufficient number of cavities that can be potential vapor generating centers. A surface that is ‘‘rough’’ for regular fluids is ‘‘smooth’’ for cryogenic fluids. Only a special surface treatment that creates a micropore surface layer can produce a surface that is sufficiently ‘‘rough’’ for cryogenic fluids.

Thus, from the above consideration, it can be concluded that the wall material thermal conductivity may noticeably affect the HTC during nucleate boiling only in the case of a very limited number of potential vapor generating centers on a heating surface. The limited number of potential vapor generating centers can be mainly related to surface treatment (polished surfaces, etc.) or to boiling at sub-atmospheric pressures.

Guo and El-Genk [53] performed water pool-boiling experiments on a Pyrex glass substrate coated with SnO_2. They found that the microlayer evaporation rate increased as the thickness and thermal conductivity of the heated wall increased, due to improved lateral heat conduction. The values of the accommodation coefficient of evaporation as well as lateral heat conduction significantly affect the liquid microlayer evaporation rate on the highly conductive wall, especially during the early stage of the transient. In contrast, a low-conductivity heated surface or a thin coating of low-conductivity material on a heated metal substrate significantly reduces the evaporation rate of the liquid microlayer, and the effect of the heated metal substrate is negligible unless the coating is very thin.

Kutateladze [19] pointed out that the effect of boiling surface thermophysical properties can be expressed in the form of a ratio of the thermal assimilability of the surface material to that of the liquid:

$$\bar{\Lambda} = \left(\frac{\chi_w}{\chi_l}\right) = \left(\frac{\sqrt{k_w c_w \rho_w}}{\sqrt{k_l c_{pl} \rho_l}}\right). \tag{15}$$

According to Gordov and Yagov the HTC is roughly proportional to $\bar{\Lambda}^{0.4}$, but Grigor'ev et al. [41] assumed that this effect is much stronger. However, Kutateladze [19] noted that it was too early to use this dependency in technical calculations, because the quantitative effect of this parameter on the HTC was not fully investigated.

2.3. Effect of heated wall thickness

The effect of heated wall thickness on the HTC during pool-boiling should be considered in conjunction with the effect of thermophysical properties of the boiling-surface material. Kichigin and Pioro [54] showed that the depth of penetration of the temperature oscillations for stainless steel and copper plates depends on the frequency of these oscillations and on the thermophysical properties of the boiling surface material (mainly thermal conductivity). At a frequency level of about 100 Hz, the depth of temperature oscillation penetration is 0.3 mm for stainless steel plate and 1.4 mm for copper plate. At a frequency level of about 10 Hz, this depth becomes 0.8 mm for stainless steel plate and 4.4 mm for copper plate. Therefore, the depth of temperature oscillation penetration inside a boiling surface decreases when the frequency increases and wall thermal conductivity decreases. This means that for low conductivity materials such as plastics, stainless steels, etc., the heated wall thickness may have some effect only for very thin walls (0.3–2 mm) within the frequency range of 2–100 Hz. In contrast, for highly conductive materials such as copper, aluminum, brass, etc., the heated wall thickness may have some effect for quite thick walls (1.4–10 mm) within the same frequency range.

Chuck and Myers [55] found that for nucleate pool-boiling of water, ethanol and *n*-heptane on stainless steel plates with thicknesses of 0.025, 0.051, and 0.13 mm, the effect of thickness on the HTC is minor. However, the HTC increases somewhat with increasing plate thickness for a larger ΔT; however, for a smaller ΔT the trend is opposite.

Margini and Nanei [56] investigated saturated pool-boiling of water at atmospheric pressure on horizontal non-metallic rods plated with copper, silver, zinc, nickel and tin, with thicknesses ranging from 5 to 250 μm. Average surface roughness values of the boiling surfaces were within the range of 0.7–1.0 μm. They found that, for nickel, tin, and zinc, the HTC increased with decreasing heater thickness (in particular, the HTC for nickel and tin increased up to 500–700%, and for zinc up to 100%). However, at certain values of heater thickness (‘‘limiting value’’), its effect on the HTC became negligible. This ‘‘limiting value’’ for the heater thickness was 70 μm for zinc, and 15 μm for both tin and nickel. No appreciable heater thickness effect was found for copper and silver plating. It should be pointed out that these experiments and corresponding findings might be affected by the circumferential conjugated effect, due to a non-uniform distribution of the HTC over the rod circumference.

2.4. Effect of contact angle

The work required for vapor bubble creation on non-wetted surfaces (θ close to 180°) is very small, and the probability of vapor bubble generation tends to be 1. In reality, measured contact angles ranged from about 90° to 140° [13,14]. This means that wettability may decrease the work required for vapor bubble creation on smooth surfaces by 2–3 times. However, the probability for vapor bubble generation would be still quite small, and the required overheating would be quite high. According to Skripov [57], even at $\theta = 129°$ for water at atmospheric pressure, the required overheating decreases only by 32 K compared to the ultimate overheating of 202 K at bulk boiling.

Low wettability ($\theta > 90°$) slightly affects vapor bubble creation and overheating, but has a positive effect on nucleate boiling in terms of its stability.

Wang and Dhir [35] conducted experiments with water boiling at atmospheric pressure on vertical copper surfaces with different wetabilities (contact angles of 90°, 35° and 18°) and found that, at a contact angle of 90°, only 1–10% of the cavities present on the surface were vapor generating centers. Based on these experiments they concluded that the number of active vapor generating centers decreased as the wettability of the boiling surface improved (i.e., as values of the contact angle decreased).

Real (i.e., technical) surfaces are never absolutely smooth. They are more or less rough, and are characterized by microstructure. Only microcavities can be active centers for vapor bubble generation, especially microcavities that have low wettability by liquid.

It is known [58,59] that

$$D_b \sim \theta\sqrt{\frac{\sigma}{g(\rho-\rho_g)}}. \qquad (16)$$

The original Fritz formula uses values of the static contact angle (θ). However, Han and Griffith [62] found that the Fritz formula worked as long as the true (non-equilibrium) bubble contact angles were used.

In general, these values should be known for various fluids at different pressures. Nevertheless, these data are very limited and inconsistent. According to Griffith and Wallis [5] the average value of θ does not depend on water saturation pressure. However, Labuntsov et al. [60] showed that there is a weak effect of the saturation pressure on θ for water boiling on a silver surface at $p_s = 0.1-15$ MPa (see Fig. 5). Zhilina [61] found that θ is proportional to $p_s^{0.3}$ for water boiling at $p_s = 0.1-1.5$ MPa on copper, steel, and nickel surfaces (see Fig. 5). These inconsistencies and contradictions are explained by proposing many reasons for discrepancies, such as difficulties in obtaining accurate θ measurements during boiling, and significant effects of negligible contamination of the boiling surface by oxides, fat, and other deposits. Therefore, in practice, the task of obtaining accurate values of the true contact angle during boiling is unrealistic.

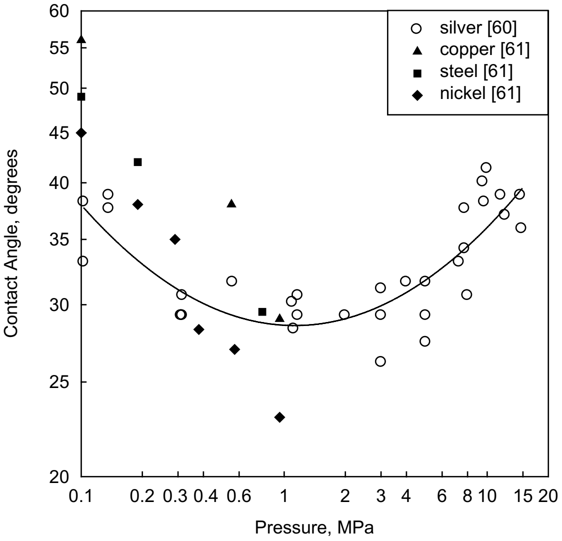

Fig. 5. Effect of pressure on contact angle at water boiling on surfaces of various materials: solid line fits data for water boiling on silver surface.

Due to this, the Fritz formula can only be considered as a theoretical approach. In general, part of the formula $\left(\sqrt{\frac{\sigma}{g(\rho_f-\rho_g)}}\right)$ is used in many practical non-dimensional correlations for the HTC as a characteristic dimension for nucleate pool-boiling in the Nusselt number. It is assumed that this expression is proportional to the vapor bubble departure diameter. In the literature, this expression is also called the "capillary constant of liquid".

2.5. Orientation effect on HTC

The effect of boiling surface orientation on the HTC is noticeable [63]. The HTC is at its lowest value on horizontal plates with the boiling surface facing down than on any other surface. For a vertical tube bundle immersed in a pool, the HTC is higher on the upper part of the tube bundle due to the increased velocity of the rising vapor. A similar effect was found in a horizontal tube bundle immersed in a pool—the HTC is higher on the upper tubes due to increased single-phase convection. This effect is more significant at low heat fluxes.

Kang [64] conducted experiments with pool-boiling on a horizontal, inclined, and vertical tube and found that the orientation effect on the HTC could be significant. According to his findings, the HTC is higher on an inclined tube (about 45° from the horizontal plane) compared to horizontal and vertical orientations. This effect seems to be due to decreased bubble slug formation on a boiling surface and improved liquid access to the surface.

2.6. *Effects of other parameters on boiling HTC*

2.6.1. *Effect of surface shape*

In general, it should be pointed out that any surface other than a flat surface may have a non-uniform HTC distribution; for example, a horizontal cylinder submerged in a pool. It is obvious that HTCs over a cylinder circumference vary from the bottom to the top of the cylinder. Kang [64] found that the highest HTC was on the horizontal tube bottom and the least was at the top.

Therefore, the non-uniform circumferential temperature field causes circumferential conjugated heat flux [65] inside the boiling surface, in addition to local internal heat fluxes around active vapor generating centers, thus affecting the boiling process. In this particular case, the average measured HTC will depend on the number and locations of thermocouples around the cylinder circumference and thermal conductivity of the cylinder material (higher thermal conductivity—less differences in the HTCs around the circumference). In contrast, vapor bubbles departing from a flat horizontal surface interact only with neighboring vapor bubbles, and this interaction is more or less uniform over the entire boiling surface.

2.6.2. *Effect of surface dimension*

In general, surfaces with a single vapor bubble generating center may perform differently compared to large-size surfaces with associations of vapor bubble generating centers, due to continuous interaction between neighboring vapor generating centers through the heating wall material as well as through departing bubbles.

2.6.3. *Effect of liquid level*

To some extent liquid level does not affect the HTC at nucleate boiling. Only for thin liquid layers could nucleate pool-boiling be partially or fully suppressed (see Fig. 6). According to Pioro [12], a liquid level of more than 2 mm over a flat boiling surface has no noticeable effect on the HTC within the investigated range of heat flux. Similar results were found previously by Tolubinskiy [9], Kutepov et al. [63], and others.

2.6.4. *Effect of "new" and "old" boiling surfaces*

According to Kutepov et al. [63] higher HTC values under nucleate pool-boiling conditions may be achieved on a new or unused clean surface. During the first 100–200 h of continuous boiling, the HTC decreases to a certain level and stays at this level. This decrease in HTC indicates that, after some time, a portion of the vapor generating centers loses their ability to generate the vapor phase. Stable HTC values may appear after continuous boiling for tens or even hundreds of hours.

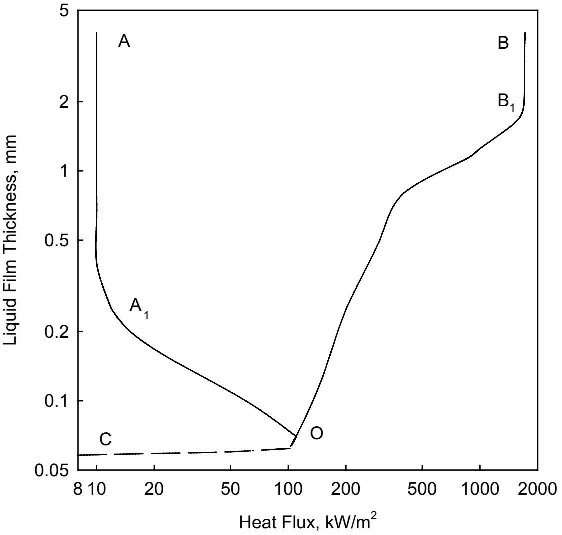

Fig. 6. Nucleate boiling boundaries for saturated water (p = 0.4 MPa) [9]. Curve AA_1 corresponds to transition from convective heat transfer to boiling, BB_1—boiling crisis, A_1O—suppressed boiling and B_1C—breakdown of boiling liquid film.

3. Summary

An exhaustive literature survey showed that nucleate pool-boiling is a very complicated process and is affected by various parameters. The effect of these parameters on the HTC is usually a compound effect and varies with changing boiling conditions. In many cases, an accurate quantitative description of the parameters that affect nucleate pool boiling is impossible. Therefore, for a proper evaluation of the boiling heat transfer correlations, the number of relevant parameters should be minimized. This would ensure that the considered boiling conditions are more common for various applications. Based on the above, nucleate pool boiling on horizontal large-size thick uniform metal plates without special surface treatment would be an ideal case for such an evaluation.

The current review showed that, in general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the surface material (thermal conductivity and thermal absorption), interaction between the solid surface, liquid and vapor, surface microgeometry (dimensions and shape of cracks and pores), etc. All these parameters affect the HTC simultaneously and are interlinked. However, there are still not enough data available to solve this complex problem; as a result, only separate effects are usually considered.

Part 2 of this paper attempts to resolve a long-lasting disagreement among scientists regarding the superiority of various approaches by evaluating several existing correlations in the literature using the same experimental database.

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