International Journal of Heat and Mass Transfer 117 (2018) 978–990

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer and critical phenomena during evaporation and boiling in a thin horizontal liquid layer at low pressures

V.I. Zhukov [a,*], A.N. Pavlenko [b]

[a] Novosibirsk State Technical University, K. Marks ave. 20, Novosibirsk, Russia
[b] Kutateladze Institute of Thermophysics, SB RAS, Lavrentiev ave. 1, Novosibirsk, Russia

ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 26 September 2017
Accepted 16 October 2017

Keywords:
Horizontal liquid layer
Evaporation
Boiling
Regime map
Heat transfer
Critical heat flux

ABSTRACT

The results of an experimental study of heat transfer and high-speed video recording of evaporation and boiling processes in horizontal liquid films of n-dodecane are presented for the wide ranges of layer height and pressure. Evaporation regimes at low reduced pressures were characterized by formation of dry spots and structures with the shape of “funnels” (depressions with a hemispherical bottom on the layer surface) and “craters” in the layers. In contrast to dry spots, the surface of “craters” is covered with a residual layer of liquid. The paper presents regime maps indicating the regions of dry spots, “funnels”, “craters”, and nucleate boiling observed for each layer height depending on the reduced pressure and heat flux density. It is shown that in the region of low reduced pressures, the Kutateladze formula describes change in hydrodynamics in the layers, whose height is equal to the Laplace constant or higher, by the regime where only “craters” remain in the layer. In the region of reduced pressures less than $7.4 \cdot 10^{-5}$ (133 Pa) the critical heat fluxes (CHF) decrease with decreasing pressure. In the range of reduced pressures from $7.4 \cdot 10^{-5}$ (133 Pa) to $5.5 \cdot 10^{-3}$ (10^4 Pa), the CHF depends weakly on the pressure. With an increase in the layer height, CHFs increase sharply, and when achieving a constant value, are described by the Yagov dependence obtained for pool boiling of liquids. For the reduced pressure above $5.5 \cdot 10^{-3}$ (10^4 Pa), in the layers with a height exceeding the Laplace constant, the CHF is the same as that calculated by the Kutateladze and Yagov formulas for nucleate boiling crisis. The slope of the curve of heat flux dependence on the temperature head depends on the layer height at both evaporation and nucleate boiling.

1. Introduction

The first relationship for calculation of the critical heat flux at pool boiling was derived by Kutateladze in [1]:

$$q_{cr} = k h_{LG} \sqrt{\rho_v} \sqrt[4]{g(\rho_l - \rho_v)\sigma}. \tag{1}$$

Kutateladze has revealed that constant k varies within the range 0.13–0.19. In [1] it is recommended to use its average value equal to 0.16, while the later paper [2] suggests to take value of 0.14.

Zuber in [3] has obtained the formula similar to (1) based on a physical model using the results of analysis of Rayleigh-Taylor and Helmholtz instabilities. In his model Zuber considers vapor film formed on a horizontal surface. At the tops of a square lattice with a side corresponding to the characteristic wavelengths of Rayleigh-Taylor instability, the vapor jets rise upward. The wavelength varies within the range of $\tilde{\lambda}_{cr} \leqslant \tilde{\lambda}_Z \leqslant \tilde{\lambda}_d$, where $\tilde{\lambda}_{cr} = 2\pi l_\sigma$ is the critical wavelength according to Taylor instability, and $\tilde{\lambda}_d = 2\pi\sqrt{3} l_\sigma$ is the most dangerous wavelength. The radius of vapor jets is taken equal to the fourth part of the critical wavelength of the Rayleigh-Taylor instability $R_Z = \tilde{\lambda}_Z/4$. The critical velocity of vapor in the jets is determined by the Helmholtz instability. The wavelength of Helmholtz instability was assumed to be $\tilde{\lambda}_H = 2\pi R_Z$ For the CHF, Zuber has derived the expression:

$$q_{crZ} = k h_{LG} \sqrt{\rho_v} \sqrt[4]{g(\rho_l - \rho_v)\sigma} \sqrt{\frac{\rho_l}{\rho_l + \rho_v}}, \tag{2}$$

where $0.12 < k < 0.157$. Zuber recommends taking $k = \pi/24 = 0.131$ as the most appropriate value.

In his cinematographic study of nucleate boiling on a horizontal heating surface, Gaertner [4] presented the detailed information on the structure of two-phase region in the immediate vicinity of the heated wall. He identified the boiling regimes with different vapor structures. His work contains the detailed description of a liquid

---

* Corresponding author.
E-mail address: vizh@inbox.ru (V.I. Zhukov).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.060
0017-9310/

Nomenclature

A_0	growth module of vapor bubble
a	coefficient of temperature conductivity, m^2/s
c_p	specific heat at constant pressure, J/(kg K)
g	acceleration of gravity, m/s^2
h	layer height, m
h_{LG}	latent heat of vaporization, J/kg
$\mathrm{Ja} = \frac{c_p \rho_l (T_w - T_s)}{h_{LG} \rho_v}$	Jacob number
k	constant
l_b	distance between bubble centers, mm
l_f	distance between "funnels", mm
$l_\sigma = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$	Laplace constant, m
P	pressure, Pa
$\mathrm{Pr} = \nu/a$	Prandtl number
q	heat flux density, W/m^2
R	radius, m
R_i	individual gas constant, J/(kg K)
T	temperature, °C, K

Greek symbols

β	volume expansion coefficient, K^{-1}
λ	thermal conductivity, W/(m·K)
$\tilde{\lambda}$	wavelength, m
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

0	departure
cr	critical
cr.h	critical at high pressures
cr.l	critical at low pressures
d	most dangerous
H	referred to Helmholtz instability
l	liquid
s	parameter on saturation line
v	vapor
w	referred to heated surface
Z	refers to Zuber theory

macrofilm, formed on the heating surface under the large vapor bubbles ("vapor mushrooms"). "Vapor mushrooms" are connected with the heating surface by several "vapor stems" that penetrate into the macrofilm. Immediately before the crisis, in the second transition region, according to Gaertner's classification, heat transfer deteriorates, as some vapor stems merge into the "vapor patches".

According to Haramura and Katto [5], the boiling crisis is caused by the mechanism of macrofilm drying under the "vapor mushrooms". In their model, vapor moves inside the "vapor stems", and Helmholtz instability arises because of interaction between vapor and liquid flow. It was assumed by the authors that the distance, where the instability develops, is equal to a quarter of Helmholtz instability wavelength, so that the initial thickness of macrofilm drying under the "vapor mushrooms" is limited in their study by this value. The formula derived in [5] is the justification of Zuber formula. However, it was obtained from consideration of the processes occurring on the wall, in contrast to [1–3], where the authors consider stability of the formed vapor film.

The models of nucleate boiling crisis [3,5] give a certain algorithm for introducing refinements with consideration of various factors. In [6], four approaches to analysis of Rayleigh-Taylor instability are considered: classical inviscid flow analysis, viscous potential flow analysis, fully viscous flow analysis, and lubrication theory. It is shown that the most dangerous instability wavelength for a thin viscous gas film can be equal to $\tilde{\lambda}_d = 2\pi\sqrt{2}l_\sigma$ instead of the value $\tilde{\lambda}_d = 2\pi\sqrt{3}l_\sigma$ obtained from the classical analysis of inviscid flow. The results obtained are applied to the existing models of nucleate boiling crisis of saturated liquid on a horizontal surface. As a result, the accuracy of predictions becomes better with increasing pressure. In [7], the analysis of interfacial instabilities based on a viscous potential flow is used to refine models [3,5]. In [3], the authors consider also Kelvin-Helmholtz instability for a circular viscous gas jet. In the macrofilm dryout model [5], the Kelvin-Helmholtz instability of the viscous potential flow is used to determine the initial thickness of a macrofilm. When processing the experimental data for water in the framework of hydrodynamic model [3] and the macrofilm dryout model [5], a significant increase in the accuracy when predicting the CHF is observed within a wide range of pressures. For organic liquids, two coefficients (a special coefficient for each theory is proposed in [7]), used for consideration of the combined effect of viscosity and density, are close to 1 in a wide range of pressures. For organic liquids, the same results are obtained as in models [3,5], where the viscosity is not taken into account.

In Yagov papers [8–11], a new model of liquid boiling crisis is developed carrying out physical estimates of evaporation of the menisci of a thin liquid film, adjacent to "dry spots" on the heating surface. Crisis initiation is associated with violation of the balance of liquid, supplied to the "dry spot" boundary and evaporated there. The boiling crisis is explained as merging and growth of the "dry spot" area on the heated surface. For pool boiling of liquid in the region of low reduced pressures $P/P_{cr} < 0.001$, the following equation is obtained in [10]:

$$q_{cr.l} = 0,5\,\frac{h_{LG}^{81/55}\,\sigma^{9/11}\,\rho_v^{13/110}\,\lambda_l^{7/110} f(\mathrm{Pr})\mathrm{g}^{21/55}}{\nu_l^{1/2} c_p^{3/10} R_i^{79/110} T_s^{21/22}}, \tag{3}$$

where the function of Prandtl number for nonmetallic liquids is $f(\mathrm{Pr}) = \left(\frac{\mathrm{Pr}^{9/8}}{1+2\mathrm{Pr}^{1/4}+0.6\mathrm{Pr}^{19/24}}\right)^{4/11}$, and for liquid metals, it is $f(\mathrm{Pr}) = 0.5$. Comparison of calculations by dependence (3) with experimental data for liquid metals is given in [9]. For the range of high reduced pressures $P/P_{cr} > 0.03$, the following relationship is derived in [8,11]:

$$q_{cr.h} = 0.06 h_{LG} \rho_v^{0.6} \sigma^{0.4} (g(\rho_l - \rho_v)/\mu_l)^{0.2}.$$

At an arbitrary pressure, CHF is calculated by interpolation formula:

$$q_{cr} = (q_{cr.h}^3 + q_{cr.l}^3)^{1/3}. \tag{4}$$

The calculated dependences are in good agreement with the experimental data on CHF for liquid boiling at low, moderate and high reduced pressures. In a series of papers [8–11], the critical analysis of hydrodynamic models of boiling crises is also performed in detail. The author's theory and critical analysis are most fully presented in [11]. According to [11], any model of crisis, which considers only hydrodynamic effects and ignores the effect of liquid viscosity and heat transfer from the heated surface, leads inevitably to the Kutateladze formula with a slight correction in the form of liquid to vapor density ratio. This can be seen from