International Journal of Heat and Mass Transfer 74 (2014) 342–352

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Observation of boiling heat transfer and crisis phenomena in falling water film at transient heating

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ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form 10 February 2014
Accepted 12 March 2014
Available online 12 April 2014

Keywords:
Falling liquid films
Boiling
Transient heating
Crisis phenomena
Subcooled liquid

ABSTRACT

This paper deals with the experimental study on transient heat transfer at boiling and development of crisis phenomena in the falling film of subcooled liquid at stepwise heat generation. Experimental data with a high temporal and spatial resolution were obtained with the use of high-speed infrared thermometry and high-speed video recording synchronized simultaneously. It is shown that at vapor bubble appearance and condensation the convective streams are formed there, which lead to a decrease in temperature in the area behind the active nucleation site and local increase in heat transfer intensity. At the same time on the free surface of liquid film the so-called "temperature waves" propagating along the liquid flow are formed. The boiling curves were obtained on the basis of experimental data, and comparison with the known models for description of heat transfer at pool boiling of saturated liquid was performed. It is shown that mechanism of appearance and development of crisis phenomena depended significantly on the Reynolds numbers. Crisis development at high Reynolds numbers relates to dry spot formation at quasi steady-state boiling and their following expansion by the mechanism of longitudinal heat conductivity in the heating wall. The wave development on the free surface at low Reynolds number ($Re = 601$), studied in current research, leads to the breakdown of the film without nucleate boiling due to the action of thermocapillary forces. The critical heat fluxes under these conditions are significantly lower than the critical values obtained for high Reynolds numbers at boiling in the falling films of subcooled water.

1. Introduction

Evaporation and boiling in thin films ensure high intensity of interfacial heat and mass transfer. Therefore, the film apparatuses are widely used in industry: refrigerating and chemical industries, various cryogenic apparatuses, heat exchangers, etc. The film flows are also realized in the slug and annular regimes of the two-phase flows in the channel systems. Studying the features of heat transfer development, in particular, for the film flow at transient heating, is important for safe and stable operation of heat exchanging devices with heat flux pulsations, for designing of low-inertia evaporators, heat exchangers-dosing units, mixers, special sorters of measuring equipment, including biotechnological, biomedicine devices, etc. This problem requires a bulk of experimental studies on boiling-up dynamics and heat transfer with various conditions of the heating, and development and testing of the appropriate theoretical models.

Heat transfer at evaporation of the falling liquid film is studied in detail [1,2]. But there are no dependences now, which can reliably describe experimental data on heat transfer at boiling and estimate the critical heat fluxes in a wide range of operation parameters [3]. This relates to boiling of both saturated liquid and liquid supplied to the heat releasing surface at the temperature below the temperature of saturation (subcooled liquid).

The results of the series of boiling heat-transfer experiments on saturated water films flowing on an inner tube of a vertically arranged annulus at atmospheric pressure are presented in [4]. Measurements of droplet entrainment by bubble bursting were performed in [5] with boiling films of water and fluorocarbons R-113, R-11 flowing downwards over the outside surface of a uniformly heated vertical tube. According to analysis of data presented in [5], the droplet entrainment rate depends on vaporization rate and, hence, it can effect significantly on the heat transfer intensity. Nevertheless, when processing a bulk of experimental data on boiling of saturated liquid in falling films and estimating the effect of droplet entrainment rate on heat transfer, Gogonin [3] made a conclusion that droplet entrainment at bubbles breakdown intensifies heat transfer insignificantly. It is also shown in this work

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.033
0017-9310/

Nomenclature

c	specific heat at constant pressure, J/(kg K)
f	frequency, Hz
h	linearized heat transfer coefficient, W/(m^2 K)
l	length, m
q	heat flux density, W/m^2
q_{eq}	equilibrium heat flux density, W/m^2
R	radius, mm
$Re = 4\Gamma/\nu$	Reynolds number
T	temperature, °C
T_0	inlet liquid temperature, °C
$\Delta T_{sub} = T_{sat} - T_0$	differences between saturation temperature and inlet liquid temperature, °C
$\Delta T = T_h - T_{sat}$	temperature drop, °C
t	time, ms
U	velocity, m/s
x, y	coordinates in the transverse and longitudinal directions of the film flow, mm

Greek symbols

δ	film thickness, mm
Γ	liquid flow rate per unit length, m^2/s
λ	thermal conductivity, W/(m K)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
$\theta = (T_{bound} - T_{NB})/(T_{d.p} - T_{NB})$	dimensionless value

Subscripts

bound	boundary
d.p	dry patch
g.c	growth and condensation
h	heated wall
NB	nucleate boiling
sat	saturation
sub	subcooling
sub.eff	efficient subcooling
w	waiting

that heat transfer at boiling at high heat fluxes in relatively thick liquid films does not depend on liquid flow rate and approaches the values obtained at pool boiling. This fact is proved by comparison of experimental data obtained at boiling of freons, water and liquid nitrogen with calculations by the model presented in [6].

It is known that the regions of efficient heat transfer at evaporation and boiling are limited in the heat flux by crisis development. When the critical heat flux is achieved, liquid is separated completely or partially from the heat releasing surface, what is accompanied by a drastic decrease in heat transfer intensity and corresponding increase the surface temperature. Development of crisis phenomena depends considerably on several factors. One of the main factors is condition of the heating, which mainly determines development of heat transfer before crisis and maximal densities of the heat flux. Regimes with heat flux pulsations are the common operation feature of several heat exchangers and systems for thermal stabilization. Heat generation can change with time in accordance with different laws, determined by the character of system functioning.

The problems of development of heat transfer crisis at transient heating in pool boiling are studied comprehensively. Two main approaches for the description of heat transfer crises at transient heating can be distinguished via the analysis of the modern state of arts: thermodynamic and thermal ones. It was shown in [7,8] that at stepwise heat generation the value of the critical heat flux, corresponding to transition of nucleate boiling into film boiling, decreases (depending on the studied liquid and reduced pressure) relative to its steady-state value. In accordance with the heat model [7], the crisis occurs due to merging of bubbles, growing on the heater surface, with following formation of a vapor layer. Results of experiments on crisis phenomena development for different laws of heat generation and model description of nonstationary heat transfer crisis with consideration of two stages of process development (the stage of nonstationary thermal conductivity up to liquid boiling-up and the stage of vapor bubble growth before the transition to the film boiling) are presented in [9]. According to the thermodynamic model [10], the upper limit temperature of the heater surface at nucleate boiling is the limit superheating of liquid. Nonstationary aspects of heat transfer and development of crisis phenomena as well as the results on visualization of transitional processes under the conditions of stepwise heat generation on a wire heater at pool boiling are shown in [11,12]. It is shown there that the heating rate effects significantly the boiling-up temperature and dynamics of transitional process.

Simultaneously, examination of the problems on crisis development in the falling films in the modern handbooks on heat transfer is usually limited by the conditions of steady-state heating. In the work [13] there are measurement results for coefficients of boiling heat transfer and critical heat flux (CHF) at boiling in the films of inert fluorocarbon (FC-72) flowing over the vertical plain wall. Experimental data fairly correlated with predictions of a CHF model based on the Helmholtz instability and subfilm dryout. Experimental investigations related to heat transfer and crisis phenomena at boiling in liquid nitrogen films flowing downwards over vertical plane plates at steady-state heat generation were carried out in [14,15]. According to experiments for investigation the crisis phenomena at boiling in falling nitrogen film [15], the values of critical heat fluxes in dependence on Reynolds number and heater length can be lower than the values predicted by CHF model [13]. The authors associate this with the fact that heat transfer crisis under these conditions is implemented by upstream propagation of the drying front, when the threshold of thermal stability of the local dry spots is achieved.

Regularities in the development of heat transfer and crisis phenomena in the falling films of saturated liquid (liquid nitrogen) at transient heating were studied in [16,17]. In those investigations characteristics of nonstationary heat transfer, data on time of boiling incipience, formation of metastable regular structures and their repulsion from the heater surface at the crisis of complete drying were obtained. It is shown that different scenarios of film flow decay occur at variation of heat flux density at liquid boiling-up. At high heating rate the decay of falling liquid film is determined by propagation regime of the self-sustained evaporation fronts with a complex shape of intermediate structures. At the same time, the effect of liquid subcooling on the dynamics of transitional process and nonstationary heat transfer at transient heating in the falling liquid films is poorly studied yet.

Recently the experimental methods with a high temporal and spatial resolution for heat transfer investigation and liquid flow visualization are being developed actively. It is necessary to note the recent papers, where the authors have used the