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Boiling Heat Transfer on Grooved Capillary Surfaces

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Abstract: - The results of experimental investigation are presented of boiling heat transfer on grooved capillary surfaces. The peculiarities are considered connected with description of the process by regularities of pure evaporation or pool boiling. Correspondence is revealed of the process to general developed boiling heat transfer law. Approximate approach is developed to evaluation of heat transfer coefficient built upon parameters of incipient boiling at given combination liquid - capillary surface. Semi-empirical equation is offered describing with adequate accuracy existing experimental data on boiling of different liquids on grooved capillary surfaces of different materials and geometrics.

Key-Words: - boiling, grooved capillary surface, incipient boiling, developed boiling, heat transfer coefficient.

1 Introduction

During last decades two efficient drivers, key role in rapidly progressing new heat pipe technology, on the one hand, and possibility of utilization for essential enhancement of the basic heat transfer processes, on the other, have attached significant importance to research of evaporation and condensation on capillary surfaces. Among them particular attention has been given to grooved capillary surfaces (GCS) adopted in different technologies [1-9]. In 1997 the new edition of the Russian high school textbook [10] has pioneered in introduction of the separate chapter devoted to heat transfer during phase conversion on grooved capillary surface. In this manner the fact has gained weighty proof that thanks to long-standing international efforts the new division of heat transfer theory has been created.

Basic regime of heat transfer on GCS is evaporation from outer surface of liquid meniscus inside groove without boiling (bubbling inside liquid itself). Besides, as bubbling creates significant additional resistance to liquid motion inside grooves, initiation of boiling is undesirable in majority of applications. However, in some cases exclusion of such a regime of heat transfer turns out to be impossible, especially, at high heat fluxes. In addition, some applications also are feasible using peculiar properties of boiling on GCS. This specific regime presents certain interest also in respect to revelation of some unknown features of boiling heat transfer.

2 Problem Formulation

Peculiarities of boiling on CGS may be reflected in the best way against the background of the regime of pure evaporation at the same surface.

Basic physical model of evaporation and condensation on GCS (Fig. 1) proceeds form certain initial assumptions [1, 10]. Among them are many times higher level of thermal conductivity of the wall in comparison with the liquid, the isothermal bottom cross-section of the grooves, simultaneously determined as a base surface for heat transfer calculation, negligibility of interfacial thermal resistance (the meniscus surface temperature is equated to vapor saturation temperature at distance from the meniscus). An important assumption also is made about fixed marginal position of the liquid meniscus between the extending sharp edges of the wall ribs with constant curvature prearranged by the wetting angle.

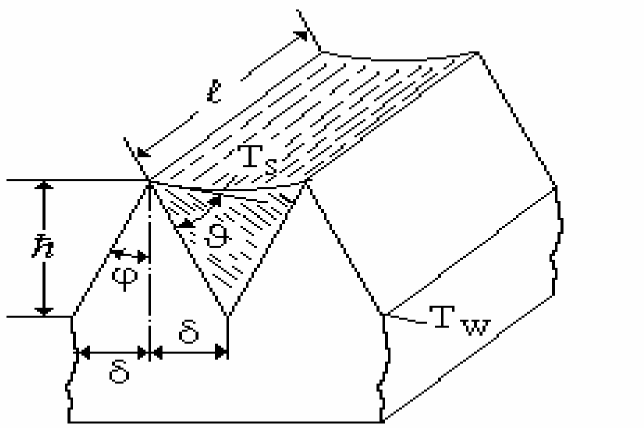

Fig. 1. Evaporation on triangular groove

Based at the condition $\lambda_1/\lambda_2>>1$, another key assumption also is made on principal role in heat transfer of the contact zone of liquid meniscus and surface micro-rib. This assumption allows to considering main way of heat transfer as thermal conductivity through the micro-rib to the zone of the liquid micro-layer with further thermal conductivity through the micro-layer from the side of the micro-rib transversely to a line tangent to the meniscus on its boundary with the micro-rib (considering the role of convection in the liquid phase as negligible). Corresponding equation for average HTC calculated for aforementioned base surface (bottom cross-section of the grooves) has the following form:

$$\alpha = \frac{1}{h}\sqrt{\frac{\lambda_1 \lambda_2}{\sin\theta \cdot tg\,\varphi}} = \sqrt{\frac{\lambda_1 \lambda_2}{\delta h \sin\theta}} \qquad (1)$$

Here α is HTC; λ_1, λ_2 are thermal conductivities of the wall and the liquid, respectively; h, δ, θ, φ - geometrics according Fig. 1.

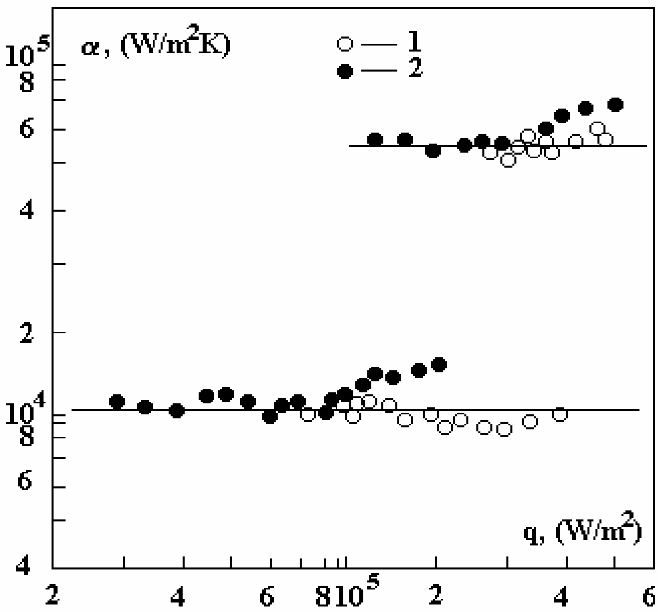

Fig. 2. Comparison of equation (1) (horizontal lines) with experimental data on steam condensation and distilled water evaporation on CGS with triangular grooves (h = 0.5 mm; 2φ = 55^0; q is heat flux) made of stainless steel (lower data) and cooper (upper data): 1 – condensation; 2 – evaporation.

Comparison of equation (1) with experimental data on evaporation and condensation [4] is presented in Fig. 2.

As it follows from comparison, equation (1) adequately describes both of processes except evaporation at high heat fluxes. The main conclusion of analysis is supported on significant dependence of HTC from capability of heating surface to concentrate heat flux in area with intensive heat transfer. This is why HTC is 5 times higher on CGS made of cooper in comparison with CGS made of stainless steel. The conclusion also is supported on independence of HTC from heat flux that follows from decisive role of heat conductivity through the system micro-rib - thin liquid meniscus.

As regards to excursion of experimental data on evaporation from theoretical solution, it coincides with beginning of initiation of bubble nucleation and growth inside grooves with further intensive shooting of micro-droplets from grooves. Besides, initiation of nucleation starts at different heat fluxes depending from previous level of HTC. Simultaneously heat transfer curve takes typical for pool boiling shape.

At the same time, as vapor bubble nucleation and growth inside grooves puts into operation intensive, additional to thermal conductivity heat removal mechanisms, the process evidently turns outside of relevance range of equation (1).

Some complexities arise also with an attempt to describe the process through regularities of pool boiling. Partly it is connected with difficulties with measuring and determination of average superheating of this specific type of micro-finned heating surface. At the same time vapor bubble growth inside restricted space marks this process as specific among other boiling processes.

On the other hand, conservatism of developed boiling heat transfer law regarding to drastic changes in the pattern of mutual motion of the liquid and vapor phases occurring in different modes of this process [11-13] leaves room for adequate interpretation by this law of boiling heat transfer on CGS.

Reasoning from all above experimental study of the process with further analysis in the framework of pure evaporation and developed boiling heat transfer models may be considered as the most suitable line of attack.

3 Experimental Study of the Process

3.1 Experimental Setup

The schematic of experimental setup serving for investigation of boiling heat transfer on CGS is presented in Fig. 3.

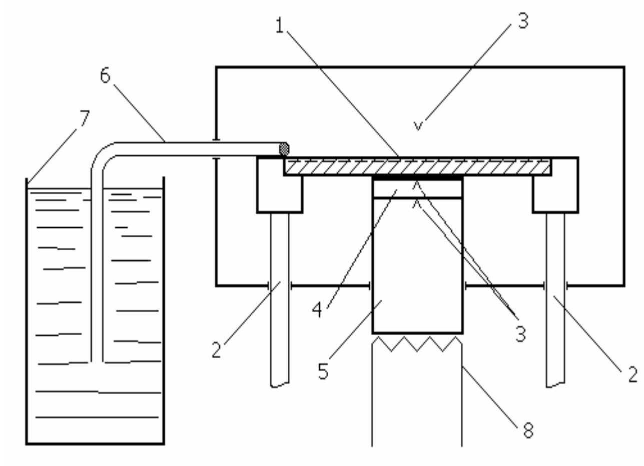

Fig. 3. The schematic of experimental setup of boiling heat transfer on CGS: 1 - experimental CGS; 2 - current leads; 3 - thermocouples; 4 - heat insulation; 5 - cupper rod; 6 - capillary feeder; 7 - vessel; 8 - compensation electric heater.

Heating of experimental CGS is provided through immediate transmission of electric current. Boling liquid is sucked in by CGS itself through capillary feeder. Heating wall temperature is measured at underside of CGS by thermocouple. Thermal compensation of the underside is provided using cupper rod, heat insulation, compensation electric heater and thermocouples allowing to avoiding distortions of heating wall temperature measurements.

3.2 Experimental Results

Two geometrics and three materials of CGS (cooper, carbon steel and stainless steel) with strongly differing thermal conductivity are used. Heat transfer through boiling on experimental CGS (ECGS) of three liquids (ethyl alcohol, water, nitrogen) is investigated. All experiments are performed at atmospheric pressure.

According to the model of pure evaporation (Fig. 1) HTC in all cases is determined for base surface (groove bottom cross-section). Temperature of base surface is determined through converting of underside thermocouple indication. In exceptional cases (boiling of water and ethyl alcohol on ECGS made from cooper) additionally HTC is determined also for micro-finned surface (in the case of ECGS of very high thermal conductivity measured heating wall temperature in a good approximation may be equated to average temperature of micro-finned surface). The results of experimental investigation are presented in Fig. 4 in coordinates HTC - heat flux.

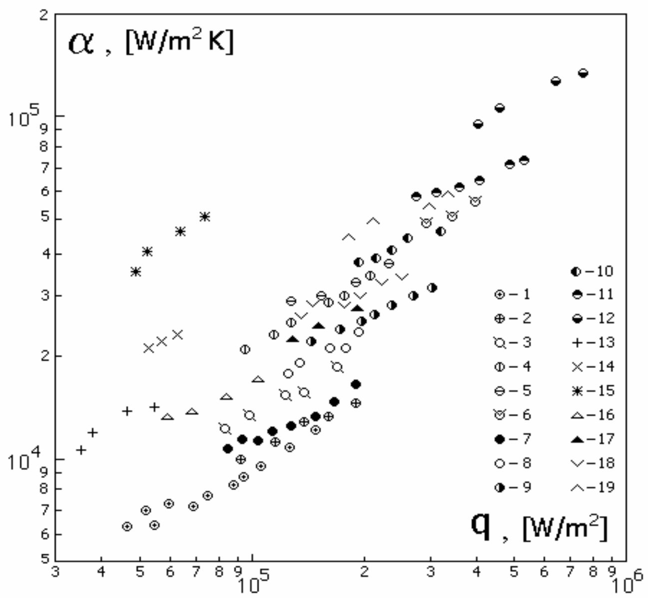

Fig. 4. The results of experimental investigation of boiling heat transfer on ECGS: 1 - ethyl alcohol - ECGS-1; 2 - ethyl alcohol - ECGS-2; 3 - ethyl alcohol - ECGS-3; 4 - ethyl alcohol - ECGS-4; 5 - ethyl alcohol - ECGS-5; 6 - ethyl alcohol - ECGS-6; 7 - water - ECGS-1; 7 - water - ECGS-1; 8- water - ECGS-2; 9 - water - ECGS-3; 10 - water - ECGS-4; 11 - water - ECGS-5; 12 - water - ECGS-6; 13 - nitrogen - ECGS-1; 14 - nitrogen - ECGS-2; 15 - nitrogen - ECGS-4; 16 - ethyl alcohol - ECGS-5 (for micro-fined surface); 17 - ethyl alcohol - ECGS-6 (for micro-fined surface); 18 - water - ECGS-5 (for micro-fined surface); 19 - water - ECGS-6 (for micro-fined surface); ECGS-1 - stainless steel, 2δ=0.5 mm; ECGS-2 - stainless steel, 2δ=0.3 mm; ECGS-3 - carbon steel, 2δ=0.5 mm; ECGS-4 - carbon steel, 2δ=0.3 mm; ECGS-5 - cooper, 2δ=0.5 mm; ECGS-6 - cooper, 2δ=0.3 mm; $2\varphi=55^0$ for all ECGS.

As it follows from Fig. 4 stratification of experimental data on HTC is quite significant depending from type of liquid, ECGS material and geometrics. Understandably, the same data gives two different groups of experimental points on boiling on cooper surface depending from treatment for base or micro-finned surfaces (the last is 2.22 times greater). The general feature of all data is expressed by similar slope of heat transfer curves characteristic for developed boiling heat transfer.

4 Analysis of Experimental Data

Correlation of the experimental data on boiling of water and ethyl alcohol on ECGS made from cooper is presented in Fig. 5 in the framework of non-dimensional correlation for developed boiling heat transfer [11-13]:

$$Nu = 1.22\cdot 10^{-2} K^{0.7}\, \mathrm{Re}_*^{\;0.25} \qquad (2)$$

Dimensionless numbers *Nu, K* and *Re*$_*$ are:

$$Nu = \frac{\alpha\rho_0}{\lambda_2};$$

$$K = \frac{q\,\rho_0^{\;2}\, r\,\rho_g}{\sigma\lambda_2 T_s};$$

$$Re_* = \sqrt{(p_s(\upsilon_g - \upsilon))}\,\frac{\sigma T_s \rho C_p}{\nu(\rho_g r)^2}$$

Here α is HTC (calculated for micro-finned surface); ρ_0 is average effective radius of nucleation sites; ρ and ρ_g are densities of liquid and vapor phases, respectively; v, v_g are specific volumes of liquid and vapor phases, respectively; r, σ and ν are specific heat of evaporation, surface tension and cinematic viscosity of liquid, respectively; P_s and T_s are saturation pressure and saturation temperature, respectively.

As it is known [11-13] universal correlation (2) describes experimental data on boiling of all classes of liquids (water, ethyl alcohol, benzene, biphenyl, refrigerant 12, refrigerant-22, refrigerant-142, helium, hydrogen, neon, nitrogen, carbon monoxide, nitric oxide, ethane, ethylene, sodium, cesium, potassium, mercury and others) on commercial surfaces (mainly rolled stainless steel tubes). Besides, all surfaces are attributed by single constant average value of ρ_0 (5 μm). The correlation (2) adequately describes also exclusive experimental data on HTC during boiling of water, sodium, refrigerant-12 and refrigerant-22 on boiling surfaces with known values of ρ_0 [14-16].

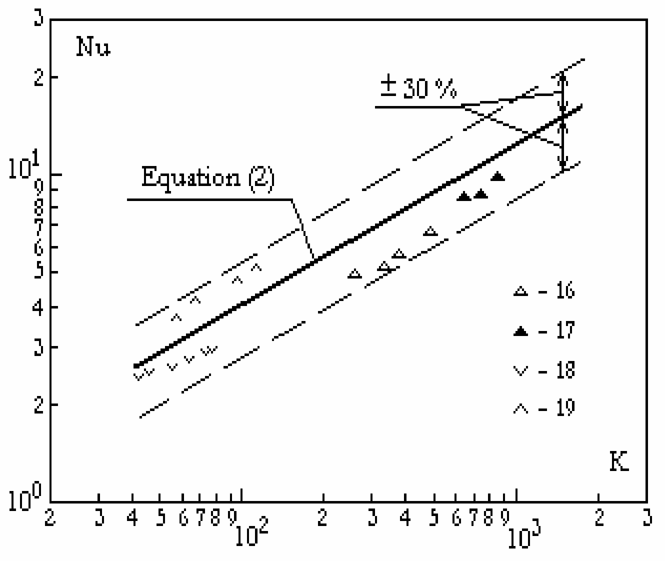

Fig. 5. Correlation of experimental data on boiling HTC (determined for micro-fined surface) of water and ethyl alcohol on ECGS made from cooper in the framework of equation (2). Legend according Fig. 4

As it follows from Fig. 5 experimental data on boiling on ECGS made from cooper quite adequately are correlated in the framework of equation (2). Here priority importance is attached to amalgamation (to an acceptable approximation) in coordinates (2) of experimental data on boiling of two different liquids (water and ethyl alcohol) on two ECGS made from cooper with different geometrics by common curve through using of single value of ρ_0.

The results of correlation may be considered as once more impressive manifestation of conservatism of developed boiling heat transfer law covering processes with drastically differing patterns of mutual motion of the liquid and vapor phases.

As regards to concrete value of average effective radius, here it is selected on the basis of the best fit of experimental data to correlation (2). Determined by this way value of ρ_0 is equal to 60 μm, to say, it is 12 times greater than on commercial surfaces. As used in experiments ECGS are manufactured through screw thread cutting, significant overdimension by ρ_0 of such a surface of the same parameter of smooth commercial surfaces (for instance, rolled tubes) is quite understandable. At the same time such a sizable overdimension may be interpreted only by retention of part of vapor of bursting bubble in groove bottom part and by playing by retained vapor of the role of nuclei through next bubble growth. As groove bottom parts of both of ECGS are identical (the same φ), sizes of retained vapor volumes also may be roughly the same. At the same time the issue remains open for immediate determination of concrete values of this parameter.

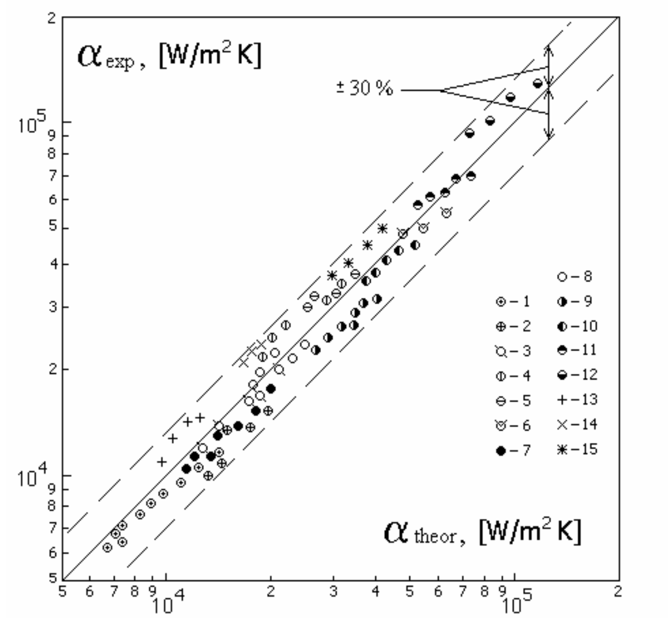

Fig. 6. Correlation of experimental data on boiling HTC (determined for base surface) of water and ethyl alcohol on ECGS in the framework of equation (3). Legend according Fig. 4.

Another approach to evaluation of HTC during boiling on CGS may be based at parameters of incipient boiling at given combination liquid - CGS.

Assuming to a certain approximation that excursion of experimental curve from theoretical solution for pure evaporation (for instance, in Fig. 2) reflects parameters of incipient boiling and further HTC curve corresponds to developed boiling heat transfer curve with typical slope $\alpha \sim q^{0.7}$ established empirically, following semi-empirical equation may be offered for HTC:

$$\alpha = \sqrt{\frac{\lambda_1 \lambda_2}{\delta h \sin \vartheta}} \left(\frac{q}{\Delta T_{in}} \sqrt{\frac{\delta h \sin \vartheta}{\lambda_1 \lambda_2}} \right)^{0.7} \qquad (3)$$

Here ΔT_{in} is base surface superheating over saturation temperature through incipient boiling.

Correlation of all experimental data on HTC determined for base surface in the framework of equation (3) is presented in Fig. 6. Doing so known values are used of

ΔT_{in} during incipient boiling of ethyl alcohol, water and nitrogen [17-18].

As it follows from Fig. 6 semi-empirical equation (4) quite adequately describes all experimental data covering three liquids, three heating wall materials and two ECGS geometrics.

5 Conclusion

Main peculiarities characteristic for boiling heat transfer on CGS are liquid phase supply by capillary head generated by groves itself, bubble nucleation and growth inside grooves and intensive shooting of micro-droplets from grooves by bursting bubbles. According analysis above experimental data this list may be enlarged by retention of part of bursting bubble in groove bottom part and by playing by retained vapor of the role of nuclei through next bubble growth.

In combination with microlayer evaporation specific heat removal mechanism by intensively discharged micro-droplets gains leading role in integral heat transfer. However, in spite of such unique combination of heat transfer mechanisms, boiling heat transfer on CGS maintains general regularities common for different types of developed boiling heat transfer processes. Once more impressively is manifested conservatism of developed boiling heat transfer law regarding to drastic changes in the pattern of mutual motion of the liquid and vapor phases occurring in different modes of boiling [11-13].

The model of developed boiling heat transfer gains further support postulating controlling role of thermodynamic conditions at nucleation sites through establishment of average HTC through multiple triggering of short-run actions of different cooling mechanisms.

Semi-empirical equation is offered based at parameters of incipient boiling adequately describing boiling heat transfer of three liquids on six different ECGS with two geometrics made from three materials with significantly differing heat conductivities.

At the same time investigation of main integral characteristics and separate mechanisms inherent for boiling heat transfer on CGS deserves further detailed experimental and analytical investigation.

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