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Heat transfer at cooling high-temperature bodies in subcooled liquids

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ABSTRACT

In subcooled water film boiling, a particular regime exists featured with very high intensity of heat transfer [3]. The authors' previous experimental studies confirmed that intensive heat transfer regime occurred in cooling of spheres from copper, nickel and stainless steel at water subcoolings from 25 K under atmospheric pressure. However, this regime was not found during cooling the hot spheres in non-aqueous liquids even at very high subcoolings (up to 170 K). The qualitative analysis of the large domain of the experimental data on heat transfer regimes in cooling high temperature bodies and comparison those with the results on steady film boiling in forced flow of subcooled water lead to the conclusion that the specific regime of highly intensive heat transfer in film boiling of subcooled liquids can exist only in an unsteady process. Basing on this idea, an approximate model of an origination of the intensive heat transfer regime in film boiling was derivate. At rather high liquid subcoolings, random contacts of a liquid wave crests with the protrusions of the wall surface roughness can cause transition to the heat transfer regime of great intensity. Liquid inflow into the region of intensive evaporation at the wetted area boundary (the contact line) is controlled by the capillary pressure gradient. Hydromechanical limit of heat flux density corresponding to the extremely high evaporation rate at this area is proportional to $h_{lg}\sigma/\nu$. Sharp surface temperature drop in the randomly wetted zone produces unsteady conductive heat flux from a volume of the cooled body. A characteristic time of this unsteady heat flux seems to be determined with a period of wavy flow at the liquid/vapor interface. We assume an analogy of natural convection in a boundary layer of subcooled liquid near a vapor film with gravitational liquid film flow that has been analyzed in the classical Kapitsa study. The model developed explains an effect of thermal effusivity of a cooled sphere metal and influence of coolant properties on occurrence of intensive regime of heat transfer in film boiling. It was shown that for several coolants (FC-72, LN_2) this regime is practically unattainable. The calculated values of the surface transient superheats satisfactorily agree with the experimental results on incipience of the intensive heat transfer regime in film boiling of different liquids at the sphere surface from different metals under wide range of subcoolings and pressures.

1. Introduction

Film boiling of subcooled water puts a question on heat transfer mechanisms of intensive heat transfer under the conditions, when the cooled body surface highly exceeds the attainable limiting temperature of the liquid (T_{lim}) and direct liquid/solid contact is impossible. This temperature corresponds to practically achievable liquid superheat and is very close to the homogeneous nucleation temperature T_{hom}. In quenching technology, initial temperature of steel parts is often as high as 800–1000 °C that certainly corresponds to film boiling, but typical average heat transfer coefficient (HTC) is estimated as 3–10 kW/(m^2 K); under water jets cooling they inform on HTC near 20 kW/(m^2 K). In some publications, one can meet statements on nucleate boiling in quenching. Even in such earnest monograph as [1], one reads that rewetting of a cooled surface in water occurs at its temperature 500 or 800 °C, and that "the water-surface contacts may occur at temperatures that are far higher than that of homogeneous water nucleate-boiling". For researchers learned the works by academician Skripov and his successors there is no question on impossibility of existence of any substance in a liquid phase at temperature higher T_{lim}. According to [2] under such conditions liquid–vapor phase transition occurs practically instantly, the characteristic time is of an order of magnitude of ns.

Aziz et al. [3] have first described a new boiling regime named as micro-bubble boiling; the paper [4] presents development of this research. The experiments of [3,4] have been conducted with nickel-coated copper spheres of 10–32 mm in diameter cooled in subcooled water at atmospheric pressure. Initial uniform tempera-

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Nomenclature

c	heat capacity
c_w	wave phase velocity
D	diameter
Gr	Grashof number
g	gravitational acceleration
h_{lg}	latent heat of evaporation
k	wave number
l_R	roughness protrusion length
Pr	Prandtl number
q_l	linear heat flux density
q_{loc}	local heat flux due to evaporation
q_v	unsteady heat conduction heat flux
T_{lim}	attainable limiting temperature of a liquid
T_w^{tr}	transient wall temperature
ΔT_0	wall superheat
ΔT_{sub}	liquid subcooling
t_0	characteristic time
u_0	characteristic velocity of natural convection

Greek symbols

β	coefficient of thermal expansion
Γ	volumetric flow per film width unit
δ	film thickness
δ_{nc}	thickness of natural convection boundary layer
λ	heat conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
ω	circular frequency

Subscripts

cr	critical
g	gas
l	liquid
m	intensive evaporation
s	saturated
tr	transition
w	wall

ture of the spheres (usually 500–700 °C) was essentially higher than T_{lim}. Under subcoolings higher than 22 K heat transfer intensity was an order of magnitude higher than in ordinary film boiling of saturated or weakly subcooled water. The term "micro-bubble boiling" was introduced because at high water subcoolings tiny vapor bubbles were visible in vicinity of a smooth vapor film around the sphere. This is noteworthy that the sphere surface temperature T_w about 700 °C exceeds not only the attainable limiting temperature of water, but also its critical temperature (by 300 K). Heat flux densities at the sphere surface calculated in [4] were as high as 5–6 MW/m^2 at $T_w > 500$ °C and $\Delta T_{sub} = 40$ K, i.e. 20–50 times higher than in film boiling of the saturated liquid. Obviously, it is impossible to consider the micro-bubble boiling as an ordinary film boiling regime. A nature of highly intensive heat transfer without the direct liquid/solid contacts presents the most intricate problem of subcooled film boiling. As for nucleate boiling, its generic feature is high intensity evaporation near the interline, i.e. the three phases boundary; a fraction of wetted surface in this boiling regime remains about 90% even in the boiling crisis region. Besides, at superheats of several hundred Kelvin fantastically high heat fluxes would be achieved in the nucleate boiling regime. In the discussed papers [3,4], there is only a qualitative statement on instability of a vapor film at the sphere surface that leads to the micro-bubble boiling.

Thirty years after publication of the paper [3] brought quite a lot of new experimental results in the field discussed; however, the works [3,4] are cited only in our papers [5–10]. Probably, the significance of these results has not perfectly recognized yet. In [6,10] we have briefly analyzed the recent experimental results on film boiling of subcooled water and discussed some contradictions in their interpretation. Nobody considers the intensive heat transfer regime as a particular one in film boiling.

2. Qualitative analysis of intensive heat transfer regime in film boiling

Our scientific team from the very beginning defines revealing the mechanisms of intensive heat transfer as an objective of the studies of subcooled film boiling. The metallic spheres of 30–50 mm in diameter are used as cooled test specimens; in distinction to all the known researches we measure the sphere temperature in several points: one is the center of the sphere and three or four are the different points of its surface. The papers [5,6] give the detailed description of the experimental methods. First, our experiments have confirmed an existence of the particular film boiling regime in subcooled water, which is featured with extremely high intensity of heat transfer. This regime occurs during cooling of the copper, nickel, and stainless steel spheres from initial temperature 700–800 °C, if water subcooling exceeds 25 K that coincide with the results of [3,4] for the copper spheres. Natural intention to investigate heat transfer in cooling the high-temperature spheres in non-aqueous liquids led to unexpected result: intensive heat transfer regime was not observed in ethanol, isopropanol, and perfluorohexane even at very high subcoolings up to 160 K [7–9]. This result, obtained in cooling at atmospheric pressure, forced us to refuse our initial idea on incipience of the intensive heat transfer regime in subcooled film boiling due to cavitation collapse of tiny vapor bubbles near the vapor/liquid interface. Regularities of the cavitation bubble collapse do not essentially differ in water and in the alcohols studied, so this idea cannot explain the observed strong difference in cooling regimes in water and in the non-aqueous liquids. At the same time, essential increase of the alcohols viscosity (especially of isopropanol) at low temperature (down to minus 78 °C) gives a basis for searching such explanation in a liquid viscosity variation. The experiments on cooling the spheres in the liquids at the fixed temperature, but at different pressures allow checking this assumption. The experimental runs with the copper and nickel spheres at pressures 0.1 – 1.0 MPa [8,9] have not revealed the intensive heat transfer regime in film boiling of ethanol, isopropanol, and perfluorohexane at high subcoolings up to 170 K. As for the tiny bubbles observed in [3,4] during micro-bubble boiling, this is very probable that they were the air-filled ones, since the steam bubbles cannot exist in highly subcooled water. Apparently, the phenomenon that gave the name to the process of micro-bubble boiling is only some concomitant effect not determining the actual mechanisms of heat transfer [10].

Nevertheless, an analysis of the large domain of the experimental data obtained leads to an important qualitative inference: the intensive heat transfer regime in film boiling of subcooled water