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Film boiling of subcooled liquids. Part I: Leidenfrost phenomenon and experimental results for subcooled water

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Film boiling of subcooled liquids is important, at least, for two applications: for systems of post-accident cooling in nuclear power plants and for quenching technology. An analysis of the previous results shows that at high water subcooling film boiling presents a particular mode of boiling heat transfer, dissimilar greatly to saturated film boiling mainly by high intensity of heat transfer; this statement appears to be true, even though the researchers themselves do not recognize it. As at the temperature much higher than that of homogeneous nucleation, liquid–vapor phase transition occurs practically instantly, an actual temperature at the liquid/solid interface cannot be higher than the attainable limiting temperature of liquid. The possible mechanisms of high intensity heat transfer between the surface and subcooled liquid at the absence of liquid/solid contact and the conditions of this regime incipience require experimental and theoretical investigations. The present paper describes the method and the results of experimental study of heat transfer during cooling the spherical patterns from nickel, stainless steel, and copper with initial temperature above 700 °C in water at subcoolings up to 70 K. In distinction to all the previous studies temperature was measured in several points of the spheres that gives new information on the cooling process. It is revealed that at high cooling rates the temperature field can lose its spherical symmetry, high temperature gradients are observed not only in the radial direction, but also along the surface. At high subcoolings the heat transfer regime of high intensity arises at the surface temperature 600–700 °C that excludes a possibility of liquid/solid direct contact; heat flux density can be as high as 5–7 MW/m^2.

1. Introduction

Almost 30 years ago the authors of [1] first presented the experimental results revealed a new boiling regime named as micro-bubble boiling. It was observed in film boiling of water at atmospheric pressure under subcoolings higher than 22 K. Nickel-coated copper spheres 10 and 20 mm in diameter were driven through water at velocities up to 1.8 m/s. The maximum initial sphere temperature T_0 was 513 °C; the water temperatures T_L were in the range 50–100 °C. Heat transfer intensity in micro-bubble boiling regime was an order of magnitude higher than in ordinary film boiling of a saturated or weakly subcooled liquid. The term "micro-bubble boiling" was introduced because at high water subcoolings tiny vapor bubbles were observed in vicinity of a smooth vapor film around the sphere. Later in [2] these investigations were developed: several copper balls of 16–32 mm in diameter with thin nickel coating were used, their drag coefficients were measured, the initial sphere temperature in some runs was about 700 °C, its velocity was near the terminal velocity of a free falling ball (1.8–2.2 m/s). Instability of vapor film and micro-bubble boiling incipience occurred in these experiments at water subcoolings ΔT_{sub} = 20–40 K. In the both papers [1,2] onset of micro-bubble boiling was accompanied by the deviation of the spheres trajectory from their vertical path during free falling; this means that some lateral forces arise when the discussed boiling regime appears. Sometimes this boiling regime arose at zero velocity, at the sphere surface when it was at the tank bottom.

As the micro-bubble boiling occurs at the solid surface temperature much higher than the attainable limiting temperature of water (T_{lim}), a direct liquid/solid contact is impossible and a question arises on mechanisms of intense heat transfer in this regime. In [2] the micro-bubble boiling in water with subcooling 38 K on the sphere of 32 mm in diameter was observed at its surface temperature T_w = 670 °C, which exceeded not only the attainable limiting temperature of water but even its critical temperature (by almost 300 K). At temperature higher than the attainable limiting one, which practically coincides with the temperature of

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Nomenclature

Bi	Biot number
a	thermal diffusivity, m^2/s
c	specific heat, J/(kg K)
D	diameter of a sphere, m
Fo	Fourier number
h_{LG}	latent heat of evaporation, J/kg
p	pressure, Pa
q	heat flux density, W/m^2
r	radial co-ordinate, m
R	radius of a sphere, m
T	temperature, K
t	time, s
u	velocity, m/s
We	Weber number

Greek symbols

α	heat transfer coefficient, $W/(m^2\,K)$
θ	polar angle in spherical co-ordinates
λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

0	initial conditions
cr	critical
G	gas (vapor)
hom	homogeneous nucleation
L	liquid
Lim	attainable limiting temperature of liquid
min	minimal temperature of film boiling
s	saturation
sub	subcooling
w	wall

homogeneous nucleation, any substance can exist merely as a vapor. In the discussed papers there is only a qualitative statement on instability of a vapor film at the sphere surface that leads to the micro-bubble boiling. In the later publication [3] the results of optical studies of film boiling of water are used also for qualitative description of the processes investigated. Nevertheless, these results seem to be of crucial importance both from theoretical and applied views. Really, according to [2] heat flux densities at the sphere surface 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. Consequently, there is fundamental difference between the micro-bubble boiling and an ordinary film boiling. Due to impossibility of direct liquid contact with a solid surface nucleate boiling is also excluded; besides, at superheats of several hundred Kelvin fantastically high heat fluxes would be achieved in a nucleate boiling regime. Thus, there is an obvious problem to understand the basic mechanisms of micro-bubble boiling and to determine the conditions of its incipience.

Unfortunately, the subsequent publications on the problem [4–6] do not concern the above micro-bubble boiling regime during cooling the high temperature bodies in subcooled water and do not mention the papers [1–3]. The authors of [4] believe that at $\Delta T_{sub} \geqslant 40$ K film boiling does not exist, since very fast cooling process was observed at such conditions; they considered the liquid subcooling effect on film boiling heat transfer at cylindrical patterns with a spherical head only for low subcooling values. In the experiments [5] aluminum, copper and steel spheres of 32 and 16 mm in diameter are used; water subcoolings did not exceed 40 K, majority of the experimental results relating to $\Delta T_{sub} \leqslant 20$ K. The paper presents a theoretical analysis of vapor film instability on the cylindrical and spherical surfaces and an equation for minimum heat flux in film boiling, but does not discuss heat transfer mechanisms in film boiling at rather high water subcoolings.

The recent paper [6] is the closest one to the studies [1,2] due its directivity on the nuclear power plant (NPP) safety. However, if the latter consider the mechanisms of vapor explosion triggering, the former orients on cooling the fuel rods in a scenario of LOCA in NPP. The investigation [6] explored quenching of stainless steel and zircaloy spheres of 17.5 mm in diameter in de-ionized and sea water. Initial temperature of the metallic spheres was 1000 °C; the coolant temperature was 33 °C. The sphere temperature was measured during cooling by means of a thermocouple imbedded in the sphere at the distance of 1.5 mm from its surface. The authors assumed that the measured temperature was approximately equal to the surface temperature; this is, probably, justifiable at rather low cooling rates, but at high heat flux densities at the surface remarkable difference between these two temperatures is inevitable. The experimental quench curves (the cooling thermograms) have revealed an observable distinction of the cooling processes in distilled water and in sea water. In pure water, the entire quenching process takes about 40 s, the film boiling lasts 16 s for the stainless steel sphere and 12 s for the zircaloy sphere. At the measured sphere temperature in the range of 550–620 °C fast cooling begins, the authors believe that nucleate boiling occurs. In sea water, according to the authors view, "film boiling seems to be absent and nucleate boiling occurs after brief transient boiling". This conclusion is based mainly on the results of video filming, but the snap shots presented in the paper hardly allowed to make unambiguous estimations. The authors fairly pointed out that in their experiments the sphere temperature was much higher than that of homogeneous nucleation. According to the classic theory of homogeneous nucleation, which was many times confirmed in experiments [7], under such conditions liquid–vapor phase transition occurs practically instantly, the characteristic time is of an order of magnitude of ns, that is several orders of magnitude less than a characteristic period in video filming. Thus, there are serious doubts in relation of the interpretation of the experimental results in [6].

Besides the mentioned thermophysical studies of film boiling in subcooled water directed mainly to nuclear engineering safety, there exists the other branch of similar investigations, which are connected with the quenching technology. Probably, the most full and condensed information on these studies is presented in a collective monograph [8], near a third of which volume is devoted to the heat transfer problems. The specialists in the quenching technology objectively are not interested in the heat transfer mechanisms, so that in their studies are not commonly cited the thermophysical investigations, in particular [1–4,7]. However, some of their experimental results are lain in the course of the discussed problem. Strictly speaking, the specialists in heat transfer, in particular, the authors of [1–6], also do not turn to the results on heat transfer at the quenching.

According to [8] after merging a hot sphere or a cylinder at initial temperature near 900 °C in coolant the vapor film is instantly formed on the surface of a pattern. This film is quite stable in saturated water and can be instable if the liquid is subcooled. A general tendency is revealed: the higher subcooling, the higher a