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Film boiling of subcooled liquids. Part II: Steady regimes of subcooled liquids film boiling

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ABSTRACT

As it was shown in the first part of the present study [1], during film boiling of highly subcooled water the particular regime of boiling occurred revealed first in the works [2,3], where the term "micro-bubble boiling" was introduced for this regime. In order to understand general regularities of the cooling process in film boiling it is reasonable to conduct investigations with different subcooled liquids. The present paper presents new systematic data on cooling the metal spheres in subcooled isopropanol and in perfluorohexane (FC-72) at very high subcoolings, up to 160 K. About thirty experimental runs with isopropanol and eight runs with perfluorohexane clearly showed that at any subcooling value the micro-bubble boiling regime with high intensity of heat transfer was not observed. Stable film boiling occurred to be the dominant cooling regime; heat transfer intensity in this regime was approximately two-three times greater than in saturated film boiling at the sphere surface. An approximate model of heat transfer in stable film boiling of subcooled liquids has been derived; it accounted for an influence of liquid movement at the vapor/liquid interface due to natural convection effect. The predicting equation obtained, with two empirical numerical factors, manifests good agreement with the experimental data of the present study including the new ones on subcooled ethanol pool boiling and with the available results of other researchers. The experiments showed that film boiling of subcooled liquids is sensible to sphere surface characteristics; some surface defects, even visually undetectable can promote more intensive local heat transfer intensity.

1. Introduction

In the first part of the present study [1] we have founded that during film boiling of subcooled water the particular regime of boiling occurred revealed first in the works [2,3]. The authors of [2,3] introduced the term "micro-bubble boiling" for this regime. Actually, there are essential grounds to speak on the particular heat transfer regime. The measured surface temperature of hot spheres in [1–3] was much higher than the attainable limiting temperature of water. A model of [4] on the mechanism of vapor-film collapse at the wall temperature above the thermodynamic limit of liquid superheat based on a hypothesis of weak spots at the surface seems to be quite reasonable. However, it is difficult to understand an origin of such weak spots at the temperatures higher than 600 °C. Even at so high heat fluxes as 5 MW/m^2 a low conductivity metallic (stainless steel) protrusion has to be longer than 1 mm in order its tip temperature becomes close to T_{lim}. It is clear that for copper [2,3] or nickel [1] spheres large temperature gradients on the surface roughness elements are impossible. In experiments of the recent paper [5] instability of vapor film at the sphere surface in cold sea water occurred, when the temperature measured at a distance 1.5 mm from the surface was essentially higher 900 °C. Although according to our estimation [1] at the instability incipience the salts deposition of several micrometers in thickness, probably, arises, the outside deposition temperature has to be much higher than T_{lim}. This means that in the discussed case a probability of local collapse of vapor film is also negligible.

Therefore, mechanisms of momentum and heat transfer at the vapor/liquid interface present now a serious challenge to researchers. In order to reveal general regularities of the cooling process in film boiling it is reasonable to conduct investigations with different subcooled liquids. In the monograph [6] influence of properties of different quenching media (quenchants) on heat transfer intensity and on quality of a quenched metal specimen is analyzed. However, only multicomponent liquids (brine, water/polymer solutions, and vegetable oils) are considered; besides, mainly technologic problems are discussed. At atmospheric pressure a choice of one-component liquids as possible coolants is rather scarce due to limitations on chemical stability. In the paper [7] very interesting and instructive photos are presented that show a stainless

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Nomenclature

A	accessory parameter according to (8), m^2
B	accessory parameter according to (8), m^4
c	specific heat, J/(kg K)
D	diameter, m
G_l	mass flow rate per film width unit, kg/(m s)
g	gravitation acceleration, m/s^2
h_{LG}	latent heat of evaporation, J/kg
$\dot{m}$	vapor mass flux at the interface, kg/(m^2 s)
Pr	Prandtl number
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
x, y	Cartesian coordinates, m

Greek symbols

α	heat transfer coefficient (HTC), W/(m^2 K)
β	coefficient of thermal expansion, K^{-1}
$\Delta T = T_w - T_s$	wall superheat, K
$\Delta T_{sub} = T_s - T_L$	liquid subcooling, K
δ	vapor film thickness, m
θ	polar angle in spherical co-ordinates
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

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

steel sphere cooling in subcooled FC-72 (perfluorohexane). At the sphere temperature T_w = 250 °C the ball with a smooth vapor film around magnetically maintained in the liquid volume is clear visible; after 30 s cooling the sphere temperature decreases lower T_{lim} = 130 °C, and explosive boiling occurs. No quantitative effects on heat transfer are discussed, but it is observed that the presence of the smooth vapor film on the sphere surface at $T_w > T_{lim}$ strongly, by a factor larger than 2, increases a descent velocity of the ball.

In our previous studies [8,9] the experimental results with propanol-2 (isopropanol) are presented. Its normal boiling point is 82.5 °C, critical point T_{cr} = 235.6 °C. Therefore, an initial safe temperature of the sphere 420–430 °C provides a sufficient range of wall superheats corresponding to film boiling. It occurred unexpected that the sphere cooling in isopropanol did not include a mode with high intensity of heat transfer in film boiling even at the high subcoolings. The typical thermograms of cooling of the 45 mm ball at isopropanol temperature −14 °C depicted in [8,9] are quite similar to those obtained in the cooling process in saturated water. A stable regime of film boiling takes longer than 60 s, the intensive cooling begins only at the surface temperature below 215 °C, i.e. in transition boiling.

The present paper presents new systematic data on cooling the metal spheres in subcooled isopropanol and in perfluorohexane at very high subcoolings, up to 160 K (Section 2). An approximate model of heat transfer in stable film boiling of subcooled liquids is developed (Section 3), the comparison of the calculated and the measured values of HTC is given in Section 4.

2. Experimental results

The schematic of the experimental facility and its description is given in the first part of this study [1]. Using the cryostat allows to maintain the temperature in the cooling liquid volume at the predetermined level in the range from 10 °C until (−80 °C). As a test specimen a stainless steel (AISI316) sphere of 38 mm in diameter (Fig. 1) was used. Four thermocouples imbedded in the specimen allow measuring temperature of its center and in three points at the surface (at polar angle θ = 50°, 90°, and 180°). Assuming that

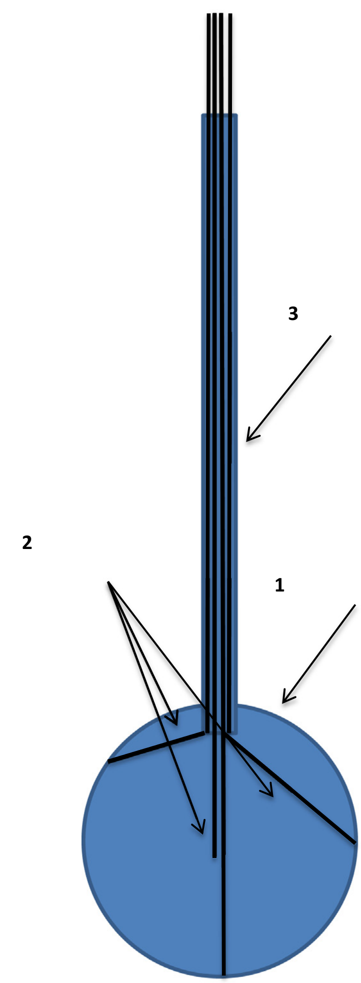

Fig. 1. Schematic of test section: 1 – sphere, 2 – thermocouples, 3 – tube-holder.

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