INFLUENCE OF PRESSURE ON FILM BOILING OF SUBCOOLED LIQUID

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ABSTRACT

Film boiling of subcooled liquid as the most available and use-proven way of quick chilling of hardening pieces, ensuring required microstructure of metal is widely used in quenching technology. A vapour explosion is the other important process, in which this boiling regime is surely observed. Under high subcooling of liquid the cooling process of high temperature bodies is featured with very high intensity and can be considered as a particular heat transfer regime. This was revealed first in 1986 by G. Hewitt and D. Kenning, who used for this regime a term "microbubble boiling" [1]. Mechanisms of very intensive heat removal from the metal surface to subcooled liquid are not understood till now, because the surface temperature in this process is much higher than the temperature of homogeneous nucleation. Some specialists do not accept even an existence of the problem itself.

For revealing regularities and mechanisms governing intense transfer of energy in this process, the present authors conduct systematic investigations of cooling of high temperature balls made of different metals in water with a temperature range from 20 to 100°C [2]. It has been determined that temperature field in the balls of diameter higher than 30 mm in the intense cooling modes loses its spherical symmetry. An approximate procedure for solving the inverse thermal conductivity problem for calculating heat flux density on the ball surface is developed. During film boiling, when the ball surface temperature is well above the critical level for water, so that the liquid cannot come in direct contact with the wall, the calculated heat fluxes reach 3–7 MW/m^2.

The main aim of this study was analysis of excess pressure effect on heat transfer during film boiling of different subcooled liquids. The experiments have been performed in the pressure range 0.1–1.0MPa at the coolant temperature -15 - +90°C for all the liquids used. The primary results of the research are the experimental thermograms of cooling the spheres under the elevated pressures.

INTRODUCTION

Film boiling of saturated liquids is a well-known physical process. In 1950, Bromley has developed an equation for heat transfer in this boiling regime, using an approach quite similar to the Nusselt analysis of vapor condensation at an isothermal plate. Typical values of HTC in film boiling do not exceed 500W/m^{2}K, because thermal conduction of vapor is a dominant mechanism of heat transfer from the heated surface to the vapor-liquid interface. The influence of pressure was investigated in [3]. Authors performed their experiments in the pressure range 1 – 35 atm for different liquids. It was shown that even at rather high pressures, intensity of heat transfer increases slightly with vapor density increase, and HTC does not exceed 1000W/m^{2}K. Later A. Sakurai et al. [4] presented a rigorous numerical solution of heat transfer in pool film boiling at a horizontal cylinder surface in subcooled liquids. A set of conservation equations is formulated in an approximation of boundary layer. The results of the numerical study agree well with the experimental data of the authors at nondimensional cylinder diameter D' about 1.3 (normed to the Laplace constant). At the lower and larger values of D' the difference between the theoretical solution and the data can be rather noticeable [5].

NOMENCLATURE

c	[J/kg K]	Specific heat
h_{LG}	[J/kg]	Latent heat of evaporation
p	[Pa]	Pressure
q	[W/m^2]	Heat flux density
T	[K]	Temperature
r	[m]	Radial co-ordinate
R	[m]	Radius of a sphere
t	[s]	Time
u	[m/s]	Velocity

Greek characters

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

Subscripts

0	initial conditions
cr	critical
G	gas (vapor)
L	liquid
s	saturation
sub	subcooling

Besides the explanation of this difference given in [4], it is worthy to note that at very low cylinder diameter the boundary layer approximation becomes invalid; it is well known that free convection problem solution with the above approximation underpredicts the corresponding data at low Rayleigh numbers, the lower Ra, the bigger difference being. The rigorous numerical solution well reproduces experimental dependences of film boiling heat transfer on wall superheat and liquid subcooling. The authors explain more than two-fold increase of HTC at subcooling 40K in comparison to film boiling of saturated liquid as an effect of shear forces at the liquid-vapor interface. This conclusion, however, seems to be rather ambiguous. In a saturated liquid shear stress at the interface also exists, but the classical solution of Bromley and some other results based on an assumption about zero liquid velocity at the interface manifest good agreement both with the experimental data and with the theoretical results in question. In a subcooled liquid shear stress increases due to increase of vapor velocity in the thinner film, but the condition $\rho_G << \rho_L$ hardly makes the effect discussed predominant in comparison with free convection in liquid. Numerical study, obviously, gave a possibility of overcoming this contradiction investigating a case with negligible body forces in liquid, i.e. assuming g=0 in momentum equation for liquid phase; unfortunately, the authors of [4] did not study this issue in details.

The paper [4] presents also an approximate analytical model of film boiling heat transfer in subcooled liquid. The model considers film boiling on vertical isothermal plate. Convective heat transfer is assumed negligible both in vapor film and in liquid boundary layer; this means that temperature profile is linear in either of regions. Basing on the assumption about dominant influence of shear stress caused by vapor flow, free convection effect on liquid flow is neglected. The analytical solution is in good agreement with the rigorous numerical one for liquids with Prandtl number closed to unity. For liquids with low and high Prandtl number an empirical correction multiplier is introduced. Comparison of the solution with the experimental data of other researchers also gives good results, if an additional empirical factor accounting for nondimensional cylinder diameter influence is introduced. We should denote that authors reached only low subcooled levels, for example 40K for water and 50K for ethanol and Freon-11.

It is well known that increasing in pressure leads to increase of saturation temperature. Kenning et al. [1] first show that increasing subcooling higher than 22K for water induces very intensive boiling regime called “microbubble boiling”. Heat fluxes in such regimes reached values up to 10MW/m^2. It looks surprising because direct liquid-solid contact is not impossible at such conditions (temperature of surface higher than critical temperature of the liquid). The authors carried out a study of cooling hot sphere from different materials in isopropanol and perfluorhexane in wide range of subcooling. In opposite to water, the cooling process in these liquids manifested stable film boiling with low values of HTC.

Increase of external pressure opens a wide field for studies of the effect of high subcooling on boiling laws. This is essential that this method of increasing subcooling keeps the liquid properties unchangeable at the liquid bulk temperature. That is why we carried out extensive research on influence of pressure on film boiling of subcooled liquids.

THE EXPERIMENTAL FACILITIES AND THE METHODS OF THE RESULTS TREATMENT

Our research program includes experiments using nickel sphere 45 mm in diameter and various cooling media. Experimental stand "High Temperature Surfaces Cooling Regimes," was created in 2013 under the program of development of the material base of the NRU "MPEI".

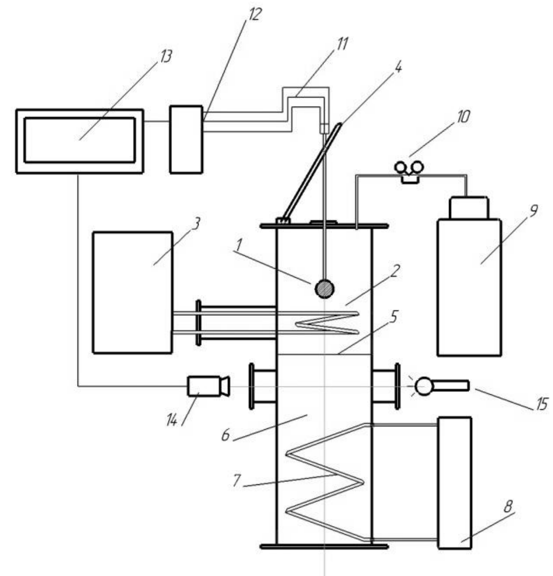

Figure 1. Schematic of experimental stand. 1 - test sphere; 2 – coil of the inductor; 3 – high- frequency inductor; 4 – replacing device; 5 – metallic diaphragm; 6 - experimental camera; 7 – coil pipe; 8 – thermostat; 9 – balloon with inert gas; 10 – control valve; 11 - thermocouples; 12 – measuring module; 13 - personal computer; 14 – video camera; 15 – halogen lamp

Schematic of the stand is shown in Figure 1. Sealed housing of experimental camera is made of stainless steel tube 219 mm outer diameter with a wall thickness of 10mm. In its upper part a coil (2) of a high frequency induction heater (3) is placed; the lower part is filled with the cooling liquid, the temperature of which is maintained at a predetermined level by means of the thermostat (8) and the coil pipe (7) immersed in the liquid. The heating zone is separated from the liquid volume by thin metal diaphragm (5), which protects the cooling medium against heat radiation. The metal sphere (1) at the beginning of the experiment is mounted inside the coil (2) by system for moving the working piece (4). Heating is controlled by the thermocouples placed inside the sphere. Power of the high frequency inductor allows obtaining high heating rate; in a moderate mode providing controlled uniform heating sphere is heated to 800°C less than for 5 minutes. There is a possibility of heating a specimen in inert gas incoming from the gas balloon (9). The heated ball moves into the cooling liquid at the level of viewing windows. During cooling signal from thermocouples (11) is transmitted through the connector NI SCXI-1303 to the measuring module NI SCXI-1102 (12), which is part of the system NI SCXI-1001. Signal detection is carried out from each thermocouple at 100 Hz. The measurement results through USB-interface are transmitted to the personal computer (13), wherein in the Lab View program temperature versus time relation is built. In some runs video filming the processes occurring at the surface of cooled sphere is conducted with a digital video camera (14) in transmitted light from a halogen lamp (15). Video is saved at the PC hard disk.

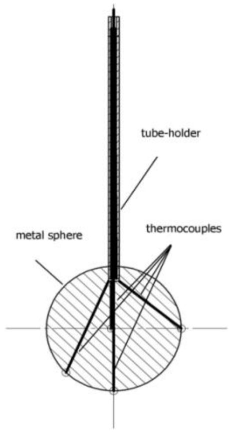

Figure 2. Thermocouples disposition scheme in a sample

Test samples are metal balls of 45mm diameter. In a ball through holes with a diameter of about 1 mm were drilled to accommodate the cable with thermoelectrodes. One variant of the thermocouples arrangement is shown in Figure 2; in this case 4 thermocouples are mounted in metal ball: three are located on the surface at the points with polar angle of 90, 135 and 180º, and one is placed in the center. In other cases a ball can be equipped with 5 thermocouples, 4 of them are on the surface. All the drillings are made from the top of sphere. Chromel-alumel thermocouple stretched inside the ball through the holes and welded by laser welding flush with the surface. Electrodes of thermocouples were collected in a tube-holder of 5 mm O.D., which is attached to the ball first on thread at a depth of 5 mm, and then the coupling place is sealed with laser welding. This technique of thermocouples embedding is definitely time-consuming, but it provides obtaining information on actual temperature field at rapid cooling of the ball without its significant distortion with measuring devices (Figure 3).

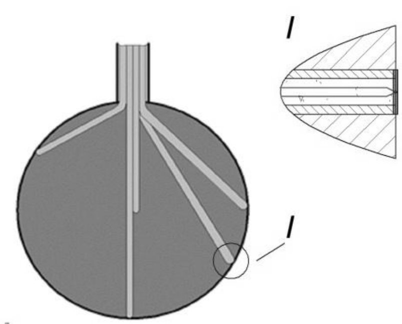

Figure 3. Thermocouples welding on surface of sample

In paper [6] we describe the methodical experiments performed with simultaneous temperature measurement with the outer thermocouples and with the ones embedded inside the sample. This methodological experiment remove any doubts on impossibility of using external thermocouples welding in studies of quenching process in subcooled liquids.

At high cooling rates, recovering the conditions at the body surface requires solving the inverse problem of thermal conductivity. This type of problems is related to ill-posed ones; their solution is ordinarily achieved by means of approximate methods. In this study factually a direct numerical solution of nonsteady heat conduction problem consistent with the measured results was found to recover the conditions at the surface of a cooled ball. The program «Rteta» developed at the Department of Engineering Thermophysics MPEI was used in solving; the temperature field in the ball was calculated by the control volume approach.

An assumption on axis symmetry of the problem seems to be quite natural, if one accounts for a region geometry and video filming results on development of cooling process along the ball surface. So the following energy equation is valid:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \lambda \frac{\partial T}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \lambda \frac{\partial T}{\partial \theta}\right) \quad (1)$$

This 2D equation is solved for description of those experimental runs, where intensive cooling front spreads along the ball surface upward beginning from the south pole. In the modes with a small rate of cooling, when the process can be considered with good accuracy as spherically symmetric, one-dimensional approximation is successfully used. In this case the 2nd term of RHS of Eq. (2) is omitted and the third kind boundary condition is used:

$$t = 0,\ 0 \le r \le R : T = T_w = T_0;\ r = 0 : \frac{\partial T}{\partial r} = 0;$$
$$r = R :\ -\lambda \frac{\partial T}{\partial r} = \alpha(t)(T_w - T_s). \quad (2)$$

The program «Rteta» allows determining heat transfer coefficient during cooling interactively. First, Eq. (1) is solved at predetermined HTC and the conditions (2) for a certain time interval. The temperature field inside the ball is calculated, and temperature at the control points is compared with the measured values for the corresponding thermocouples.

As the result of comparisons, either the HTC value is adjusted or solution moves to the next time step. For each subsequent step the solving result at the previous time step is used as the initial temperature distribution. This method gives good results in the modes with a small rate of cooling, i.e. at the steady film boiling or at small subcooling to saturation. It is revealed that it can be used also under the intensive cooling of a small diameter sphere, when deviation between the experimental thermograms is small, and the process can be considered approximately as spherically symmetric.

Experimental results

We have chosen three different liquids to perform our experiments. Here they are water, isopropanol (C_3H_8O) and perfluorohexane (C_6F_{14}). These liquids greatly differ with the thermophysical properties. For example, density of perfluorohexane is two times larger than for isopropanol, surface tension of water is 6 times larger than that for perfluorhexane. Isopropanol characterized by extra-large kinematic viscosity and perfluorhexane by very low thermal conductivity. Some properties of these liquids at 20°C are presented in Tab.1.

liquid	density, ρ, kg/m³	kinematic viscosity, ν, m²/s	thermal conductivity, λ, W/m*K	surface tension, σ, N/m
water	*997*	$9.257 \cdot 10^{-7}$	*0.598*	$72{,}75 \cdot 10^{-3}$
isopropanol	*785*	$3.034 \cdot 10^{-6}$	*0.136*	$23{,}8 \cdot 10^{-3}$
perfluorohexane	*1688*	$3.661 \cdot 10^{-7}$	*0.058*	$11{,}91 \cdot 10^{-3}$

Table 1. The liquids properties at 20°C

First experiments were performed with distilled water. We fixed temperature T_L=30°C and varied an ambient pressure with inert gas (nitrogen). The values of pressure were 1, 5 and 10atm that corresponds to saturation temperature 100, 152 and 180°C. Subcooling values at different pressures reached 70, 122 and 150K. Thermograms for average surface temperature presented in Fig. 4. The primary thermograms in these experiments differ relatively slightly, so that their averaging was justifiable.

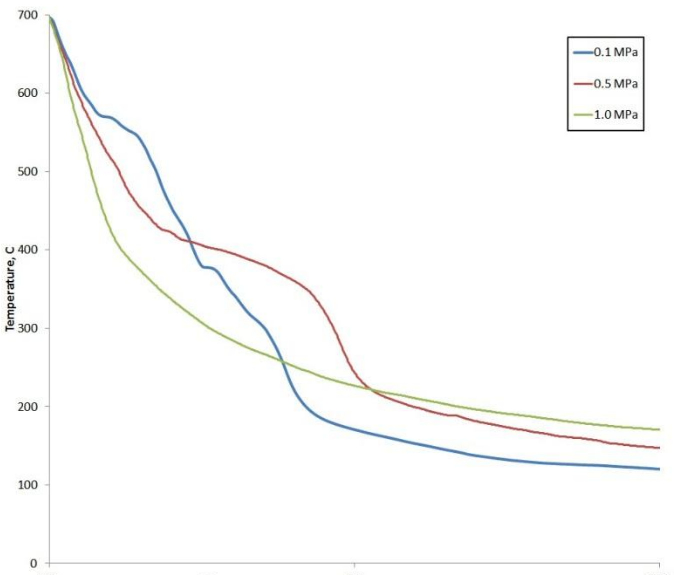

Figure 4. Average surface temperature versus time for 30°C water at 0.1, 0.5 and 1.0 MPa

Initial temperature of the test pattern was 700°C that exceeds the critical one for water more than 300K. How it is seen from figure 4, the cooling rate is very high, for example, at 1.0 MPa the wall surface is cooled from 700°C to 400°C for one second. It looks rather enigmatic, because there could be only film boiling regime in this temperature range without direct liquid-solid contact. Intensity of cooling increases with pressure.

Using the procedure presented in the previous section, we have calculated heat flux and heat transfer coefficient at the sphere surface for the whole period of boiling. The surface temperature measured with the four thermocouples was averaged at any time moment, and 1D unsteady problem was solved numerically with the boundary conditions (2). HTC at the sphere surface was found by means of iterations up to coincidence of the calculated and the measured values of the surface temperature. In Fig. 5 presented the variation HTC versus surface temperature.

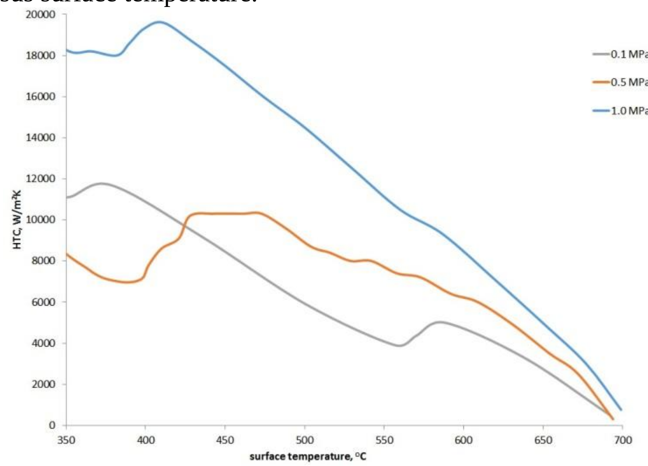

Figure 5. HTC during cooling in 30°C water 0.1, 0.5 and 1.0 MPa

We can see that the values of HTC increase with pressure increase and reach 20 kW/m^{2}K at the surface temperature 420°C under the maximal pressure (10atm). The values of heat transfer coefficient (HTC) at atmospheric pressure (7-10 kW/m^{2}K) are also high enough in comparison with typical values for film boiling of saturated liquids (≤0.5 kW/m^{2}K). From figure 6 one can clearly see that heat flux densities at all pressures remain higher than 1.5 MW/m^2 during practically entire period of intensive film boiling at the wall temperature 350-650°C. In general, the higher pressure, the higher heat flux, at 1.0 MPa it exceeds 4.5 MW/m^2 that looks unrealistic for film boiling regime.

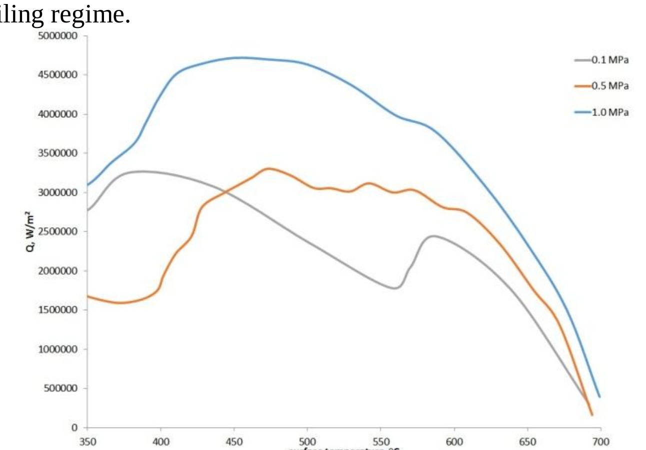

Figure 6. Heat flux density in dependence of the wall surface temperature for 30°C water at 0.1, 0.5 and 1.0 MPa

The experimental results confirmed that film boiling of highly subcooled water presents a particular regime without direct liquid/solid contacts, but with high intensity of heat transfer. Understanding of the actual mechanisms of high intensive energy transfer in this regime appears to be a serious challenge for researchers.

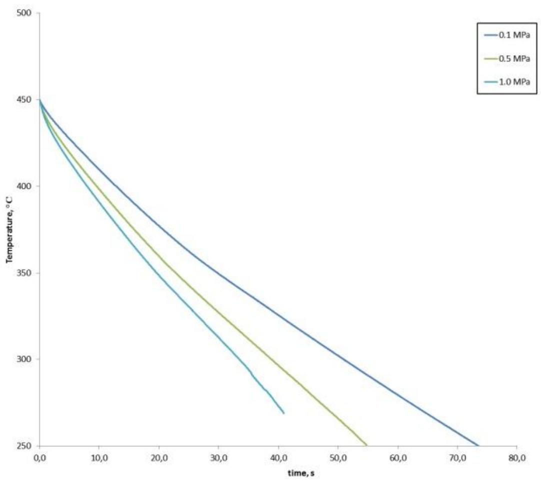

Figure 7. Average surface temperature versus time for cooling in isopropanol at -15°C and different pressures

The experiments with isopropanol were carried out at the fixed temperature T_L= -15°C and different pressures: 0.1, 0.5, and 1.0 MPa that correspond to saturation temperatures 82, 130 and 155°C, the corresponding subcooling values were 97, 145 and 170K. Cooling process in isopropanol occurs mainly in the stable film boiling regime, when the thermograms for the surface thermocouples are very close to each other. Under these conditions, the surface averaging of the thermograms is quite natural. Fig. 7 depicts such averaged thermograms for cooling the nickel sphere in isopropanol at -15°C.

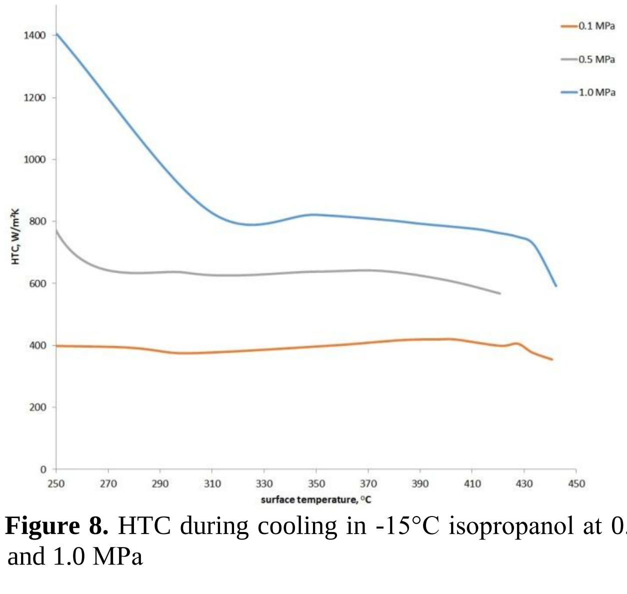

Figure 8. HTC during cooling in -15°C isopropanol at 0.1, 0.5 and 1.0 MPa

As is seen, the cooling rate in isopropanol is 1-2 orders of magnitude less than for the same nickel sphere in subcooled water. The calculated values of heat transfer coefficients and heat flux densities at the sphere surface at isopropanol cooling are in the similar relation to the corresponding values for cooling in water. Fig. 8 presents the calculated values of HTC in stable film boiling of isopropanol; these values do not exceed 1 kW/m^{2}K, that is 20times lower, than in water.

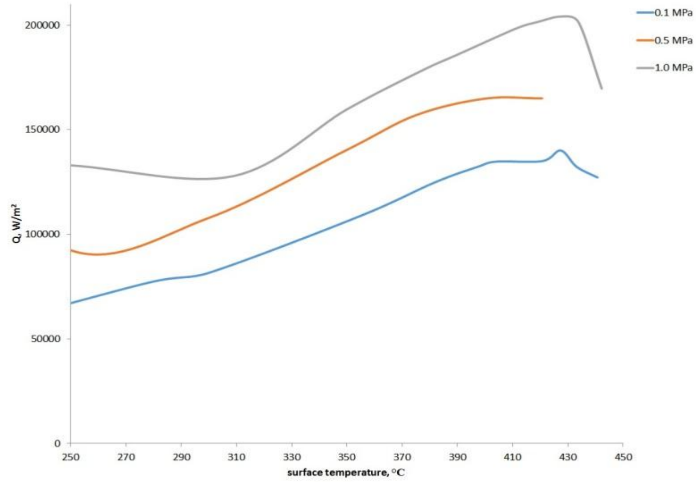

Figure 9. Heat flux density in dependence of the wall surface temperature for -15°C isopropanol at 0.1, 0.5 and 1.0 MPa

Calculated heat flux densities at the sphere surface in isopropanol are presented in Fig. 9. The maximum value of heat flux is only 200 kW/m^2, i.e. more than an order of magnitude less in comparison with cooling in water. Nevertheless, qualitatively pressure influence on heat transfer is the same for these two liquids, in the both cases HTC and q increase with pressure.

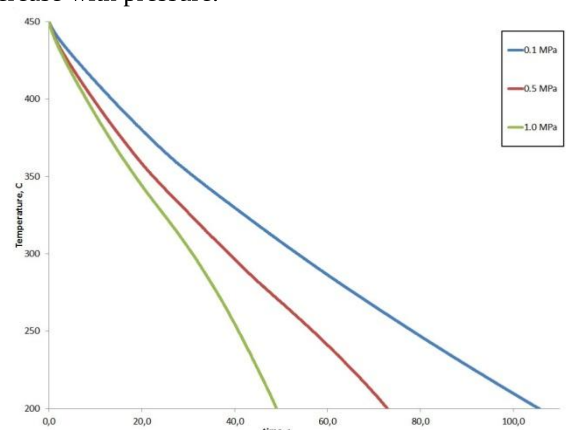

Figure 10. Average surface temperature versus time for -15°C perfluorhexane at 0.1, 0.5 and 1.0 MPa

The experiments with perfluorohexane as the cooling liquid gave the results analogous to those for isopropanol, in spite of strong difference in physical properties of these liquids. The fixed bulk liquid temperature (-15°C) corresponds to subcooling values 71, 129, and 160 K at pressures 0.1, 0.5, and 1.0 MPa correspondingly. In every cooling process, its most part corresponded to stable film boiling with the very close thermograms for the surface thermocouples. Fig. 10 presents the averaged surface thermograms of cooling the nickel sphere at the different pressures. As is seen, they are quite similar to those presented in Fig. 7 for isopropanol.

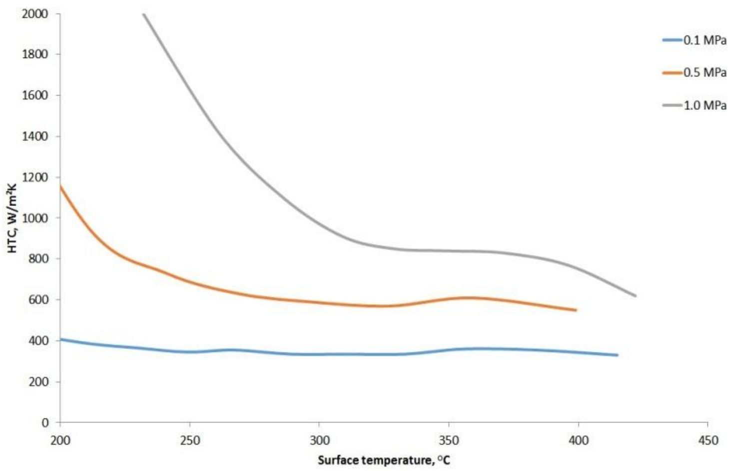

Figure 11. HTC during cooling in -15° perfluorhexane at 0.1, 0.5 and 1.0 MPa

Figs. 11 and 12 show the calculated values of heat transfer coefficient and heat flux density at the nickel sphere surface during its cooling in perfluorohexane at different pressures; in the both cases the sections of the calculated dependences related to film boiling are given. As is seen, both HTC and heat flux in perfluorohexane are very close to the corresponding values in isopropanol.

At the same time, the common trend of enhancement heat transfer in film boiling of subcooled liquids with pressure increase was also revealed in perfluorohexane. This trend is even more significant in this liquid: heat flux at pressure 1.0 MPa is twice higher than at atmospheric pressure. Probably, the reason of this effect is relative proximity to critical pressure.

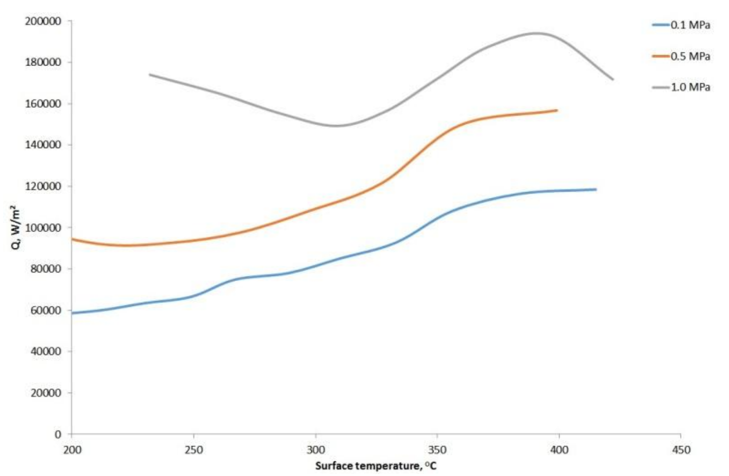

Figure 12. Heat flux density in dependence of the wall surface temperature for -15°C perfluorhexane at 0.1, 0.5 and 1.0 MPa

Conclusions:

- For the first time the experimental studies of film boiling of different liquids at elevated pressures and very high subcoolings have been performed.
- Cooling of the high temperature nickel sphere in subcooled water is featured with very high heat transfer intensity, HTC and heat flux density is 1-2 orders of magnitude higher than those for isopropanol and perfluorohexane are.
- At high water subcooling film boiling presents, obviously, a particular mode of boiling heat transfer, dissimilar greatly to saturated film boiling mainly by high intensity of heat transfer, heat flux density in this regime is 2-5 times higher than CHF in water pool boiling
- The experimental results of the present work have shown that the regimes of high intensity heat transfer occur at the cooled spheres surface at temperature 600-700°C, when direct liquid/solid contact is impossible. Heat flux densities in these regimes can be higher than 5MW/m^2, that is two orders of magnitude higher than in film boiling of saturated water.
- Heat transfer coefficient and heat flux density in stable film boiling of subcooled liquids increase with pressure in the range investigated.

Acknowledgments

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