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Heat transfer enhancement at increasing water concentration in alcohol in the process of non-stationary film boiling

P K Kanin¹, V A Ryazantsev¹, M A Lexin, A R Zabirov¹ and V V Yagov¹

¹ NRU “Moscow Power Engineering Institute”, Krasnokazarmennaya Street 14, Moscow 111250, Russia

Abstract. New experimental data on heat transfer in pool film boiling of subcooled ethanol-water mixtures at spherical surfaces are considered. The water solutions with ethanol mass fraction from 10 to 91% and temperature of liquid 50℃ were examined. All the experiments were conducted under atmospheric pressure, using the stainless steel sphere of 39 mm in diameter as a cooled body. The sphere was heated up to 450-750℃, depending on ethanol concentration, and immersed into the experimental vessel with subcooled mixture. As it is expected, boiling heat transfer intensifies with ethanol concentration decrease, and duration of cooling decreases. It means that stable film boiling duration decreases, and earlier transition to intensive heat transfer regime occurs.

1. Introduction

Basing on our hypothesis presented in [6], the appearance of intensive film boiling mode depends on a liquid latent heat of evaporation ($h_{LG}$), surface tension (σ) and viscosity (ν). Using liquid mixtures instead of pure components can be considered as a convenient way to investigate the influence of liquid properties. That is why in 2017 we have started the experiments with water/alcohols binary mixtures. The main goal of this work is to reveal the influence of coolant properties ($h_{LG}$, σ) influence on incipience of high intensive film boiling regime.

It is known that under specific conditions even small admixtures of water in a coolant can lead to high intensity of heat transfer process [7]. The approach of [7] was based on the relative version of the method of controlled pulse heating of a wire probe at constant current mode. As was shown by the authors, in single pulse experiments water addition significantly perturbs the values of both boiling-up temperature and heat transfer intensity. The impact was manifested in a decrease in the spontaneous boiling-up temperature at simultaneous increasing intensity of heat transfer in the watered samples. The present paper presents new experimental data on heat transfer during film boiling of subcooled aqueous solutions of ethanol. A stainless steel sphere of 39 mm in diameter was used. The experiments were conducted at atmospheric pressure with mixtures of various ethanol concentration (mass fraction of ethanol 10 ... 91%, with 10% step). The temperature of mixture was 50℃. To the best of the authors’ knowledge, there is no experimental data on nonsteady heat transfer during binary mixtures film boiling. Therefore, the new results described in this article may fill this gap.

2. Experimental facility

The experiments were conducted at the stand, which scheme depicted in Fig. 1. The experimental pattern immersed in liquid through open atmosphere that allow to control the pattern surface's state
and cleanness. Besides, such the experimental facility makes it possible conducting large amount of experiments (nearly 90) on various mixtures (mass fraction of ethanol 10 ... 91%, with 10% step) with various temperature of liquid (from -10 to +70°C with 20 K step) in short time.

Fig. 1. Scheme of experimental setup: 1 – experimental pattern, 2 – HF inductor, 3 – inductor coil, 4 – experimental vessel, 5 – thermostat coil (connected with the thermostat), 6 – thermocouples wires, 7 – pattern transferring system, 8 – measurement module, 9 – PC.

Depending on ethanol mass fraction in the mixture, the stainless steel ball was heated to temperature 450 – 750°C (the less mass fraction of ethanol the higher initial temperature of the ball). For thermocouples installation 4 through holes were drilled from the top part of the ball to the surface points with polar angles 45, 90, 135 and 180°, and one hole was drilled to the ball centre. The thermocouple junctions (type K) were welded flush with the surface by means of laser welding, their cables passed through the holes and further to the data acquisition system.

At high intensity of heat transfer, the temperature field in the sphere is not uniform and not spherically symmetric. Under such conditions, one has to solve an inverse heat conduction problem (IHCP) in order to calculate heat flux density at the sphere surface. In this study, a numerical solution of direct unsteady heat conduction problem has been found in order to recover the boundary conditions at the surface of the cooled sphere. The problem simplifies, when a cooling process is spherically symmetric; this occurs mainly in film boiling of saturated or weakly subcooled water ($\Delta T_{sub} \leq 20$K). This approximation is also used for rather small spheres even at high intensity of heat transfer at the sphere surface. To restore the surface conditions direct spherically symmetric nonstationary heat conduction problem is solved numerically by means of the RTETA program developed in MPEI [8].

3. Results and discussion

The paper will present only a part of the experimental results obtained. All the experiments were conducted under the conditions, when the stable film boiling regime could be observed. This allows controlling the surface temperature corresponding to vapor film collapse, when the more intensive process starts. All the thermograms at stable film boiling had similar shapes shown in Fig. 2. The curves depict temperature variation in the central (solid line) and the surface points of the sphere during cooling in 91% (ethanol mass fraction) solution with liquid temperature of +50°C. As is seen, the sphere is cooled from 450 to 200°C approximately for 80 s. At low ethanol mass fractions in the solution, quite different type of cooling thermograms is observed. This other type is shown in Fig. 3
that relates to the test pattern cooling in the mixture with 10% ethanol mass fraction and at the same temperature 50°C. In this experimental run the pattern centre is cooled from 630 to 540°C approximately for 1.5 s, while its surface temperature decreases almost by 400 K for the same time. This is obvious that with ethanol mass fraction decrease, the duration of stable film boiling regime decreases.

![Graph showing temperature vs. time for different conditions](image1)

**Fig. 2.** Thermogram of 39mm stainless steel ball cooling in 91% ethanol solution with liquid temperature of 50°C. Central thermocouple (1) and surface thermocouples at the values of polar angle \(\theta\), deg: (2) 45, (3) 180.

![Graph showing temperature vs. time for different conditions](image2)

**Figure 3.** Thermogram of 39mm stainless steel ball cooling in 10% ethanol solution with liquid temperature of 50°C. Central thermocouple (1) and surface thermocouples at the values of polar angle \(\theta\), deg: (2) 45, (3) 180.

For testing the hypothesis on the conditions of an incipience of intensive heat transfer regime in film boiling, it is important to determine experimentally the surface temperature values, corresponding to the stable film boiling transition to a more intensive process. Fig. 4 shows how this transition temperature varies with the ethanol mass fraction in the mixture. In this figure the experimental data (dots) present the average temperature of the sphere surface that corresponds to the above transition; a simple linear approximation is also given. It is should be mentioned that all the points in the picture are obtained from a qualitative analysis of the experimental thermograms.

That is why according to our estimations, an uncertainty of this temperature determination is near 50 K. Nevertheless, this dependence seems to be meaningful. As can be seen, the transition temperature dependence on the ethanol mass fraction is close to linear. All the points corresponding to the mass fraction from 91 to 60% are lower than \(T_{cr}\) of mixtures and lower than (or near) \(T_{lim}\). For instance, the \(T_{lim}\) of the 91% solution is 212°C; as can be seen from Fig.4, the transition temperature is about 165°C. Hence, one can confidently consider the boiling regimes of these mixtures at atmospheric pressure as stable film boiling regimes, similar to our experiments on pure ethanol [5]. As for the solutions with
the ethanol mass fraction from 50% and lower, in all the experiments the transition temperature is much higher than $T_{lim}$ or even $T_{cr}$ of the mixtures. For the 50% solution, the average temperature of the sphere surface corresponding to the boiling regimes transition is near 410°C. This is higher than $T_{cr}$ of the mixture with such composition by 90K. For the mixture with the 10% ethanol mass fraction, intensive heat transfer occurs when the average temperature of the ball surface is near 550°C, while $T_{cr}$ = 364°C. This clearly shows that the cooling process in mixtures with high water mass fraction occurs in micro-bubble boiling regime.

![Figure 4. Transition temperature variation with ethanol mass fraction in a mixture](image)

4. Conclusion
Subcooling increase at the fixed water/ethanol mixture composition leads to a decrease in duration of the stable film boiling regime. Cooling process in pure ethanol and in mixtures with its mass fraction $\geq$ 50% occurs in this regime at rather low heat transfer intensity. At lower ethanol concentration, the vapor film collapses at certain transition wall temperature, and higher intensive process of cooling starts. The cooling process in mixtures with high water mass fraction can be related to micro-bubble boiling regime. On our point of view, the reason of increasing of the transition temperature is in variation of some mixture properties, especially, an increase of latent heat of evaporation and surface tension. This fact is in agreement with our hypothesis of incipience of the intensive cooling regime in subcooled liquids film boiling [6].

The interaction between a hot surface and subcooled liquid may lead to the dangerous and destructive vapor explosion observed in metallurgical and pulp and paper industry and pose a potential hazard in the operation of nuclear reactors [1], in cryogenic systems, and in the transport of liquefied natural gas.

According to the homogeneous nucleation theory [2], if temperature of a hot body surface is much higher than the limiting attainable temperature of a liquid, a vapor film appears around the body almost instantaneously. This means that cooling of high temperature metal bodies in liquids occurs in film boiling regime; under steady conditions, this regime is characterized with low rates of heat transfer. However, in the experiments on cooling the high temperature spheres in water at subcoolings higher than 25 K, the vapor film collapses and huge HTC are observed. Maximum rates of heat flux density can achieve 10 MW/m$^2$. The English researchers G. Hewitt and D. Kenning with their co-workers first described this unusual intensive process in 1986-1990; they named it micro-bubble boiling [3]. The goal of our study is to reveal regularities and mechanisms of this phenomenon.

Our scientific group has performed many experiments on hot patterns cooling in subcooled water and nonaqueous liquids (ethanol, isopropanol and perfluorohexane) at atmospheric and elevated pressures [4]. As for water, the intensive heat transfer regime occurred in the experiments on the spheres from different metals at pressures of 0.1-1.0 MPa at subcoolings above 25 K [5]. However, among the nonaqueous liquids, the micro-bubble boiling regime was observed only on ethanol under high pressures and high subcoolings [6]. Therefore, the question arises: what water properties, different
from those of nonaqueous liquids, cause vapor film collapse and beginning of high intensive heat transfer regime?

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