Investigating the effect of submerged impingement jet on heat transfer in water-alcohol mixtures

P K Kanin¹, T A Gubanova¹, A R Zabirov¹,² and V V Yagov¹

¹NRU “Moscow Power Engineering Institute”, 14 Krasnokazarmennaya Street, Moscow 111250, Russia
²Joint Institute for High Temperatures of Russian Academy of Sciences, Bd.2, 13 Izhorskaya Street, Moscow, Russia

E-mail: gubanova.ta@mail.ru

Abstract. This paper presents new results of experiments on spherical sample cooling with submerged impingement jet in subcooled water-alcohol mixtures. The influence of the ethanol concentration on the occurrence of intensive boiling regime is detected. Experiments are carried out on a stainless-steel sample in a water-ethanol mixture, in a wide range of concentrations and temperatures. The result includes an increase of the heat transfer intensity at exposure of the submerged impingement jet. The intensive boiling regime is detected with a higher ethanol content compared to experiments in a calm liquid.

1. Introduction

Boiling of subcooled liquids is an integral part of the quenching technology. Understanding the mechanisms of this process is important for nuclear and thermal energy, in particular, for cryogenic technology. Jet cooling has been used in production technologies for many years. Experiments have shown that even a small liquid disturbance can have a significant effect on the process [1]. The reason for the random instability of the film boiling may be due to liquid mixing. However, this is again possible under the conditions of liquid subcooling. Experiments are carried out using a device that injects a liquid jet onto the cooled surface at the same temperature as in the volume of the coolant.

An approximate model of intensive heat transfer during film boiling was developed at the Department of Engineering Thermophysics of MPEI [2]. When the surface temperature is lower than the limiting attainable temperature, the contact of the liquid with the surface roughness elements becomes possible. Such contacts may lead to a transition to the intensive heat transfer during film boiling of subcooled liquids. Naturally, this model explains the effect of the impingement jet. The jet mechanically acts on the vapor film, makes it thinner, and as a result, the number and total area of contacts of the liquid with projections of surface roughness increase. It is clear that local cooling increases, which was also reported by the authors of [3], who carried out experiments to cool the highly heated flat steel plate with a stream of water. The experiment was filmed in detail. Really sedimentation of solids on the hot plates and also the increased roughness of the plate can easily penetrate through a steam film and interact with flowing liquid. They act as a kind of micro-ribs and thus cooling occurs faster. The authors of [4] investigated changes in the heat transfer characteristics during boiling by changing the exit velocity of the submerged jet and the nozzle diameter. The flow of saturated FC-72 exited the nozzle and hit the heated circular test section. The Reynolds number Re of the jet outlet varied depending on the change in the jet outlet velocity and the nozzle diameter. At a
fixed number $Re$, the heat flux increased with increasing jet velocity and with decreasing nozzle diameter, which indicated that the kinetic energy of the jet was a key parameter in the heat flux increase. Our experiments were conducted at almost the highest possible speed of the device. Cooling in pure ethanol, as in the previous work [5], took place at a low heat transfer intensity. The intensive boiling mode was possible only at a very high subcooling. Approximately the same case was observed for cooling in a mixture with a mass fraction of 80% ethanol. But an earlier transition to an intensive heat transfer mode was observed in 60% mixture, even with subcooling of 10°C.

Previously, it was found that only a disturbance of cooling uniformity was significant for cooling in ethanol. According to the analysis of thermograms, the transition temperatures did not exceed the critical temperature of ethanol. Although the cooling rate increased, these results cannot be attributed to the intensive boiling regime. Ethanol-water and isopropanol-water solutions without the action of the jet have also been previously investigated in [6,7]. All experiments were conducted at atmospheric pressure using stainless steel and nickel spheres, respectively. The purpose of the tests was to investigate the influence of properties (such as evaporation heat, surface tension and viscosity) on the heat transfer intensity. According to our hypothesis, the emergence of an intensive film boiling regime depends on the above properties. As expected, heat transfer from boiling increases and cooling duration decreases with the reduction of ethanol and isopropanol to 50% or less. This means that vapor film stability decreases and there is an earlier transition to an intensive heat transfer regime. The article [8] found that the transition temperature exceeds $T_{lim}$ and even $T_{cr}$ of the liquid at elevated pressures and with a water fraction in the mixtures over 50%. It is interesting to know at what concentration of ethanol the intensive boiling regime appears in the presence of a submerged impingement jet.

2. Experimental facility

![Figure 1. Experimental facility scheme: test sample (1), cooling liquid (2), impinging jet device (3), tube holder (4), transferring lever (5), HF inductor (6), experimental vessel (7).](image-url)
Experiments were carried out on an experimental facility, the scheme of which is shown in Figure 1 and in more detail in our previous work [5]. The setup allows testing only at atmospheric pressure and in a temperature range from 0°C to 100°C for a liquid. Experiments were conducted with different mixtures (ethanol mass of 0 ... 95.5%). Depending on the mass fraction of ethanol in the mixture, the stainless-steel balls (40 mm diameter) were heated to a temperature of 450–750°C (the lower the ethanol mass fraction, the higher the initial temperature of the ball). The temperature of the cooling liquid \( T_{\text{liq}} \) ranged from 30°C to 70°C for ethanol and from 50°C to 90°C for a distilled water. To install the thermocouple, 5 through holes with polar angles of 45, 90, 135 and 180° were drilled, and one hole was drilled to the center of the ball. Thermocouple (type K) compounds were welded loosely with the surface by laser welding. The heated sample was immersed in a tank and the injection device supplied it with a liquid of the same temperature as the tank. The average speed of the jet at the outlet of the nozzle was 10 m/s. The distance from the cut of the nozzle to the surface was approximately ~ 4 mm. It is important to note that the jet hit the cooling liquid before the sample immersion.

3. Results and discussion

Figure 2 contains an example of thermograms, demonstrating the effect of a submerged jet. The transition to the intensive boiling mode occurs instantly in the experiment with a jet, which is significantly different from the experiment without it.

![Figure 2](image)

**Figure 2.** Thermogram of 40 mm stainless steel ball cooling in 40% ethanol solution with liquid temperature of 30°C. Cooling with submerged jet (a) and without it (b). Central thermocouple (1) and surface thermocouples at the values of polar angle \( \theta \), deg: (2) 90, (3) 135, (4) 180.

The duration of the cooling process depends heavily on the ethanol content and the mixture subcooling \((\Delta T_{\text{sub}})\). For example, for 80% of the solution, the process lasted 45 seconds at a liquid temperature of +70°C and 16 seconds at a temperature of +30°C. For 40% of solution, the process lasted 18 seconds at liquid temperature \( T_{\text{liq}} = +70°C \) and 11 sec at a temperature \( T_{\text{liq}} = +30°C \). Some experiments were filmed to better visualize the effect of the submerged impingement jet. Figure 3 shows the film release during metal sphere cooling at 40% mixture at a temperature of +30°C. It is important to note that the liquid subcooling was quite high, in which case the process of intensive heat...
transfer occurred almost immediately. The cooling period was 14 s, and the time interval between frames was 1.75 s.

In liquids with high water content and high subcooling, it was not noticeable, because the vapor film was destroyed almost immediately and the process of heat transfer was very intensive. In liquids with a high ethanol content and a $T_{liq}$ close to the saturation point, the process was quite different. The jet destroyed the vapor film and formed an extremely small area of liquid contact with the surface. But there was no further increase in the area of this contact. After the liquid supply to the surface stopped, the vapor film was restored and the stable film boiling process continued.

![Figure 3. Visualization of boiling on the surface of the steel sphere at 40% mixture at +30°C with the action of a submerged impingement jet of the same liquid.](image)

![Figure 4. Thermogram of 40 mm stainless steel ball cooling in 80% ethanol solution with liquid temperature of 70°C. Central thermocouple (1) and surface thermocouples at the values of polar angle $\theta$, deg: (2) 90, (3) 135, (4) 180.](image)
The above is an example of a thermogram for cooling a sample in a solution with a high ethanol content (Figure 4). During experiments in 80% mixture, the ball was heated to a temperature of ~450°C. The thermograms show the change of temperatures in the center and on the surface. The cooling process lasted 45 seconds. During the first 35 seconds stable film boiling occurred. Next, the transition to an intensive heat transfer mode was observed. The transition temperature was approximately $T_tr \sim 245$°C. The jet did not have a significant effect. Only the stability of the vapor film was disturbed. However, the micro-bubble boiling mode could take place in 80% solution with more subcooling. Already at liquid temperature $T_{liq} = 50$°C there was an earlier transition to the intensive mode. The transition temperature was $T_{tr} \sim 300$°C, which was above the critical, not to mention the limiting one.

**Figure 5.** Thermogram of 40 mm stainless steel ball cooling in 20% ethanol solution with liquid temperature of 70°C. Central thermocouple (1) and surface thermocouples at the values of polar angle $\theta$, deg: (2) 90, (3) 135, (4) 180.

The cooling process in a low ethanol liquid looks very different. Figure 5 providing an example of such an experiment shows significant differences from the previous thermograms. In this case the sample was heated to ~600°C and cooled in the solution for 70 s. The intensive heat transfer process takes place in 4–8 seconds. The transition temperature is approximately 400°C, which is higher than $T_{cr}$ and $T_{lim}$. This can be seen from thermograms for thermocouples with 90° and 180° polar angles. Thermograms behave somewhat differently at 135°. Most likely, this is due to the fact that the first two are located closer to the impact area of the impingement jet, and the last one is further away.

The previous paper presented the results of the steel ball cooling in the water-alcohol mixtures at a temperature of 50°C without the action of a submerged jet [6]. The authors obtained a transition value of the mass of alcohol in solution, at which a micro-bubble boiling mode was created. Only at mass fractions of 50% and below the temperature of the transition to an intensive heat transfer process was higher than $T_{cr}$ and $T_{lim}$. The jet experiments presented in this article were conducted for the same purpose. In contrast to the previous results, the micro-bubble boiling mode was already observed in a mixture with 80% alcohol by mass, but with $T_s$ subcooling over 40°C. However, by boiled in 60% of the solution, the transition temperature was much higher than $T_{cr}$ and $T_{lim}$ even if the subcooling was low. At liquid temperature of 70°C it was 336°C. It is possible to draw a conclusion about the intensifying effect of the submerged impingement jet on the heat transfer process.
Conclusions
Experiments with submerged jet are of particular interest. Jet cooling has long been used in manufacturing processes, e.g., for heat-resistant rail lining, for cooling of heat-loaded elements of radio-electronic equipment, etc. It is planned to construct an approximate model describing the effect of the jet on the destruction of the vapor film on the basis of such experiments.

We assume that the jet mechanically influences the vapor film, makes it thinner, and as a result, the number and total area of contact of the liquid with protrusions of surface roughness increase. An increase in the number of such contacts intensifies the heat transfer process, and, consequently, reduces the cooling time. An intensive heat transfer regime occurs during the action of a submerged jet and at a water fraction in mixtures over 50%. It is noteworthy that similar results have been obtained in experiments at elevated pressures.

Acknowledgments
This study was conducted at the National Research University “Moscow Power Engineering Institute” and financially supported by the Russian Science Foundation, Grant No. 20-79-10363.

References
[1] Moreaux F, Beck G and Archambault P 2010 Quenching Theory and Technology ed Liseic B. Tensi et al (Boca Raton, FL: CRC) 10 289
[2] Yagov V V, Zabirov A R and Kanin P K 2018 International Journal of Heat and Mass Transfer 126 823–30
[3] Leocadio H, Van Der Geld C W M and Passos J C 2018 Physics of Fluids 30 122102
[4] Cardenas R and Narayanan V 2012 International journal of heat and mass transfer 55 4217–31
[5] Kanin P K, Gubanova T A, Zabirov A R, Shcherbakov A V and Yagov V V 2021 3rd International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE) 1–5
[6] Kanin P K, Ryzantsev V A, Lexin M A, Zabirov A R and Yagov V V 2018 J. Phys.: Conference Series 980 012029
[7] Lexin M A et al. 2020 High Temperature 58 369–76
[8] Zabirov A et al. 2020 Experimental Thermal and Fluid Science 118 110130