The influence of anionic surfactant in water on the quenching process

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Abstract. Understanding the patterns of heat transfer during quenching is important for many technical applications. Of particular interest is the boiling regime, which is characterized by high intensity and occurs at surface temperatures exceeding the temperature of attainable liquid superheat. This work is aimed at studying the effect of surfactants on the onset of intense heat transfer during quenching. For this, experiments were carried out on quenching spheres made of different metals (nickel, stainless steel and zirconium) in water with different concentrations of surfactants. The surfactant was alkylbenzene sulfonate, the concentration of which varied from 0.1 to 2%. The analysis of the obtained cooling thermograms revealed the influence of not only the surfactant concentration on the beginning of the intensive cooling mode, but also the state of the heat transfer surface.

1. Introduction

The high heat transfer rate associated with fine fragmentation of the liquids causes rapid vaporization of the cold liquid and the resulting high pressure mixture expands against the low-pressure surroundings. Since this process has the potential for releasing destructive mechanical energy and high pressure load to the system, it has been a safety concern in severe nuclear reactor accidents as well as many industrial accidents such as in metal foundries and paper mills. One way of studying the suppression of steam explosions has been the change of the physical properties of water; in particular, viscosity and surface tension. These properties were altered by dissolving small amount of additives such as polymers and surfactants. A number of studies have been reported on the effects of such additives on the suppression of vapor explosions. The studies of surface tension effects [1-4] indicate that dilute solutions of surfactants have a mitigating effect on both spontaneous and triggered vapor explosions, but there has been no observation of complete suppression of the explosion. Also it was reported that the surfactants rather increased the efficiency of explosions in a certain range of coolant temperature (~20 °C) [2].

In work [5] it was noted that density and viscosity of coolant liquid practically do not change with small additives of surfactants, while the surface tension changes significantly. In addition, the critical heat transfer is affected by the linear size of the sample. So, for thin wires, the critical heat flux increases with the increase in the concentration of surfactants, and for large bodies, for example, a 12 mm ball used in work [5], the critical heat flux decreases. Experiments have shown a decrease in critical heat flux when surfactants are added to water. In addition, there was a slight decrease in the minimum film boiling temperature, and an increase in the quenching time for surfactant solutions in comparison with pure water.
In work [6] comprehensive studies oriented at studying the effect of adding various substances to the water on the quenching process were carried out. Various salts, complex carbohydrates (sugar), surfactants, and ionic liquids were used as impurities. The authors found that the concentration of surfactants does not significantly affect the Leidenfrost temperature, which is due to the fact that the concentration in the volume of the solution differs from the concentration at the interface between liquid and vapor.

The influence of the addition of surfactants on the quenching process of vertical cylindrical samples (50x10 mm) in water was investigated at work [7, 8]. In comparison with pure water, cooling in aqueous surfactant solutions is characterized by lower values of minimum temperature of film boiling regime and critical heat flux, and, as a result, by longer cooling. The authors assume that the main reason for this effect is to reduce the surface tension and increase the stability of the liquid-vapor interface.

This work is aimed at the experimental study of the effect of surfactants on the temperature of the beginning of the intensive boiling regime (minimal film boiling temperature or Leidenfrost temperature), which in the text will be referred to as the transition temperature $T_{tr}$.

2. Experimental facility
Basing on the results of previous studies [9-14] main purpose of our experiments was to study the effect of changing of coolant surface tension in quenching process.

The experimental unit created in 2013 allows to conduct experiments in a wide range of coolants temperatures (from -200 °C to +200 °C) and pressure (up to 1.5 MPa). The experiment consists in heating the sample to a predetermined temperature and then immersing it into the test liquid.

In all our experiments spheres 40 mm in diameter from nickel, stainless steel and zirconium are used as the tested sample. Several thermocouples located at surface of ball at different polar (90, 135 and 180°) angle and one located in center. Surfactant solutions and pure distilled water were used as coolant liquid. All experiments were carried out at atmospheric pressure. Coolant temperature ranged from 50 to 90 °C. Sulfanol (alkylbenzene sulfonate) was used as anionic surfactant. The following mass concentrations were selected: 0.1, 0.25, 0.5, 1 and 2%. Figure 1 shows isotherm of surface tension of aqueous surfactant solution of sulfanol with different sulfanol mass concentration at border with air.

![Figure 1. Isoterm of surface tension of aqueous solution anionic surfactant (sulfanol) at border with air.](image)

3. Results and discussion
The main primary results of the experiments are thermograms of cooling. Typical thermogram of cooling process presented at figure 2 gives change in the temperature in the center of the tested sample and at several points of its surface over time of cooling process. This figure sows three typical cooling modes. At the beginning of cooling process (0-16 s) there is stable film boiling which is characterized
by low heat transfer coefficient. Between 16 and 18 sec there is intensive cooling regime with high heat transfer coefficient. After 18 sec it was observed cooling by nucleate boiling mode and natural convection.

In many experiments the intensive cooling regime occurred almost simultaneously over the entire surface of the sphere. Therefore the value of transition temperature $T_{tr}$ (transition between film boiling and intensive cooling regime) was taken as the average over three surface thermocouples.

At figures 3-5 presented transition temperature as dependence of liquid temperature and sulfanol concentration for different sphere materials. It can be seen from the figures that surfactant additions lead to a decrease in $T_{tr}$.

**Figure 2.** Thermogram of cooling (material of tested sample – nickel; diameter of tested sample – 40 mm; coolant – 0.25% water-sulfanol solution; coolant temperature – +60 °C).

**Figure 3.** Transition temperature $T_{tr}$ for different coolant temperature and surfactant concentration (material of tested sample – nickel; diameter of tested sample – 40 mm).
Figure 4. Transition temperature $T_{tr}$ for different coolant temperature and surfactant concentration (material of tested sample – zirconium; diameter of tested sample – 40 mm).

Figure 5. Transition temperature $T_{tr}$ for different coolant temperature and surfactant concentration (material of tested sample – stainless steel; diameter of tested sample – 40 mm).

During experiments, when nickel and zirconium were used as material of tested samples, layer of oxide film was detected on its surface. In additional as tests were carried out contaminations precipitated on samples surface from solution. This fact affected on the intensive cooling regime in addition to sulfanol concentration.

The transition temperature was significantly lower in experiment with polished surface of tested sample than in experiment with oxidized surface. For purity of comparison distillated water without surfactant was used as coolant in both experiments. From data obtained in these experiments it can be concluded that there is an effect of cooling surface properties on the intensity of the cooling process.

Values of transition temperatures $T_{tr}$ obtained in experiments with surfactant solutions as coolant
are mainly between ones in experiments with pure water as coolant for the polished and oxidized surfaces of tested samples, except for the results at high subcooling level.

The growth of the oxide film was not so significant for stainless steel sphere. It can affect value of transition temperature at high subcooling level. As it is shown at figure 5 when subcooling level lower than 26 °C increase in surfactant concentration entails decrease in $T_r$ as well as samples from nickel and zirconium. At lower coolant temperatures on contrary increase of count of sulfanol in solution leads to increase in transition temperatures.

4. Conclusion
Experiments were carried out on samples of different materials (stainless steel, zirconium and nickel), on pure water and aqueous solutions of surfactants of different concentrations (0.1 - 2%) in a wide range of liquid subcooling ($50 > \Delta T_{sub} > 0$ K). An analysis of the experimental results made it possible to formulate the following conclusions:

- Both during quenching in pure water and during quenching in surfactant solutions, an increase in $T_r$ with increasing subcooling is observed in all samples;
- There is a dependence of $T_r$ on the thermophysical properties of the metal. If we compare the $T_r$ obtained on “fresh” nickel, steel, and zirconium, then the minimum $T_r$ values are observed on the metal with the highest thermal effusivity coefficient, i.e. on nickel. The state of the surface of the body to be cooled (contamination, oxidation) has a strong effect on the quenching process;
- Almost always, when cooled in surfactant solutions, $T_r$ is lower than when quenched in pure water throughout the entire $\Delta T_{sub}$ range. This is most likely caused by the stabilization of the liquid-vapor interface and a decrease in the surface tension coefficient.

It should be noted that the experiments performed are still of a qualitative nature. To more accurately determine the effect of surfactants, experiments with minimal surface oxidation and contamination are required.

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