Calculation analysis of the processes of boric acid droplet entrainment during WWER emergency cooling

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Abstract. This paper presents results of the calculation analysis of processes of droplet entrainment of boric acid by steam flow at a loss of coolant accident (LOCA) on nuclear power plant (NPP) with WWER. A review of the available literature data on the research of this process is presented. It has been found that the existing data do not cover all the parameters, such as temperature, pressure and acid concentration, which are characteristic for a possible emergency situation at NPP with WWER. The dependence obtained by analysis allows estimating the size of droplet entrained by steam flow during an emergency process in WWER reactor plant with operation of a complex of passive safety systems.

1. Introduction

One of the most actual tasks faced today by the nuclear power industry is to ensure the safety of modern NPP to prevent accidents that can have a negative ecological impact on the environment. For example, in the project of WWER-TOI reactor unit safety of the reactor during LOCA is provided by the operation of passive safety systems (PSS). They ensure heat removal from the core by successive supply of boric acid solution with a concentration of 16 g kg⁻¹ to the reactor from the hydro accumulators systems of the first, second and third stages, as well as supply condensate from the steam generators operating in the condensation mode [1]. At this time the core is in a boiling mode, therefore due to the evaporation of the coolant and operation of passive systems, the increase of the amount of boric acid in the core is possible [2]. As a result, the conditions of its crystallization and further deposition in the lower part of the reactor vessel can be achieved. This, in turn, can lead to deterioration of the heat removal from fuel elements. However, this process can be slowed down as a result of entrainment of droplets of boric acid with steam leaving the core and entrainment of boric acid due to the solubility of steam.

Consequently, the study of boric acid removal from the core has a great practical importance for the analysis of possible accidents at NPP with a new generation of WWER equipped with passive safety systems.

A review of available studies of boric acid solubility in steam [3-7] has shown that the results presented there do not cover the entire range of parameters (temperature, pressure and acid concentration) typical for a potential accident on NPP with WWER. Thereby, experimental studies of the solubility of boric acid in steam in a wide range of concentrations and at different pressures have been performed at JSC «SSC RF – IPPE» [8]. The dependence of the change in the distribution coefficient of boric acid between phases on its concentration in the core model has been obtained.
Studies of droplet entrainment process were carried out by various researchers [9-13]. For example, in [9] results of experiments on the study of the process of long-term boiling of boric acid carried out in Finland on the REWET-II test facility are presented. The volumetric scale of this facility is 1:2333 relative to WWER-440 reactor, and the height scale is 1:1. The main purpose of the experiments was to determine the concentration of boric acid in the core and pressure chamber, as well as in the outgoing steam. Experiments have shown that in the core simulator it is possible to achieve such high concentrations of boric acid, which lead to its crystallization and blocking the circulation of the coolant.

Also it was shown in [9] that droplet entrainment affects the rate of increase of boric acid concentration in the reactor. In the tests without a separator to limit a droplet entrainment, the concentration of boric acid in the core simulator reached the equilibrium level below the saturation level and crystallization was not observed. The reason for this was that the steam carried away the same amount of boric acid solution that came with water. In the test with a separator on the steam removal line, the concentration of boric acid reached the saturation level after 14 hours.

Experimental studies of droplet entrainment of moisture and separation of steam were performed in the Soviet Union within justification of efficiency of steam turbine plants. Generalizing dependences characterizing the motion of a two-phase flow (including drops terminal velocity) obtained on the basis of analysis of these tests are presented in [10].

Papers [11, 12] present the results of computational-experimental studies of droplet entrainment of boric acid for the reactor CAP-1400. The experiments were carried out on the FATE test facility, built with a scaling ratio of 1:1. The test facility includes pipelines of the fourth stage Automatic Depressurization System (ADS-4) and hot leg of primary circuit made of transparent acrylic glass. The experiments were carried out at a pressure of 0.1 MPa. The processes of entrainment of concentrated boric acid solution with steam through the pipeline of ADS-4 system connected to the hot leg of the primary circuit were investigated. Boric acid solutions with various additives were used in the experiments. As a result of the calculation and experimental studies, it was concluded that the capture of boric acid droplets was not as intense as when using distilled water. This means that the presence of H$_3$BO$_3$ and other impurities in the water has a significant impact on the process of droplet entrainment.

Thus, based on analysis of publications on droplet entrainment, it can be concluded that the studies were carried out at parameters not typical for an accident at NPP with WWER with operation of passive safety systems. This implies the need to perform experimental and computational studies of the process of boric acid droplets entrainment in relation to WWER operating in emergency boiling mode.

The main task of this research is to determine the magnitude of boric acid droplets entrainment in an accident. To achieve this purpose it is necessary to solve the following problems:

- to carry out calculation analysis of mass transfer processes in WWER reactor facility;
- to determine the terminal velocity of boric acid droplets and the maximum droplet diameter that can be carried away by the steam flow.

2. Calculation analysis
Steam separated from the boiling water of the reactor core is not a dry saturated steam, because it contains a certain amount of moisture droplets. This moisture enters the steam flow during the crushing of liquid during bubbling, destruction of jets and rupture of shells of steam bubbles. As was mentioned above, the entrained moisture leads to a decrease in the concentration of boric acid in the coolant and allows slowing down the processes of its crystallization and accumulation in the reactor core. Therefore, it is necessary to know the conditions under which droplets entrainment takes place.

The process of crushing the liquid is accompanied by the formation of droplets of various sizes. Larger drops under the influence of the initial kinetic energy obtained in the fragmenting process are thrown to a greater height. The thrown drops are either carried away by a stream of steam, or fall back on an evaporation surface. If the height at which a drop is thrown is greater than the height of the steam space or approximately equal to it, then such a drop can be tightened into steam pipes (where the steam velocity are much higher than in the steam space of the vessel) and taken out of the reactor. In addition, sizes of drops that can be transported by a stream in the steam space of the reactor are also carried away.
As it known, drops of liquid are carried by the flow of steam when its superficial velocity \( w_{0''}\) is higher than the terminal velocity \( w_{\text{ter}} \)\[10\]. Under the terminal velocity we understand the relative speed of a drop, at which the frictional forces balance the weight of the drop:

\[
w_{\text{ter}} = \left( \frac{4 g d_{\text{drop}} \bar{\rho} - \rho'}{3 \bar{\xi} \rho'} \right)^{1/2},
\]

where \( \bar{\xi} \) is the coefficient of resistance, depending on the Reynolds number; \( g \) is the acceleration of gravity, m s\(^{-2}\); \( d_{\text{drop}} \) is the drop diameter, m; \( \rho' \) and \( \rho'' \) are the densities of water and steam, respectively, kg m\(^{-3}\).

If the terminal velocity is more than superficial velocity of steam \( w_{\text{ter}} > w_{0''} \), then drops will fall back on the evaporation surface \[10\]. For values of Reynolds number \( \text{Re} < 2 \) the coefficient of resistance \( \bar{\xi} \) can be determined by dependence

\[
\bar{\xi} = \frac{24}{\text{Re}},
\]

where \( \text{Re} = \frac{w_{0''} d_{\text{drop}}}{\nu} \), \( \nu \) is an coefficient of kinematic viscosity.

Within the range \( 10^3 < \text{Re} < 2 \times 10^5 \) the coefficient of resistance \( \bar{\xi} \) can be taken equal to \(~0.4\) and if the values of \( \text{Re} \) number are in the range from 2 to \( 10^3 \) then values of \( \bar{\xi} \) are determined by the dependence presented in \[10\].

The superficial velocity of steam in a reactor’s vessel during LOCA is equal to:

\[
w_{0'} = \frac{Q'}{S},
\]

where \( Q' \) is the volumetric flow rate of steam at the outlet of the core, m\(^3\) s\(^{-1}\); and \( S \) is the flow cross section of reactor vessel for steam rising from the core, m\(^2\).

The volumetric flow rate of steam through the core can be determined by the formula:

\[
Q' = \frac{N_{\text{res}}}{r \rho},
\]

where \( N_{\text{res}} \) is the power of core residual heat, \( r \) is the evaporation heat, J kg\(^{-1}\).

The value of the residual energy release can be calculated according to the Wei-Wigner formula:

\[
N_{\text{res}} = 6.5 \times 10^2 N_0 \tau_c^{0.2},
\]

where \( N_0 \) is the nominal thermal power of the WWER-1200 reactor, MW, and \( \tau_c \) is the time after the start of the accident, s.

Using data on the inner diameter of the shell of the protective tube unit (PTU), and the number of these tubes and their diameters, we determine the flow cross section for the steam rising from the core:

\[
S = \frac{\pi d_{\text{PTU}}^2}{4} - n_1 \frac{\pi d_{\text{CPS}}^2}{4} - n_2 \frac{\pi d_{\text{IMS}}^2}{4},
\]

where \( d_{\text{PTU}} = 3.3 \) m is the inner diameter of PTU; \( d_{\text{CPS}} = 0.18 \) m is the diameter of the protective tube of the control and protection system (CPS); \( d_{\text{IMS}} = 0.108 \) m is the diameter of protective tube of the in-core monitoring system (IMS); and \( n_1 = 61 \) and \( n_2 = 60 \) are the numbers of protective tubes of CPS and IMS, respectively.

Earlier it was noted that during an accident, as a result of the joint operation of passive safety systems, the steam generator is transferred to the mode of condensation of steam coming from the core. According to the calculations presented in \[15, 16\], in this case the pressure in the primary circuit will be in the range 0.2-0.5 MPa. For comparison the terminal velocity of droplets and the superficial velocity of steam flow will consider three fixed pressure values from the range: 0.2, 0.3 and 0.5 MPa.
In case of LOCA after the emergency shutdown of a reactor, the thermal power of the core decreases sharply and, due to the rupture of main circulation pipeline, in a few tens of seconds the pressure in the primary circuit falls down to the level of 0.5 MPa. Therefore, in the following calculations $\tau_c = 10$ s was taken as initial time.

Substituting the values from (4) - (6) into the formula (2), we can calculate the superficial velocity of steam above the core $w_0'$. Comparison of this velocity with the terminal velocity calculated by formula (1) for droplets of different diameters is shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** The dependence of the superficial steam velocity and the terminal velocity on the power of residual heat at different droplets diameters. a – $p=0.2$ MPa, b – $p=0.3$ MPa, c – $p=0.5$ MPa.

Analysis of figure 1 confirms the possibility of boric acid droplet entrainment. The parameters of the accident have a decisive influence on the process of droplets entrainment. On the one hand, this process will weaken over time, as the decay power is reduced. At the same time, as the pressure in the reactor decreases, the steam density decreases too. This leads to an increase in both the volumetric flow rate and superficial velocity of steam. As a result, the kinetic energy of the steam flow increases, which allows it to carry away heavier and larger drops of liquid.

Thus, as can be seen from figure 1, droplets can be carried away by the steam flow if their terminal velocity not exceeds the superficial velocity of steam. Equating terminal velocity of droplets and the
superficial velocity of steam, it is possible to determine the maximum diameter of droplets which can be carried away by steam flow in dependence on the decay power and pressure in the primary circuit. The figure 2 shows changes of the maximum diameters of the droplets carried away by the steam flow as the decay power decreases at different pressure values in the primary circuit.

![Figure 2](image)

Figure 2. Dependence of the maximum size of droplets entrained from the core on the decay power and primary circuit pressure.

The dots in figure 2 are denoted the maximum diameters of droplets carried away by the rising steam flow. They have been obtained from the analysis of figure 1. These dots with an accuracy of 15% can be described by the following formula:

$$d_{\text{max}} = (4.02 \times 10^{-3} e^{-12.8p}) N_{\text{rev}}^{(2.23p+1.38)}$$

where $p$ is the pressure in the primary circuit, MPa.

In the analysis it was assumed that the surface tension of the liquid has no effect on the size of the droplets entrainment. However, it does have a significant effect on this process and therefore, for a more accurate determination of the value of droplets entrainment of the boric acid for the conditions of the accident at WWER-1200 reactor, experimental studies are necessary.

Conclusion

In “SSC RF – IPPE” JSC, a computational analysis of droplet entrainment process has been performed for the case of WWER loss of coolant accident. The results of analysis allowed determining the maximum size of liquid drops that can be carried out from WWER core with the flow of steam-water mixture into the steam generator. It is established that the process of droplets entrainment is affected by the decay power, the pressure in the reactor and the surface tension of boric acid.

To reduce the conservativeness of the results obtained, it is necessary to carry out an experimental measurement of the surface tension of the $\text{H}_3\text{BO}_3$ solution with the parameters typical for an accident with WWER.

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