Determination of the main parameters of the process of boric acid droplet entrainment from the WWER reactor in case of an accident

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Abstract. The article presents the results of a calculation study of the process of mass transfer of boric acid from a WWER reactor in the event of an accident. An analysis of the literature data in this field of study was carried out. As a result, it was found that studies of the mass transfer of boric acid were performed with parameters not typical for the emergency operation of passive safety systems of nuclear power plants with WWER. The results of the calculation of the main parameters in the WWER reactor in the event of an accident with a rupture of the main circulation circuit are shown. The calculation analysis allowed us to determine that the maximum diameter of the droplets entrained by the steam is in the range 0.11-0.23 mm.

1. Introduction

In the event of a possible emergency with a rupture of the main circulation pipeline (MCP) [1], activation of the hydro accumulators' systems of the first (HA-1), second (HA-2) [2] and third (HA-3) stages occurs sequentially. As a result, a solution of boric acid with a concentration of 16 g/kg is supplied to the WWER-TOI reactor within 72 hours [3]. Besides, condensate from three non-emergency loops are transferred to the reactor from the steam generators (SG), which are put into emergency operation mode due to the functioning of the passive heat removal system (PHRS) [4]. The mass transfer processes occurring in the WWER reactor in an accident with loss of coolant (LOCA) are shown in figure 1.

Due to the depressurization of the reactor and a sharp decrease in pressure in the primary circuit, the core goes into a boiling state. Accordingly, taking into account the low concentration of acid in the steam leaving the reactor [5], it is possible to increase the concentration of boric acid in the core coolant and achieve conditions for its crystallization on the elements of the internal components of the core and the outer surface of the fuel rods, which can lead to deterioration of heat removal [6, 7]. One of the most critical factors affecting the concentration of $\text{H}_3\text{BO}_3$ in the core is the drop entrainment of boric acid with steam [8]. It is also known that the presence of impurities in the primary circuit steam significantly affects the steam generator's efficiency in emergency condensation mode [9,10]. For a correct estimation of the effect of boric acid on the operation of SG in emergency condensation mode, it is necessary to know its mass is entering the tube bundle. To calculate the amount of boron that has left the core, it is necessary to determine the maximum size of drops of boric acid, leaving the reactor due to droplet entrainment.
Figure 1. The scheme of mass transfer processes in the WWER in the event of LOCA: 1 – core, 2 – reactor shaft, 3 – fuel assembly bottom nozzle, 4 – fuel assembly, 5 – pipe of core flooding system, 6 – main circulation pipeline (MCP) rupture, 7 – cold branch of MCP, 8 – hot branch of MCP, 9 – steam space of the emergency reactor, 10 – steam generator, 11 – steam line of PHRS, 12 – condensate line of PHRS, 13 – non-condensable gases discharge line, 14 – HA-1 vessel, 15 – HA-2 vessels, 16 – HA-3 vessels, BS – boric acid solution, SGM – steam-gas mixture, DE – droplet entrainment.

There are several papers devoted to studies of mass transfer of boric acid in steam in the literature. In [11], the results of experiments to determine the solubility of boric acid in steam are presented. The dependence of the distribution coefficient between phases on the concentration of acid in solution was obtained. Also, the effect of the pH of a boric acid solution on the value of this coefficient was found. In [12], the mass transfer of metaborates with water steam was studied at a fixed temperature, concentration in solution, and with different pressures. As a result, the dependence of the boron's volume concentration in the gas phase on pressure was determined. It was found that with increasing pressure, the concentration of acid in the steam also increases. Similar studies dedicated to boron entrainment from sodium borate and boric acid solutions are also presented in [13]. As a result, correlations with concentration, temperature, pH value, and some other parameters were obtained. It was found that the concentration of boron in the steam can be about several percent of the concentration of boron in the solution.

In the study [14], the influence of the presence of droplet entrainment of boric acid on the processes of its accumulation in the core of an emergency reactor was determined. In experiments with a moisture separator, a supersaturation of the solution occurred, and crystallization of boric acid began. In [15, 16], the results of experiments on the droplet entrainment of boric acid from the hot branch of the main circulation circuit of the CAP-1400 reactor through the auxiliary pipeline of the ADS-4 safety system are shown. It was found that the presence of boric acid in the coolant significantly reduces the total fluid flow due to droplet entrainment.

Thus, based on the analysis of the papers, it can be concluded that studies of the mass transfer of boric acid were performed with parameters not typical for the emergency operation of passive safety systems of promising nuclear power plants with VVER. This result poses the task of conducting experimental and calculation studies of the droplet entrainment of boric acid.
2. Determination of the main parameters in a WWER reactor during an accident

During an accident with a rupture of the main circulation circuit, the pressure in the reactor rapidly decreases, the effluent coolant instantly boils, evaporates and enters the volume of the containment. Almost all boric acid entering the reactor from the HA-1 system in the first seconds after the accident is also poured into the containment and does not take part in the processes of mass transfer in the core. Therefore, for the simulation, the time range after 1000 seconds of an accident was selected, when the pressure in the primary circuit begins to stabilize at a new level.

To assess the rate of evaporation of the coolant and determine the speed and flow rate of steam, it is necessary to know the power of heat generation in the core after the accident. Given that the rated power of the WWER-TOI reactor is $N_0 = 3300$ MW, the law of residual energy release can be written as follows:

$$N_{res} = 6.5 \cdot 10^{-2} \cdot N_0 \cdot \tau_s^{-0.2} = 21.45 \cdot 10^7 \cdot \tau_s^{-0.2},$$  \hspace{1cm} (1)

The accident time $\tau_s$ is in the range from 1000 to 259200 seconds, i.e., within three days of the emergency process.

Previous calculations showed that during the accident, the pressure in the core would be in the range of 0.2-0.5 MPa. The law of pressure change over time during the emergency process can be determined by approximating the calculated data from [17]:

$$P(\tau_s) = 1.9266 \cdot \tau_s^{-0.184} \hspace{1cm} (2)$$

Steam flow rate at the outlet of the core can be determined from the following relationship:

$$Q^* = \frac{N_{res}}{r \cdot \rho^*},$$  \hspace{1cm} (3)

where $r$ is the heat of vaporization, J/kg; $\rho^*$ is steam density on the saturation line, kg/m$^3$.

To assess the speed of the steam rising in the reactor vessel, it is necessary to know the flow rate of the vessel at the level of the axis of the hot nozzles, taking into account the presence of the reactor internals. Knowing the inner diameter of the shell of the protective tube block, the number of pipes, and their diameters, the flow area for the steam generated in the core was determined as $F = 4.46$ m$^2$.

Then the superficial steam velocity can be calculated by the following equation:

$$w_0 = \frac{Q^*}{F}. \hspace{1cm} (4)$$

The mass flow rate of steam, which is independent of the pressure in the reactor, can be determined by the following formula:

$$G = Q^* \cdot \rho^*, \hspace{1cm} (5)$$

where $Q^*$ is the volumetric flow rate, m$^3$/s; $G$ is the mass flow rate, kg/s.

To calculate the volumetric flow rate and mass flow rate of steam for a given law of pressure change during an accident, it is necessary to obtain dependencies for the densities of water and steam by the time, kinematic viscosity and heat of vaporization using the tables of thermophysical properties [18]:

$$\rho^w(\tau_s) = 896.43 \cdot (1.9266 \cdot \tau_s^{-0.184})^{-0.032} \hspace{1cm} (6)$$

$$\rho^s(\tau_s) = 4.9314 \cdot (1.9266 \cdot \tau_s^{-0.184})^{-0.9185} \hspace{1cm} (7)$$

$$\nu(\tau_s) = 2 \cdot 10^{-7} \cdot (1.9266 \cdot \tau_s^{-0.184})^{-0.242} \hspace{1cm} (8)$$

$$r(\tau_s) = 2 \cdot 10^6 \cdot (1.9266 \cdot \tau_s^{-0.184})^{-0.047} \hspace{1cm} (9)$$

where $\nu$ is the kinematic viscosity, m$^2$/s; $\rho^w$ is water density on the saturation line, kg/m$^3$.

The obtained dependencies of the change of the superficial speed and mass flow rate of steam in case of emergency process are presented in figures 2 and 3.
Determination of the dependencies describing the main parameters during the WWER reactor operation in a boiling emergency mode allows to proceed with the determination of the effect of drop entrainment on the change in the concentration of boric acid in the reactor.

3. Determination of the maximum diameter of the soaring drops

The moisture content of the steam is determined by the number of droplets being thrown to the height where the steam outlet channels (hot reactor nozzles) are located and transported by the steam flow from the steam space. At high altitudes of the steam space, transportation has the main effect on the droplet entrainment. However, the ratio between the discharged and the transported moisture substantially depends on the flow rate (steam load). The height of the drop of transported moisture droplets is not limited. Conventionally, it can be taken equal to the height at which the absolute velocity of the drops becomes equal to the steam's velocity. The further movement of the droplet is determined only by the dynamic effect of the steam flow on it. Thus, the transported moisture of the steam does not depend on the height of the steam space. The height between the cold and hot nozzles of the WWER reactor exceeds 1 m, taking into account the boiling of the boric acid solution in the core at the level of cold nozzles, the moisture of the steam will depend only on the transported moisture. To determine it, we need to know the size of the soaring drops.

In [19], it was noted that droplets are freely transported by the flow when its superficial velocity is higher than the soaring speed \( w_s \). Under the soaring speed we understand the relative velocity of the droplet, at which the friction forces balance the weight of the droplet.

\[
    w_s = \sqrt{\frac{4}{3} \cdot \frac{g \cdot d_{drop}}{\xi} \cdot \frac{\rho - \rho^*}{\rho^*}}, \quad (10)
\]

where \( \xi \) is the coefficient of friction; \( g \) is the gravitational acceleration, m/s\(^2\); \( d_{drop} \) is droplet diameter, m.

If the soaring speed is greater than the superficial steam velocity and the height at which the drop is thrown is less than the height of the steam space, the drop will fall back onto the evaporation mirror.

The dependence of the coefficient of friction on the Reynolds number lying in the range from 2 to 1000 (this condition is satisfied in this case) can be found in [19].

\[
    \xi(Re) = \frac{25.3}{Re^{0.6}}, \quad (11)
\]

where \( Re = \frac{w_0 \cdot d_{drop}}{v} \).

\[
    \xi(Re) = \frac{25.3}{Re^{0.6}}.
\]
To find the dependence for calculating the maximum diameter of the soaring droplets $d_{\text{drop}}$, equate the superficial steam velocity (4) with the soaring speed (10), substitute (3) in (4), as well as (11) and (12) in (10), and it can be obtained that the dependence of the change in the size of the soaring droplets on the power of the residual energy release is the following:

$$d_{\text{drop}}(N_{\text{res}}) = (N_{\text{res}})^{\frac{7}{8}} \cdot C_1$$

(13)

where

$$C_1 = \left( \frac{25.3 \cdot \nu^{0.6}}{4 \cdot \frac{3}{g \cdot \rho - \rho}} \right)^{\frac{5}{8}} \cdot \frac{1}{(r \cdot \rho' \cdot F)^{\frac{7}{8}}}$$

To obtain the dependence of the droplet size on time, substitute the law of residual energy release (1) into (13):

$$d_{\text{drop}}(\tau_s) = (\tau_s^{-0.2})^{\frac{7}{8}} \cdot C_2$$

(14)

where

$$C_2 = \left( \frac{25.3 \cdot \nu^{0.6}}{4 \cdot \frac{3}{g \cdot \rho - \rho}} \right)^{\frac{5}{8}} \cdot \left( \frac{6.5 \cdot 10^{-2} \cdot N_0}{r \cdot \rho' \cdot F} \right)^{\frac{7}{8}}$$

In order to obtain the dependence for calculating the diameter of the droplets, taking into account the law of pressure change, it is necessary to substitute relations (6) - (9) into equation (14).

$$d_{\text{drop}}(\tau_s) = (\tau_s^{-0.2})^{\frac{7}{8}} \left( \frac{25.3 \cdot \nu(\tau_s)^{0.6}}{4 \cdot \frac{3}{g \cdot \rho(\tau_s) - \rho(\tau_s)}} \right)^{\frac{5}{8}} \cdot \left( \frac{6.5 \cdot 10^{-2} \cdot N_0}{r(\tau_s) \cdot \rho'(\tau_s) \cdot F} \right)^{\frac{7}{8}}$$

(15)

The dependence describing the maximum diameter of droplets carried away from the reactor is shown in figure 4. As it can see from the figure, the maximum diameter of the droplets entrained by the steam is in the range 0.11–0.23 mm.

![Figure 4. The dependence of the change in the size of the soaring drops, taking into account the given law of pressure.](image-url)
4. Conclusion
In IPPE JSC, the calculation of the main parameters of boric acid droplet entrainments in the WWER reactor in the event of an accident with a break in the main circulation circuit was performed. The calculation analysis allowed us to determine the range of maximum diameter of the soaring drops of boric acid, carried away by the steam flow. The results can be used to safety justification of WWER reactors equipped with a complex of passive core flooding systems.

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