Experimental study of heat transfer processes during the operation of WWER steam generator in emergency mode on a single-tube model

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Abstract. The paper presents the results of experimental research of the heat transfer processes during the operation of a WWER steam generator in emergency condensation mode. The experiments are carried out at a research facility with a test section in the form of a single-tube model of a steam generator. The geometric characteristics of the tube and the main research parameters, such as temperature and pressure, are similar to the real steam generator. Several stages of research are planned: with pure water steam, with a fixed concentration of boiling boric acid and with a variable concentration of acid in the solution. The results of the first series of experiments performed on pure water steam are presented. As a result of research, the heat flux density is determined, and the values of the heat transfer coefficient during steam condensation in a single horizontal tube are calculated.

1. Introduction
In the most modern Russian nuclear reactor WWER-1200, along with traditional active safety systems, new passive systems are also used. The first reactors of this project with the V-392M reactor facility are built and operated at units 6 and 7 of the Novovoronezh NPP. They use a system of passive heat removal through air heat exchangers (PHRS), as well as passive core flooding system of the first and second stages (HA-1 and HA-2) (Fig. 1.)

The passive heat removal system consists of four independent channels, one for each steam generator (SG). In a hypothetical accident with a rupture of the main circulation pipe, the passive heat removal system ensures switching of the horizontal steam generators to operate in the condensation mode. This process ensures the core make-up during 24 hours of emergency.

The steam generator operation in this mode is negatively affected by the presence of non-condensable gases in the primary reactor circuit. These include: nitrogen entering the circuit when hydraulic accumulators of the first stage are actuated, as well as products of water radiolysis and decomposition of hydrazine hydrate dissolved in water coming from the HA-2 system.

Their influence on the steam condensation processes in the tube bundle of the steam generator in emergency mode was investigated during a series of 24-hour experiments at the large-scale test facility HA-2M. They took into account not only the flow of non-condensable gases from the reactor due to gas generation in it, but also the possibility of entering the gas-vapor mixture from the containment into the reactor through a rupture of the main circulation pipeline. As a result of the analysis of experimental data it was found that the condensation power of the steam generator decreases by less than 25% on the first day of the accident [1].
Figure 1. Passive safety systems for the WWER-1200 with a V-392M reactor facility.  
1 – core, 2 – HA-1, 3 – HA-2, 4 – steam generator, 5 – main circulation pump, 6 – PHRS heat exchanger.

During the operation of passive safety systems, a solution of boric acid with a concentration of 16 g/kg enters the core from the tanks of the passive core flooding system [2]. As a result of its boiling, in addition to non-condensable gases, boric acid dissolved in steam also enters the tube bundle of the steam generator. It can adversely affect the processes of heat transfer to the secondary circuit. The concentration of acid in the steam directly depends on its content in the boiling coolant. Due to the long duration of the cooling process (at least 24 hours), the concentration of boric acid in the coolant can reach high values.

The experiments carried out at IPPE JSC show that if the concentration of H₃BO₃ in a boiling solution is 230 g/kg, then the content of boric acid in the vapor reaches 0.4 g/kg [3]. The results of the calculations show that after 24 hours of the emergency process, the concentration of boric acid in the core is about 300 g/kg [4]. One of the ways to extend the operation of WWER passive safety systems is to use additional tanks in the passive core flooding system. In this case, the concentration of boric acid in the core will be higher.

Some papers found in the literature studied the effect of boric acid on the processes of long-term cooling of the reactor core with water under pressure in a case of emergency [5–8]. In [5], the results of a review of experimental and computational studies of the processes of transfer of boric acid in the reactor core and its effect on the cooling conditions of the core were presented. It was shown that, when the crystallization conditions are reached, blocking of the flow cross-section of the fuel assemblies is possible. It leads to a significant increase in the temperature of the claddings of the fuel elements and even to an increase in the level of the dried part of the core. In [6], the results of an experimental study of the effect of boric acid on the conditions of long-term cooling of the reactor were presented. The work was performed at the REWET-II stand. The installation was a full-height 19-rod assembly with energy release at a scale of 1:349. As a result of the experiments it was found that there was no mixing of the boric acid solution, which led to the presence of a significant stratification of the concentration in height. It was also shown that the lower is the pressure, the higher is the chance of the onset of crystallization of the acid. The work [7] considered the crisis caused by the formation of a plug blocking the flow cross-section of the core. In the paper [8], the problems of heat transfer crisis during the boiling of aqueous H₃BO₃ solutions were studied. It was shown that the value of the boundary vapor content decreases with increasing concentration of boric acid.

Thus, based on the analysis of the publications, it can be concluded that the studies of the effect of boric acid on heat transfer and long-term cooling of the core do not concern the processes of steam
condensation in the tube bundle of the steam generator. So it is necessary to carry out an experimental study of the effect of boric acid on the operation of SG in the condensation mode.

2. Test facility
To study the effect of boiling of boric acid on the processes of steam condensation, a research facility “Single-tube model” was constructed at IPPE JSC. The principal diagram of the test facility is shown in Fig. 2.

![Figure 2. Principal diagram of the test facility. 1 – gas cylinder, 2 – reducer, 3 – porthole, 4 – solution preparation tank, 5 – feeding line, 6 – evaporation section, 7 – lifting section, 8 – connecting lines, 9 – model of SG single tube, 10 – single tube shell, 11 – air condensers, 12 – water seal, 13 – probe condenser.](image)

The test facility includes: a solution preparation tank (SPT), evaporation and lifting sections, a single-tube model of a steam generator (STM), two heat exchangers simulating the operation of PHRS. The main equipment of the facility is interconnected by technological lines and equipped with shut-off valves. The length of the single-tube model is 9 meters, which corresponds to the minimum length of the full-scale heat transfer tube of the steam generator. The height from the level of the boiling liquid to the line of steam extraction in the lifting section corresponds to the distance from the evaporation surface in the WWER reactor vessel to the lower generatrix of the cold branch of the main circulation pipeline. Auxiliary equipment includes: pressure and temperature maintenance systems and a boric acid solution supply system.

The steam flow rate entering the model corresponds to the flowrate in a real steam generator at different stages of the accident, taking into account the scale factor of the tube bundle.

The control and measuring devices installed in the facility allow recording the following parameters during the experiments: pressure, temperature, flow rate of the condensate, and the height of the boric acid solution in the evaporation section. The pressure is recorded using a METRAN-150-DI gauge (measurement error: up to ± 0.1% of the pressure range). Measurement of the liquid level at the bench is carried out by a METRAN-100-DD gauge (measurement error: up to ± 0.1% of the pressure range). Cable thermocouples of K type with a 1 mm diameter are used for temperature measurement (measurement error 1 °C). The sampling frequency of the measuring channels of the collection system is 4 Hz.
The principal measured values are the concentration of boric acid in the condensate at the outlet of the single-tube model and the condensation power of the single-tube model, determined by the flow of condensate formed.

3. Test procedure
The main goal of the research program is to conduct experiments to study the processes of steam condensation in a model of a steam generator tube in the presence of boric acid dissolved in steam, as well as to determine its concentration in the resulting condensate.

The experiments are supposed to be carried out in three stages: with pure water steam, with a fixed concentration of boiling boric acid, and with a variable concentration of acid in the solution. The pressure range is 0.2–0.35 MPa, which is typical for the WWER emergency with a rupture of the main circulating pipeline [9].

The following test procedure has been developed. In the case of experiments on pure steam, the required volume of water is poured into the solution preparation tank. At other stages of research, distilled water and dry boric acid are alternately supplied to the SPT, where they are mixed to prepare a solution with a given concentration of $H_3BO_3$. Next, with the help of a reducer, the gas volume of the tank is filled with nitrogen in order to establish the necessary pressure. Then the heating of the boric acid solution to a predetermined temperature starts. In parallel with this, the main elements of the facility are warmed up with the help of electric heaters: the solution supply line from the tank to the test section, the OTM shell, the evaporation, and lifting sections. After reaching the required temperature, the mixing device is switched on again, ensuring the complete dissolution of boric acid. Visual control over the state of the solution is carried out through the portholes.

After warming up, the evaporation section is filled with a boric acid solution with concentrations corresponding to the concentration in the SPT. Then, by gradually opening the needle valve on the supply line of the boric acid solution, the flowrate from the SPT is set corresponding to the steam flowrate from the test section (this leads to stabilization of the level of boiling liquid). At the same time, in order to prevent the presence of a steam-air mixture in the working equipment, the steam-air mixture is blown off from the main equipment into the atmosphere by opening the purge valves.

In parallel with the preparation of the boric acid solution, the water in the STM shell is warmed up by heaters to the saturation temperature. Then, by opening the fittings, the steam generated as a result of heat transfer from the condensed steam of the “primary circuit” to the medium of the “secondary circuit” enters the air condensers simulating the operation of the PHRS heat exchangers and returns as condensate to the volume of the single-tube model shell. After that, according to the test program, the power of the heaters on the STM shell is set to obtain the necessary temperature difference between the circuits.

Several stationary states are achieved during the experiments, characterized by a constant pressure value of the first and second circuits. During the tests, periodic condensate sampling is carried out, which allows determining the condensation power of the SG single-tube model, and during the stages of experiments with boric acid, its concentration in the formed condensate (by titration method).

4. Results of the experimental study
At the first stage of the research program, the experiments on pure water steam were carried out, and the basic values of the condensation power of a single-tube model of a steam generator were obtained.

The experiments were performed at two steam pressures: 0.2 and 0.35 MPa, corresponding to the parameters of the primary circuit of the WWER reactor in the event of a beyond design-basis accident with a rupture of the main circulation pipeline. The pressure value of the second circuit was adjusted by changing the power of the air condensers. In total, at this stage of the research, 20 stationary regimes were obtained.

The dependence of the condensation power $N$ of the single-tube model on the temperature difference between the circuits $\Delta t$ is shown in Fig. 3. As can be seen, the temperature head between the circuits
varies in the range of 1.5-4.2 °C in the experiments. It should be noted that the increase in Δt by three degrees leads to an almost five times increase in the condensation power.

In Fig. 4 the dependence of the change in the heat transfer coefficient $k$ on the temperature difference between the circuits is shown. It can be seen from the figure that, with experimental

![Figure 3. The dependence of the condensation power on the temperature difference between the circuits at different pressures. 1 – 0.2 MPa, 2 – 0.35 MPa.](image)

![Figure 4. The dependence of the heat transfer coefficient $k$ on the temperature difference between the circuits. 1 – 0.2 MPa, 2 – 0.35 MPa.](image)

parameters corresponding to the full-scale ones in WWER emergency with a rupture of the main circulation pipeline, the heat transfer coefficient is in the range of 200-1300 W/m²K. These values of $k$ suggest the presence of undeveloped boiling processes in the second circuit of the steam generator in this case.

**Conclusion**

To study the processes of heat transfer during the operation of the WWER steam generator in emergency condensation mode, the test facility was built at the IPPE JSC, and the experimental procedure was developed.

At the facility, the first stage of research using pure water steam was performed. The experiments were carried out at two primary circuit pressures: 0.2 and 0.35 MPa. During the experiments, the features of heat transfer processes during the operation of the VVER steam generator in emergency condensation mode were identified, and the values of the heat transfer coefficient were determined.

The data obtained will be used as the basis for further stages of research with boiling boric acid. Also, the experimental data can be used for calculating the simulation of emergency processes in the WWER reactor facility during the operation of passive safety systems.

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