Analysis of the influence of heat and mass transfer processes in the WWER equipment on the duration of effective operation of passive safety systems

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Abstract. The paper presents the results of an experimental study of the possibility of increasing the autonomous operation of passive safety systems of the WWER-1200 reactor facility. In the course of experiments conducted at IPPE JSC, processes that have a significant impact on the performance of these systems were studied. Non-condensing gases coming from the reactor negatively affect the operation of the steam generator in emergency condensation mode. They can significantly reduce the intensity of the condensation process and the duration of cooling the core. At a large-scale test facility HA-2M, the experiment was conducted to determine the maximum duration of a steam generator in the absence of removal of non-condensable gases from its tube bundle.

1. Introduction

The WWER-1200 reactor facility is the most modern operating Russian water-cooled water-moderated reactor. One of the significant features of this reactor is the inclusion of passive safety systems in its design [1]. Their set and ultimate heat sink medium (air or water) depend on the project. For example, the V-392M reactor facility's safety systems, constructed and operated at units 6 and 7 of the Novovoronezh NPP, include an air-cooled passive heat removal system (PHRS), as well as passive core flooding system from the first and second stages (HA-1 and HA-2).

PHRS is designed for long-term removal of residual heat from the core in various emergencies, for example, in case of a large break Loss-of-Coolant Accident (LB LOCA) with the loss of all alternating current sources. The safety system consists of four independent channels, one for each steam generator (SG). In the case of LOCA, the passive heat removal system puts the horizontal steam generators into operation in the condensation mode of the primary circuit's steam. The joint operation of PHRS, passive core flooding system from the first and the second-stage hydro-accumulators, provides for the continuous removal of residual heat from the core for 24 hours in the complete absence of power sources. The operability of these systems was confirmed in a series of experimental studies at large-scale test facilities: PSB-WWER at JSC EREC [2] and HA-2M at IPPE JSC [3].

However, according to the requirements for new-generation nuclear power plants, passive safety systems should be designed for 72 hours of stand-alone operation. To achieve this goal, it is necessary to solve several problems. They are associated with various heat and mass transfer processes in the main equipment of passive core cooling systems. One of the main tasks is to ensure the effective long-term operation of PHRS.
Non-condensable gases and boric acid dissolved in the steam coming from the primary loop of the reactor could negatively affect the operation of the SG in condensation mode and so on the effectiveness of PHRS [4]. They can significantly reduce the intensity of the condensation process in the tubes. During the first day of the accident, the operability of the steam generator is maintained by removing the steam-gas mixture from the cold header into the volume of emptying tanks of the HA-2 system. After 24 hours, the tanks are empty, so the process of gases blow-off from the tube bundle is terminated. For this reason, the power of the steam generator starts to decrease. However, this is not an instant process, and it takes some time before reaching the limit of the minimum allowable condensing power [5]. Therefore, one of the major tasks is to determine the duration of the SG operation in condensation mode after the termination of the removal of the steam-gas mixture from the tube bundle.

Thus, to determine the maximum duration of the effective operation of passive cooling systems for the core of new WWER projects, it is necessary to study condensation of steam from the steam-gas mixture in a horizontal tube bundle of a steam generator in the absence of removal of non-condensable gases. These processes were investigated at IPPE JSC in the experiment performed at the HA-2M large-scale test facility.

2. Literature review

Studies of the effect of non-condensable gases on the efficiency of heat exchangers are widely represented in the literature. In papers [6, 7], a computational analysis of condensation processes is performed at various mass fractions of non-condensable gases, pressure values, and temperature differences.

A large number of experimental studies have also been carried out. In the study, the results of which are presented in [8], the heat transfer characteristics were measured during film condensation of gas-steam mixtures in a horizontal pipe under forced convection. The influence of pressure (4–124 kPa), mass fraction of gas (0.02–32%), steam velocity (0.3–26 m/s) and heat flux (12–455 kW/m²) on heat transfer is analyzed. In paper [9], condensation of steam – air mixtures on the vessel wall were studied. As a result, the heat transfer coefficient's dependence on the mass ratio of steam and air was obtained. The influence of a large amount of carbon dioxide on the condensation of steam on a horizontal pipe [10] and a flat surface [11] in the mass fraction of CO₂ from 11.2% to 95% was analyzed. In [12], the authors investigated the effect of surface wettability on the condensation heat transfer of a gas-steam mixture on horizontal flat and finned tubes. The results of an experimental study of the processes of steam condensation at atmospheric pressure are presented in [13]. The experiments were carried out in a wide range (10-60%) of the mass content of He, N₂, and CO₂.

Another substance that can affect condensation in the tube bundle of a steam generator is boric acid dissolved in steam. It enters the steam from a coolant containing acid boiling in the core [14]. Several research works were dedicated to the study of the boric acid solubility in saturated water steam. In [15], the results of a study of the boric acid solubility in steam by the method of estimation of an insignificant part of a solution of a given concentration are presented. The studies were carried out in the pressure range from 0.1 to 20 MPa. The concentration of boric acid in water varied from 0.2 to 22 g/kg. The tests carried out at IPPE JSC have shown that if the concentration of boric acid in a boiling solution is 230 g/kg, then the content of H₃BO₃ in the steam reaches 0.4 g/kg [16].

It is necessary to know the thermophysical properties of the boric acid that affect the processes of mass transfer in the core. Experimental data on the density and kinematic viscosity of boric acid solutions in a wide range of parameters have been obtained at IPPE JSC [17].

The heat and mass transfer processes occurring in the WWER steam generator during an emergency operation have some features. These include: low heat fluxes (not more than 1.5 kW/m²), the presence of natural circulation in both SG circuits, the presence of the mutual influence of PHRS heat exchangers and steam generators. Besides, condensation occurs inside horizontal pipes of small diameter (13 mm). The review results have shown that the above-described features of the operation of a WWER steam generator in condensation mode are presented only partially in the literature, which sets the task of
carrying out experimental studies of these processes. The research was performed at the large-scale thermal-hydraulic test facility HA-2M at IPPE JSC.

3. Test facility
At the HA-2M test facility, the steam condensation processes in the presence of non-condensable gases in the tube bundle of a WWER steam generator were studied. When carrying out a research program, several 24-hour experiments were conducted. In one of them, the possibility of extending the operation of passive safety systems due to the steam generator functioning in the condensation mode without removing non-condensable gases was investigated. Fig. 1. shows a principal diagram of the test facility.

![Figure 1. Principal diagram of the HA-2M test facility. 1 – model of the containment, 2 – model of the reactor (test section), 3 – simulator of the rupture, 4 – mixing chamber, 5 – heat exchangers, 6 – heaters of HA-2 line, 7 – source of non-condensable gases, 8 – steam generator model, 9 – model of a PHRS heat exchanger, 11 – auxiliary tank (B3), 12 – steam condenser.](image-url)

The main part of the test facility is a containment model. This is a cylindrical metal vessel with a spherical bottom and a flat top cover. Outside, it is covered with thermal insulation designed to reduce heat loss. In the upper part of the model, heat exchangers-condensers are located. Their task is to condense the steam entering through the rupture simulator from the reactor model. It allows regulating the pressure in the system.

The inner part of the containment model is placed in the test section, being this is the steam-heated model of the reactor. The reactor model has two slotted nozzles, the height of which corresponds to the internal diameter of the full-scale main circulation pipe (850 mm). They are designed to simulate rupture at the inlet and outlet of the reactor.

The reactor model is connected to the steam generator model (scale 1:48). The tube bundle of the SG consists of a 248 stainless steel tubes with an average length of 10.5 m and a diameter of 16x1.5 mm arranged in 62 rows.

The steam generator model is connected to the PHRS model by steam and condensate lines, forming the natural circulation circuit.

Auxiliary equipment includes an auxiliary tank (B3); steam heat exchangers for heating water of the HA-2 system; centrifugal pumps HC1 and HC2, for supplying process water to heat exchangers and to the basic equipment; steam and water pipelines equipped with shutoff and control valves.

The length of the steam generator tubes, their diameter, height, and geometric characteristics of the tube bundle correspond to the full-scale ones. The height of the pipe simulating the rupture of a cold branch of the main circulation circuit is equal to its inner diameter (850 mm).
4. Test procedure

In the experiment, the second stage of the LOCA is simulated. It occurs after cooling of the medium of the second circuit to a temperature below that of the coolant of the first circuit. In this case, the steam generator starts the operation in the mode of condensation of steam entering the SG tube bundle from the reactor. Accidents are surmounted by the operation of PHRS and HA-2 passive safety systems. The main task of the test is to determine the condensation power of the steam generator model and the influence of possible influx of the air-steam mixture from the containment model into the reactor on it.

The test was carried out at an initial pressure of 0.35-0.39 MPa, corresponding to the pressure in the event of an accident. Before the start of the experiment, the test facility was transferred to the stationary mode. At this preliminary stage, pure steam was supplied to the test section, after warming up the equipment of the test facility, the first stage of the experiment was started by injecting non-condensable gases into the steam in the mixing chamber. Concentrations of non-condensable gases at the inlet to the test section were determined according to the calculation of the emergency process carried out in OKB "Gidropress". After passing through the reactor model, the steam-gas mixture passed through a connecting pipeline into the steam generator model, where it condensed.

Heat was removed from the SG using a simulator of the PHRS heat exchanger (Fig. 1). The gas-steam mixture was removed from the steam generator model’s cold header for 24 hours.

The steam flow-rate from the test section was used to simulate a decrease in the power of residual heat during the accident. The power control system of the water condenser provided modeling of the change in the power of the PHRS depending on the pressure in the steam generator.

After the end of the first 24 hours, the second stage of the test started. The supply of water from the HA-2 system and, at the same time, the removal of the steam-gas mixture from the cold SG header were terminated. As a result, the filling of the steam generator's tube bundle with non-condensable gases started, and its condensation power began to decrease. The experiment was finished upon reaching the minimum measurable steam generator power.

The instrumentation and automation system ensures the control of the equipment condition, as well as the registration and regulation of the parameters of the processes carried out during the experimental studies. The uncertainty of the temperature measurement channels consists of the error of amplifiers (0.8%) and the error of the calibration characteristics of thermocouples (0.1%) and is 0.81%. The uncertainty of the pressure measurement channels consists of errors of amplifiers - (0.2%), "Metran-100 DI" gauge - (0.25%), and is 0.38%. The uncertainty in measuring the steam flow rate for the test section and the steam generator model is determined by the error of the Metran-332 vortex steam flow meter and is 1.5%.

5. The results of experimental studies

The principal measured parameter in the test was the condensation power of the steam generator model. Fig. 2 shows the change in condensation power throughout the experiment. From Fig. 2, it can be seen that the condensation power of the steam generator model in the first 24 hours of the experiment decreased to 88% of the initial value \( N_0=105 \text{ kW} \). After the termination of the gas-steam mixture removal, the condensation power of the SG model fell to 22% of the initial one (approximately 20 kW). The duration of this phase of the test was 26.5 hours.

Fig. 3 shows the change in the pressure difference between circuits in the steam generator model. As shown in Fig. 3, this value did not change significantly during the first stage of the experiment. Moreover, the pressure difference even decreased by the end of 24-hour period, which indicates an increase in the efficiency of heat transfer processes in the steam generator tube bundle. By the end of the first stage of the test, the value of DP reached 51 kPa. Termination of the removal of the gas-steam mixture from the SG model cold header led to a deterioration in the efficiency of heat transfer and to an increase in the pressure drop between the circuits. This value reached 180 kPa at the end of the experiment.
Conclusion
The WWER steam generator operation in condensation mode has been investigated on the large-scale test facility at IPPE JSC. It has been found that after the emptying of the HA-2 tanks and the termination of the removal of non-condensable gases from the steam generator cold header, the duration of its operation was 26.5 hours. During this time, the condensing power of the steam generator model fell four times.

Based on the obtained experimental data, it is planned to conduct further studies on the effect of boric acid dissolved in steam on condensation processes in the tube bundle of a steam generator.

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References
[1] Efanov A D, Kalyakin S G, Morozov A V, Remizov O V, Tsyganok A A, Generalov V N, Berkovich V M and Taranov G S 2008 Proc. 16th Int. Conf. on Nuc. Eng. (Orlando) 793–9
[2] Bucalossi A, Del Nevo A, Moretti F, D’Auria F, Elkin I V and Melikhov O I 2012 Nuclear Engineering and Design 250 633–45
[3] Morozov A V and Remizov O V 2012 Thermal Engineering 59(5) 365–70
[4] Morozov A V, Remizov O V and Tsyganok A A 2010 Transactions of the American Nuclear Society 102 676–7
[5] Morozov A V, Shlepkin A S, Kalyakin D S and Soshkina A S 2017 Thermal Engineering 64(5) 329–35
[6] Dehbia A, Janasza F and Bell B 2013 Nuclear Engineering and Design 258 199–210
[7] Cha’o-Kuang C and Yan-Ting L 2009 International Journal of Thermal Sciences 48(9) 1777–85
[8] Lee W C and Rose J W 1984 Int. Journal of Heat and Mass Transf. 27(4) 519–28
[9] Murase M, Kataoka Y and Fujii T 1993 Nuclear Engineering 141 135–43
[10] Ge M, Zhao J, Wang S 2013 Applied Thermal Engineering 61(2) 334–43
[11] Ge M, Wang S, Zhao J, Zhao Y and Liu L 2018 Thermal Fluid Science 92 13–9
[12] Hu H W, Tang G H and Niu D 2015 Int. Journal of Heat and Mass Transf. 85 513–23
[13] Lu J, Cao H and Li J M 2018 Int. Journal of Heat and Mass Transf. 12(6) 559–67
[14] Morozov A V, Pityk A V, Sahipgareev A R and Shlepkin A S 2018 Journal of Physics: Conf. Series 1105 012103
[15] Styrikovich M A, Martynova O I and Tskhvirashvili D G 1985 Power Eng. New York 23(2) 127–9
[16] Morozov A V, Pityk A V, Sahipgareev A R and Shlepkin A S 2018 Journal of Physics: Conf. Series 1105 012056
[17] Morozov A V, Sorokin A P, Kalyakin D S, Sahipgareev A R and Shlepkin A S 2019 Atomic Energy 125 (3) 178–84

Figure 2. Change in the condensation power of the steam generator model on time.

Figure 3. Change in pressure difference between the circuits of test facility during the experiment.