EXPERIMENTAL INVESTIGATION OF NON-CONDENSABLE GASES EFFECT ON NOVOVORONEZH NPP-2 STEAM GENERATOR CONDENSATION POWER UNDER THE CONDITION OF PASSIVE SAFETY SYSTEMS OPERATION

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ABSTRACT

The design substantiation of the heat removal efficiency from Novovoronezh NPP-2 (NPP-2006 project with VVER-1200 reactor) reactor core in the event of primary circuit leaks and operation of passive safety systems only (among these are the systems of hydroaccumulators of the 1st and 2nd stages and passive heat removal system) has been performed based on computational simulation of the related processes in the reactor and containment. The computational simulation has been performed with regard to the detrimental effect of non-condensable gases on steam generator (SG) condensation power.

Nitrogen arriving at the circuit with the actuation of hydroaccumulators of the 1st stage and products of water radiolysis are the main sources of non-condensable gases in the primary circuit.

The feature of Novovoronezh NPP-2 passive safety systems operation is that during the course of emptying of the 2nd stage hydroaccumulators system (HA-2) the gas-steam mixture spontaneously flows out from SG cold headers into the volume of HA-2 tanks. The flow rate of gas-steam mixture during the operation of HA-2 system is equal to the volumetric water discharge from hydroaccumulators. The calculations carried out by different integral thermal hydraulic codes revealed that this volume flow rate of gas-steam mixture from SG to the HA-2 system would suffice to eliminate the “poisoning” of SG piping and to maintain necessary condensation power.

In support of the calculation results, the experiments were carried out at the HA2M-SG test facility constructed at IPPE. The test facility incorporates a VVER steam generator model of volumetric-power scale of 1:46. Steam to the HA2M-SG test facility is supplied fed from the IPPE heat power plant. Gas addition to steam coming to the SG model is added from high pressure gas cylinders. Nitrogen and helium are used in the experiments for simulating hydrogen.

The report presents the basic results of experimental investigations aimed at the evaluation of SG condensation power under the inflow of gas-steam mix with different gases concentration to the tube bundle, both under the simulation of gas-steam mixture outflow from SG cold header to the HA-2 system and without outflow. As a result of the research performed at the HA2M-SG test facility, it has been substantiated experimentally that in the event of an emergency leak steam generators have condensation power sufficient for effective heat removal from the reactor provided by PHR system.

INTRODUCTION

NPP-2006 project of nuclear power plant with water-moderated water-cooled power reactor (VVER) has been developed in the Russian Federation by State Corporation ROSATOM organizations. NPP-2006 project is a typical design of new Generation III+ reactor with improved technical and economical performances. The purpose of this project is to
achieve up-to-date safety and reliability characteristics at the same time as optimized capital investments for plant construction. The design is based on VVER plants which have proved their reliability through one thousand reactor years of failure-free operation. The project provides for use of VVER reactor with electrical power output up to 1150 MW (with possible up-rating to 1200 MW).

In respect to safety, the design implies observation of all requirements of Russian scientific and technical documentation, as well as maximum consideration for IAEA recommendations. The major distinguishing feature of the project is the use of additional passive safety systems in combination with traditional active systems. NPP–2006 is an evolutionary project based on the best solutions of the NPP–92 project. The NPP–92 project has been certified by European Utility Requirements (EUR) as related to NPP with light water reactor of new generation.

The second phase of Novovoronezh NPP (NV NPP-2) is the building site for leading units of NPP–2006 (Fig. 1). In 2007, Atomenergoproekt (Moscow) started the activities in constructing the 1st power unit of Novovoronezh NPP-2 in the framework of the Federal Target Program “Development of the Nuclear Power Industry of Russia in 2007-2010 and -2015”. Unit 1 of NV NPP-2 is scheduled for launching in 2012, Unit 2 in 2013.

The NPP-2006 project with VVER-1200 (V-392M reactor facility) provides for use of passive safety systems. They involve second-stage hydro-accumulators (HA-2 system) and passive heat removal system (PHRS). In the event of an accident with rupture of primary pipelines and loss of electric power supply sources, these systems are utilized to remove residual heat from the reactor core.

![Novovoronezh NPP-2](image)

**Figure 1. Novovoronezh NPP-2 power units**

PHRS should ensure the transition of steam generators to the regime of condensation of steam flow from the core thus providing the makeup of primary circuit. The efficiency of the system can be affected to a great extent by the presence of non-condensable gases in the primary circuit. The main sources of gases are: nitrogen dissolved in hydro-accumulators water and the processes of water radiolysis. The gases generated may plug up the steam generator pipelines thus causing significant deterioration of heat transfer.

The circuit designs considered in the project make it possible to remove non-condensable gases in the gas-steam mixture arriving from SG cold headers into the volume of second-stage hydro-accumulators. At the same time, it was necessary to ascertain if the gas removal is adequate for ensuring the design operation of SG in the steam condensation mode. For this purpose, series of experimental studies was carried out at the large-scale test facility HA2M-SG (Hydro Accumulators of 2nd stage Modernized and Steam Generator).

1. LARGE-SCALE EXPERIMENTAL FACILITY HA2M-SG

The HA2M-SG is a large-scale experimental facility designed for studying the performance of passive safety systems available in the new generation VVER reactor design. It consists of VVER steam-generator model, tank-accumulator of steam supplied from IPPE heat power plant, PHRS heat exchanger simulator cooled by service water. The main units of the test facility are connected by pipelines equipped with shut-off valves. The altitude marks of the facility are the same as for the real project design. All the facility units and pipelines are thermally insulated to reduce thermal losses. The arrangement of the main equipment of the HA2M-SG test facility is shown in Fig. 2. The basic parameters of the test facility are presented Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Working environment</td>
<td>Water, steam, steam-water mixture</td>
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<td>Maximum pressure, MPa</td>
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<tr>
<td>Maximum temperature, °C</td>
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<tr>
<td>Basic Equipment of the Test Facility</td>
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<td>Steam Generator Model</td>
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<tr>
<td>Scale</td>
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<tr>
<td>Vertical pitch of pipes, mm</td>
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</tr>
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<td>Material of tube bundle</td>
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<tr>
<td>PHRS Heat Exchanger Simulator</td>
<td></td>
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<tr>
<td>Maximum power, kW</td>
<td>800</td>
</tr>
<tr>
<td>Cooling medium</td>
<td>Service water</td>
</tr>
<tr>
<td>Tank–Accumulator of Steam</td>
<td></td>
</tr>
<tr>
<td>Volume, m³</td>
<td>16</td>
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</tbody>
</table>
1.1 Auxiliary test facility systems

The schematic diagram of the HA2M-SG test facility with auxiliary systems used for performing the tests is presented in Fig. 3. The test facility includes the following auxiliary systems: pressure control system, two-channel non-condensable gas supply system, gas-steam mixture blow-off system and condensate collection system from hot and cold headers of SG model.

The pressure control system of the HA2M-PG facility (pos. 1, Fig.3) provides the stability of thermal-physical parameters during the experiments. The main element of the system is the condenser equipped with shut-off and control valves. During the experiments, the flow rate of steam from the tank-accumulator to the condenser was controlled by the valve V75. Steam was condensed in the condenser cooled with service water through the valves V76 and V77 with subsequent draining. The variation of steam flow-rate enabled the pressure at the test facility both to be decreased or increased. The valve V25 was adjusted at the command given from the facility stuff based on the data provided by steam pressure gauge installed at the SG model inlet. The use of this system allowed the pressure during the experiments to be maintained within an accuracy of ±0.008 MPa.

To study the effect of non-condensable gases on the SG condensation capacity, the system of gas supply into the primary circuit was realized at the HA2M-PG facility (pos. 2, Fig.3). The system included two channels providing the supply of two gases to the primary circuit: nitrogen and helium both separately and as a mixture. Both channels of the system include four standard gas cylinders of 40 l in volume, with the one – high-pressure gas cylinder – being connected to others three via the gear unit. During the experiments, non-condensable gases were supplied into the facility primary circuit from three cylinders with the pressure being maintained approximately by 0.3 MPa higher as compared to steam pressure at the test facility. The pressure in the cylinders decreases as the gases are supplied; after the pressure value reduces by 0.08 MPa from the initial level, the cylinders are filled from the high-pressure cylinder via the gear unit. The flow rates of non-condensable gases were controlled by means of pre-tested needle valves V63 and V78 installed in the impulse line. In addition, the gas supply pipelines were equipped with shut-off valves, air vents and pressure measuring instruments – manometers and Metran-100-DI type gauges.

A uniform supply of gases is ensured by using perforated nipples mounted inside the steam pipe as well as by small volume of non-condensable gases in comparison with steam volume. The system admits maintaining constant concentration of steam-gas mixture at the inlet of SG model.

The HA2M-SG facility provides for the system of steam-gas mixture removal from SG cold header designed for studying the effect of blow-off rate on SG condensation capacity (pos.3, Fig.3). The system comprises a steam-gas mixture take-off line, condenser cooled by service water, unit for separation of condensate being discharged to the measuring tank and non-condensable gases, and shutoff valves. The blowing-off was controlled by two needle microvalves V72 and V73 mounted in series in the impulse line before the point of steam-gas mixture inlet into the condenser. The impulse lines and sampling lines were insulated thermally. They were heated by special heaters to prevent steam condensation before it is supplied to control valves. During the experiments, the steam-gas mixture was blown off from the tap of SG cold header located below the pipe-lines at an elevation of +6,255 mm.

The main objective of the experiments performed at the large-scale thermal-hydraulic test facility HA2M-SG was to evaluate condensation capacity of the SG model. The capacity was evaluated both by the readings provided by vortex steam flow-meter Metran-332 type at the SG inlet and by direct measurements of condensate amount formed in the SG tube bundle using the condensate collection system (pos. 4, Fig.3). The system consists of a measuring tank of 8.2 l in volume equipped with a level meter based on of Metran-100-DD type gauge, valves V65 and V80 for collecting condensate from hot
Figure 3. Schematic diagram of the HA2M-SG test facility.
1 - pressure control system, 2 - non-condensable gas supply system,
3 - steam-gas mixture blow-off system, 4 - condensate collection system

and cold headers, respectively, and drain valve V81. The measuring tank and supply lines were thermally insulated to prevent additional condensate causing the decrease in measurement accuracy. During the experiments, after steady-state condition being achieved, the condensate amount was measured by filling the measuring tank and registering the level with subsequent draining through the valve V81.

1.2 Instrumentation system of the test facility

The instrumentation installed at the facility make it possible to register basic parameters of the test facility both during the preparation of experiments and performance of experiments. The layout of gauges and measuring devices of the HA2M-SG test facility is shown in Fig. 4.

The following basic parameters of the facility were registered during the tests:
- pressure in the primary circuit, tank-accumulator and at the inlet of the SG model;
- pressure in the secondary circuit, at the outlet of the SG model and at the inlet of PHRS simulator;
- temperature of the primary circuit medium in the vicinity of steam flow meter;
- temperatures of the secondary circuit medium at the inlet/outlet of the SG model, at the inlet/outlet of PHRS heat exchanger simulator;
- temperatures of service water at the inlet/outlet of the pipelines of PHRS heat exchanger simulator;
- flow rate of the primary circuit medium (steam) at the inlet of the SG model;
- flow rate of service water at the inlet to PHRS heat exchanger simulator;
– water levels in the tank-accumulator, SG model, hydraulic gate of the primary circuit and downcomer region of secondary circuit pipeline;
– pressure in nitrogen and helium supply lines, non-condensable gas supply system;
– water level in the measuring tank used for collection of condensate.

In addition, the SG model was equipped with more than 100 thermocouples providing the control of temperature in the primary and secondary facility circuits both in the tube bundle and in the SG intertube space [1].

The pressure along the facility circuit was measured by piezoresistive pressure transducers METRAN-100-DI. The water levels were measured by hydrostatic method using pressure difference transducers METRAN-100-DD. Chromel-copel thermocouples with a diameter of 1.0 mm were used to measure temperature. The flow rate of service water through the PHRS heat exchanger simulator was evaluated by measuring pressure difference at the orifice meter with the METRAN-100-DD transducer. The sampling of measuring channels of the data acquisition system was implemented with a frequency of 1 Hz.

The steam flow rate at the inlet of the SG model was measured by the vortex steam flow meter METRAN-332 with a frequency of 0.125 Hz.

The reduced error of temperature measuring channels as a sum of amplifier module error (0.8%) and thermocouple calibration characteristic error (0.1%) was estimated as 0.81%. The reduced error of pressure and level measuring channels is made up of the current signal amplifier error (0.1%) and the METRAN-100 sensor error (0.25%), i.e. it is 0.3%. The measurement error of the primary circuit steam flow rate is defined as the error of steam vortex flow-meter Metran-322 type, and it is 1.5%.

2. EXPERIMENTAL PROCEDURE. BOUNDARY AND INITIAL CONDITION

The boundary and initial conditions for the experiments at the large-scale test facility were specified based on the results of computational modeling of the processes in the reactor facility. The analysis of beyond design basis accident with significant coolant leakage was carried out using the TECH-M-97 computer code [2]. Based on the calculation results (Fig. 5), in the experiments related to the effect of non-condensable gases on the SG model operation in the condensation mode the pressure was maintained in the range of 0.37-0.38 MPa.

In Fig. 6, the NV NPP-2 PHR system power as a function of SG pressure is presented for the maximum ambient air temperature of +38°C. The characteristic presented was obtained experimentally at the full-scale PHRS model in the Gidropress Design Bureau [3].

Taking into account the SG model scale (1:46) and the fact that only one of four PHRS channels is simulated at the test facility, the condensation capacity of the SG model was 76 kW in the end.

In the experiments without non-condensable gases, the SG condensation capacity was chosen based on PHRS heat exchanger performance for the given pressure with regard to scaling factor of the test facility with atmospheric air temperature varied in the range from -37 to +38°C. Thus, the range of condensation capacity in the experiments was from 75 up to 170 kW [3].

The concentration of non-condensable gas at the SG model inlet was evaluated based on the calculation data on gas generation in the NV NPP-2 primary circuit under beyond design basis accident conditions. The running time of the flow stage of additional passive core flooding system (HA-2 system)
was chosen as a time interval for the calculation of gas concentrations. This was due to the fact that water flow-rate from hydro-accumulators determines the flow rate of replacing steam from SG cold header and, hence, the steam-gas mixture blow-off rate from SG piping.

For the sake of modeling at the facility, the first hour after beyond design basis accident was chosen, with the maximum gas generation in the core according to the calculations. As mentioned above, nitrogen dissolved in hydro-accumulators and the products of water radiolysis are the basic sources of non-condensable gases. In the experiments, helium was used instead of hydrogen, which was supplied with the same model concentration as hydrogen. Thus, the gas-steam mixture containing 2.095 g of nitrogen (N2) per 1 kg of steam and 0.047 g of helium per 1 kg of steam was supplied to the SG model inlet during the experiments [3].

Heat losses of the facility depended on the working pressure and were made up of the losses from the SG model housing and losses over the pipelines length. The evaluated value of heat losses was about 18 kW.

The program of experiments at the HA2M-SG test facility included three stages:

- investigation of steam condensation in SG tube bundle without non-condensable gases;
- study of steam condensation in the SG model in the presence of non-condensable gases;
- investigation of steam condensation processes in the SG model in the presence of non-condensable gases with gas-steam mixture outflow.

The objective of the final stage of experiments with pure steam was to determine condensation capacity of the HA2M-SG facility SG model in the absence of non-condensable gases. The tests were focused on evaluating the condensation capacity as a function of pressure (temperature) in the secondary circuit. The flow rate of cooling water in the PHRS heat exchanger simulator and pressure in the primary circuit of the test facility were variable parameters at this stage of the experiments.

The objective of the second stage of experiments (with steam-gas mixture) was to estimate the effect of non-condensable gases in steam on the condensation capacity of the SG model. The experiments should result in obtaining the correlation describing the loss of SG condensation effectiveness as it is being poisoned with gases, with the pressure in the primary circuit and cooling water flow rate through the PHRS heat exchanger simulator being constant.

The objective of the final stage of experiments with steam-gas mixture and its blowing off was to estimate the effect of non-condensable gases blowing off from the primary circuit upon the condensation effectiveness of SG model.

The experiments on the large-scale HA2M-SG test facility were carried out according to the following procedure. At the beginning of the experiment, the tank-accumulator, SG model, PHRS heat exchanger simulator and the pipelines of the primary and secondary circuits of the test facility were heated in succession. The facility equipment was heated until steady-state parameters of the environment (pressure and temperature) in both circuits. A uniform thermal field along the height of the SG intertube water and stable values of pressure in the primary and secondary circuits were the determining indicator of sufficient preheating of the test facility. Simultaneously, the air was blown off by opening the corresponding valves to prevent the presence of steam-air mixture in the circuits.

Then, the required values of SG condensation capacity and pressure in the primary and secondary circuits were established by using the valve in the service water circuit. After a new steady-state regime at the test facility had been achieved, the parameters were recorded by the computer controlled data acquisition system.

Further, according to the test program, the supply of non-condensable gas of the preset concentration to the SG model inlet was initiated, and in the gas blow-off experiments the gas-steam mixture was blown off from the SG tube bundle. The gas-steam mixture blow-off flow rate of 0.217 l/s corresponded to the design blow-off of steam-gas mixture into the volume of HA-2 system tanks at the first stage of flow-metric characteristic, taking into account the scale of the test facility.

### 3. THE RESULTS OF EXPERIMENTS

#### 3.1 Experiments without non-condensable gases

The experiments without non-condensable gases were carried out at a pressures of 0.36 MPa in the power range of 75 ÷ 170 kW. Based on the processing of experimental results, the SG condensation capacity was obtained as a function of the secondary circuit temperature (Fig. 7). The average condensation capacity of SG was evaluated by steam flow rate at the SG model inlet provided that steam was fully condensed in the SG tube bundle and did not pass through the hydraulic gate of the primary circuit. The water level in the hydraulic gate was determined according to level meter readings.

Fig. 8 shows the change of overpressure in the primary and secondary circuits in the experiment performed at the minimum condensation capacity of the SG model \( N_{\text{out}} = 76 \text{ kW} \).

![Figure 7. SG condensation capacity as a function of the secondary circuit temperature. \( P_1=0.357\text{÷}0.361 \text{ MPa} \)](image)
As the steam flow rate at the SG model inlet was the main measured quantity in the experiments, it was evaluated by two methods: using a vortex flow-meter and by direct measurement of condensate amount in the SG tube bundle. The comparison of the results obtained by these two methods is presented in Fig. 9. As it may be seen from the figure, there is a rather close agreement between the measurement results. The maximum discrepancy is about 6%.

Thus, during the experiments without non-condensable gases the basic values of the SG model condensation capacity were obtained.

3.2 Experiments with non-condensable gas supply

The experiments with the presence of non-condensable gas were carried out for the pressure of 0.371 MPa and initial condensation capacity of \( N_{\text{con}} = 76 \) kW. After the parameters of the primary and secondary circuits being stabilized, the three-component gas-steam mixture containing nitrogen and helium of specific concentrations was supplied to the test facility. The total time of gas injection was 17000 s.

Fig. 10 shows the change of the SG model condensation capacity in the experiment. As it may be seen, the condensation capacity of the SG model decreased from 77 kW down to 20 kW, i.e. practically four times. The decrease in capacity was due to accumulation of non-condensable gases in piping and, consequently, reduction of useful heat-transfer surface.
3.3 Experiments with steam-gas mixture outflow

The experiments with steam-gas mixture outflow were carried out at the following initial conditions - pressure of 0.379 MPa, condensation capacity of 76 kW. The gas-steam mixture blow-off was performed from the bottom of the SG model cold header. The value of blow-off flow-rate was set before the non-condensable gases were supplied to the facility, and it was as great as 0.217 l/s, what corresponded to the gas-steam mixture outflow into the volume of HA-2 system at the first stage of flow-rate characteristic.

After the gas-steam mixture blow-off rate had stabilized, gases were supplied to the SG model inlet with the flow-rate for mass concentration of gases in the mixture be at a level: \( C_{\text{N}_2} = 2.095 \text{ g N}_2/\text{kg of steam}, \quad C_{\text{He}} = 0.047 \text{ g He/}

\text{kg of steam. The duration of gas supply to the test facility was 6,000 s, i.e. 1.5 times greater than that of the first stage flow-rate characteristics of the HA-2 system.}

Fig. 12 shows the change of condensation capacity in the experiment. It is seen that after the initiation of gas supply the condensation capacity drops to a level of 55 kW, then it smoothly increases and stabilizes at a level of 67 kW, which is by 12\% less than the initial value but suggests, however, the SG operability in such mode.

![Figure 12. SG condensation capacity in the experiment with gas supply and steam-gas mixture outflow](image)

**CONCLUSION**

The experiments carried out at the large-scale thermal hydraulic test facility HA2M-SG proved the efficiency of NV NPP-2 VVER steam generator model in the condensation mode.

The tests without non-condensable gases were carried out at a pressure in the primary circuit of 0.36 MPa that corresponded to the reactor pressure in case of main circulation pipeline rupture. As a result, the SG condensation capacity as a function of temperature in the secondary circuit was obtained.

The tests with the presence of non-condensable gases in steam of the primary circuit allowed to evaluate characteristics of the SG “poisoning” and to establish that the presence of non-condensable gases caused significant decrease of the SG condensation capacity. It can result in the deterioration of heat removal from the core.

The tests with gas outflow showed that the removal of steam-gas mixture with the flow rate corresponding to the flow-rate of the HA-2 system first stage enabled one to maintain the SG condensation capacity sufficient for effective heat removal from the reactor.
NOMENCLATURE

VVER – Russian water-moderated water-cooled power reactor;
RCP – reactor coolant pipeline;
SG – steam generator;
PHRS – passive heat residual system.

$N$ – condensation capacity, W;
$p$ – pressure, MPa;
$t$ – temperature, $^\circ$C
$\tau$ – time, s.

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REFERENCES

