# ELABORATION OF THE THERMAL-HYDRAULIC CHARACTERISTICS OF THE REACTOR PLANT BASED ON THE OPERATION EXPERIENCE OF THE POWER UNIT WITH BN-800 REACTOR

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**Abstract**

The analysis and elaboration of the thermal-hydraulic characteristics based on the results the reactor plant (RP) commissioning allow validating the algorithms of passing the modes and sufficiency of the margins applied in the project related to the thermal-hydraulic characteristics of the main equipment.

The paper presents the comparative analysis of the start-up algorithms and operation modes at various power levels of the BN-800 RP of the power unit 4 of the Beloyarsk NPP applied in the project and realized during the commissioning of the unit. There are presented the comparison results of the operation mode parameters and thermal-hydraulic characteristics of the main equipment obtained during operation of the BN-800 RP with the calculated ones using verified and validated software ТР-БН (TR-BN). Based on the summation of the operation data of the BN-800 RP the conclusion regarding sufficiency of the margins applied in the project for the thermal hydraulic characteristics of the intermediate heat exchanger and main circulation pumps of the primary and secondary circuits.

The results of the completed research are used for validation of algorithms of passing the modes during normal operation of the BN RP and operation conditions of the main equipment.

## INTRODUCTION

The Beloyarsk NPP Unit 4 equipped with the BN-800 reactor was commissioned on October 31, 2016. This was preceded by a large set of activities. Tests were performed to verify the design mode parameters of the BN-800 reactor plant (RP) and the thermal-hydraulic characteristics of the main equipment (intermediate heat exchanger (IHX), steam generator (SG), primary (MCP-1) and secondary (MCP-2) main circulation pumps).

The operation modes in which the reactor plant shall reliably operate for most of the time are the normal operation modes. They include scheduled modes of reaching the rated power at the plant startup, steady-state modes with rated parameters, scheduled shutdowns and operation at the RP reduced power associated with the failure of individual units and equipment (or tripping of heat removal loops). The most representative normal operation modes are the startups and scheduled shutdowns in which the reactor power varies from 0 to 100% at a corresponding variation of thermal-hydraulic parameters.

This paper summarizes the actual data on the BN-800 RP based on the results of the initial operation period of the power unit and updates the thermal-hydraulic characteristics of IHX and MCP-1, 2 with account of the analysis results calculated by the certified RATO and Piping Systems Fluid Flow 3 (PSFF) programs [1, 2]. It presents the results of a comparative analysis of the RP calculated and operation data in the startup and scheduled shutdown modes performed using the TR-BN certified program [3].

## Used Computer Programs

To perform a computational analysis of the thermal-hydraulic characteristics of IHX, MCP-1, 2 and BN-800 RP in the normal operation modes, a certified software package is used.

The RATO program [1] is designed for the analysis of sodium coolant parameters in the shell-and-tube counterflow sodium-to-sodium heat-exchange apparatuses at the specified geometry and the steady-state mode parameters of coolants in a 2D scenario. The distribution of flow rates and temperatures on the heat exchanger shell side is determined based on a numerical solution to the system of averaged differential equations in a cylindrical anisotropic porous body consisting of rod bundles [4]. The program is used to obtain the distribution of coolant temperature and speed in the tube bundle of IHX of the BN-800 RP.

The PSFF program [2] is designed for the analysis of thermal-hydraulic parameters in a hydraulic network of arbitrary configuration in the steady-state modes at forced coolant circulation. The program allows to determine the coolant pressures and flow rates as a result of solving a system of nonlinear equations of hydraulics in a 1D scenario [5]. The analysis of hydraulic resistances is performed using the empirical relationships. The hydraulic characteristics for the paths of primary and secondary circuits of the BN-800 RP are calculated using this program.

The TR-BN program [3] is designed for the analysis of static parameters (temperatures and flow rates in heat-transfer circuits) in the RP with a three-circuit scheme of heat transfer from the reactor to the turbine generator at various power levels. It allows to promptly perform multivariate optimization and prediction static analyses of normal operation modes [6]. The temperature distribution in the circuits is described by the system of equations of thermal balance and heat transfer which is solved by iteration method [7]. The program is used to determine the thermal-hydraulic parameters of the BN-800 RP in the normal operation modes.

## Used Operating Database

At the initial operation stage of Unit 4 with the BN-800 RP, a set of tests was performed to determine the thermal-hydraulic and mode parameters of the equipment and the RP in general.

Within the framework of testing programs the following studies were performed: “Thermal balance analysis for primary, secondary, and tertiary circuits at power operation”; “Determination of thermal-hydraulic characteristics for primary, secondary, and tertiary circuits at power operation”. Their results were used to analyze the IHX and RP thermal-hydraulic parameters in the normal operation modes. Actual steady-state RP parameters by circuits for all the loops at various power levels were obtained. The values of thermal power by circuits were calculated and the actual RP thermal power was determined.

The actual hydraulic characteristics for primary and secondary circuits were obtained during the startup-and-adjustment activities within the framework of testing programs to determine the MCP-1 flow rate for various power levels and the hydraulic characteristics of secondary circuit.

The startups and scheduled shutdowns were tested on three and two loops in order to perform a comprehensive implementation of algorithms and to update the thermal-hydraulic parameters at the stages of power startup and pilot-industrial operation of the power unit with the BN-800 RP.

## Analysis of IHX Thermal-Hydraulic Characteristics

The actual IHX characteristics were assessed based on the data obtained during the tests of Unit 4 with the BN-800 RP in the steady-state modes at the power from 60 to 100 %. Three or two loops of the plant with the number of sections in the SG ranging from 8 to 10 were in operation.

The actual heat transfer coefficient was determined using a 1D method on the assumption that the sodium flows longitudinally along the entire heat transfer surface from the following equation:

*N = kф⋅F⋅Δtln*, (1)

where N is the thermal power transferred inside one IHX from the primary sodium to the secondary sodium, W;

*kф* is the actual heat transfer coefficient occurring during the IHX operation within the RP, W/(m2⋅°С);

*F* is the IHX heat transfer surface, m2;

*Δtln* is the logarithmic temperature head for the heat exchanger operating by the counterflow scheme which is calculated by the temperatures specified in the measurement system printouts,°С.

Since the installation of individual sensors on each IHX is not envisaged for a number parameters (flow rates, temperatures), the heat transfer coefficients were assessed by the averaged loop parameters for two IHX.

At the design stage, in order to guarantee the transfer of the required power to the IHX, it is necessary to take into account the deviations of main initial parameters from rated values which affect the IHX thermal efficiency, i.e., uncertainties of formulas for heat transfer calculation, error of thermal-physical properties, tolerances for tubes manufacturing, deviation of mode parameters, plugging of tubes, etc. A margin for the heat transfer surface is introduced into the design to compensate for these deviations.

When processing the experimental data, it is accepted that the difference between the actual IHX efficiency and the design one is caused mainly by the difference between the design and the actual occurring heat transfer coefficients. Therefore, the coefficient of actually used margin for the IHX heat transfer surface in relation to the calculated value is determined from the following correlation:

*N = kр.ф/Кз.ф⋅F⋅Δtln*, (2)

where *Кз.ф= kр.ф/kф* is the coefficient of actually used margin;

*kр.ф* is the calculated heat transfer coefficient obtained based on the actual parameters, W/(m2⋅°С).

The design heat transfer coefficient is:

*kп = kр.п/Кз.п,*(3)

where *kр.п* is the calculated heat transfer coefficient obtained based on the design parameters, W/(m2⋅°С);

*Кз.п* is the margin coefficient applied in the design.

Fig. 1 shows the coefficient of actually used margin and the design margin coefficient for the IHX heat transfer surface which are obtained in 1D approximation using the TR-BN program.



*FIG. 1. Dependence of margin coefficient (used margin) for IHX of the BN-800 RP on the loop power (1D approximation)*

The margin (used margin) for the IHX heat transfer surface is determined by the following formula:

*η = (Кз - 1)·100 %* (4)

where *Кз* takes the value of either *Кз.ф* or *Кз.п.*

Based on the results of processing the experimental data using formulas (1, 2, 4) it is determined that the coefficient of actually used margin for the IHX heat transfer surface at the power levels from 75 to 100% is in the range of 20-37% and equals on average 29%. The determination error for this margin, with account of the errors for the main measuring instruments (temperature and flow rate of primary and secondary sodium, pump rotation speed) and the analysis of reactor thermal power, is 15%. The margin applied in the design is 57%.

The complexity of IHX thermal-hydraulic analysis is associated with the presence of longitudinal and transverse flow of the primary coolant in the region of inlet/outlet windows which leads to an uneven distribution of coolant flow rates on the shell side and, as a result, to non-uniformity of temperature distribution and heat removal along the height and radius of tube bundle. The value and nature of the coolant distribution non-uniformity on the shell side depends on the correlation of inertial forces and volume resistivity forces when flowing around the tube bundle longitudinally and transversally. In case of this flow pattern, in order to validate the IHX efficiency, a thermal-hydraulic analysis in a 2D approximation had to be performed using the certified RATO program.

The IHX 2D thermal-hydraulic analysis together with obtaining the spatial pattern of temperature and speed distribution in the IHX allows to partially eliminate the excessive margin for the IHX surface accounting for the longitudinal and transversal flow-around on the greater part of the tube bundle and to assess the required design margin.

Fig. 2 shows the coefficient of actually used margin for IHX obtained using the RATO program on the condition of ensured actual temperatures and transferred power inside the IHX. As it can be seen in Fig. 2, the coefficient of actually used margin does not exceed 9%. The margin applied in the design, obtained using the RATO program, is 28% (Fig. 2). Therefore, the difference between the design margin and the coefficient of actually used margin is around 20% (actual margin) which ensures the increased IHX heat transfer capacity. As it can be seen from the comparison of Fig. 1 and Fig. 2, the longitudinal and transverse flow of the primary coolant in the region of inlet/outlet windows reduces the IHX heat transfer efficiency by around 20-30% as compared to a purely counterflow heat exchanger adopted in 1D approximation.



*FIG. 2. Dependence of margin coefficient (used margin) for IHX of the BN-800 RP on the loop power (2D approximation)*

Based on the performed analysis and with account of the initial data uncertainties (errors of measuring instruments, plugging of some tubes, deviations of mode parameters, etc.), when designing a similar IHX using 2D computer codes, the design margin for the heat transfer surface may be adopted at the level of 20-30 %.

## Analysis of Pump Hydraulic Characteristics

To determine the working rotation speeds of MCP-1, 2, the analysis of actual hydraulic characteristics of primary and secondary circuits of the BN-800 RP obtained during testing was performed.

The guaranteed provision of the rated sodium flow rate in the circuits makes it necessary to adopt the margins for the MCP-1, 2 head. The margin value is determined with account of the adopted tolerances during the manufacture of equipment, pipelines and deviations in the determination of hydraulic characteristics during design. The reduced margins for the MCP-1, 2 head allow to improve the mass and size characteristics of pumps (all other conditions being equal). The margins for the head of BN-800 RP pumps are assigned with account of the experience in designing and commissioning the BN-800 RP.

As a result of testing to determine the hydraulic characteristics of the primary circuit, the values of sodium flow rate through the bypass flow meters of MCP-1 at various rotation speeds of pump shafts were obtained. The hydraulic characteristics of the BN-800 RP primary circuit are determined based on the experimental hydraulic characteristics of the primary circuit elements (core, MCP-1, throttles) as a result of analysis using the certified PSFF program. The analysis results are verified based on the readings of MCP-1 bypass flow meter. As it can be seen in Fig. 3, there is a good coincidence between the experimental and calculated data on the sodium flow rate through the bypass flow meter and the difference does not exceed 8%. The working rotation speeds of MCP-1 during operation of two and three pumps are determined with account of analysis results (Fig. 4). The value of MCP-1 rotation speed ensuring the rated flow rate of primary sodium is lower than the design value by 5%. At the same time, the required MCP-1 speed is ensured by regulation using the frequency converter. The results of a comparative analysis show that the margin for the MCP-1 head applied in the design is sufficient.

  
*FIG. 3. Sodium flow rate through the bypass flow meter of MCP-1*



*FIG. 4. Hydraulic characteristic of MCP-1*

The secondary sodium flow rate was measured and the working rotation speed of MCP-2 was determined within the framework of testing to determine the thermal-hydraulic characteristics of the BN-800 RP secondary circuit. Fig. 5 shows the hydraulic characteristics of secondary circuit loop calculated using PSFF program and obtained based on the testing results. The results of testing for the loss of pressure in the secondary circuit are lower than those calculated using the program and the difference does not exceed 14%. The value of MCP-2 rotation speed ensuring the rated flow rate of the secondary sodium is lower than the design value by 8 % (Fig. 5). At the same time, the required MCP-2 speed is ensured by regulation using the frequency converter. The results of a comparative analysis show that the margin for the MCP-2 head applied in the design is sufficient.



*FIG 5. Hydraulic characteristic of secondary circuit*

  
*FIG. 6.**Hydraulic characteristic of MCP-2*

The obtained results show that the adopted margins for the MCP-1, 2 head allow for the rated flow rates of primary and secondary sodium in the rotation speed control range of 5-10 %.

## Analysis of RP Thermal-Hydraulic Parameters

The thermal-hydraulic parameters of the BN-800 RP in the normal operation modes are analyzed with account of parameter measurement for primary, secondary, and tertiary circuits in the steady-state modes at power levels of 5, 15, 25, 35, 50, 60, 67, 85, 100% Nном. The actual reactor thermal power was determined based on the weighted average values for all three circuits. When performing analyses using the TR-BN program, the analysis results of thermal-hydraulic characteristics for IHX and MCP-1, 2 specified in this paper were used.

The results of a comparative analysis specified in Fig. 7-9 show that there is a satisfactory coincidence between the calculated and operation parameters. The deviations are: not more than 9 °С for the primary sodium temperature and 3 °С for the secondary sodium temperature, not more than 8 °С for water/steam at the steam generator outlet, and they fall within the error band specified in the certification passport of the TR-BN program.

The analysis of testing results regarding the variation of mode parameters showed a satisfactory coincidence with the algorithms applied in the design. In particular, the transfer to the steam mode, connection of the SG superheating modules, variation of MCP-1, 2 rotation speed, time hold periods at various power levels associated with the restrictions from the reactor and turbine side were performed in general as per the requirements of the design (Fig. 10). The differences in the passing of modes were associated with the reduction of actual parameter variation speed aimed at reducing the temperature impact on the equipment and fuel rod. The increased duration of mode passing in the course of testing is also caused by the presence of additional time hold periods at various power levels intended to check the equipment condition, the parameter stabilization and recording.

Therefore, the use of the TR-BN program allows to calculate the BN reactor plant thermal-hydraulic parameters at various power levels with an acceptable accuracy. The validity of algorithms applied in the design is confirmed for the startup and scheduled shutdown modes.



*FIG. 7. Dependence of primary sodium temperature in the BN-800 RP on the loop power*



*FIG. 8. Dependence of secondary sodium temperature in the BN-800 RP on the loop power*



*FIG. 9. Dependence of water/steam temperature in the BN-800 RP on the loop power*



*FIG. 10. Design variation of the BN-800 RP parameters in time. Startup and reaching the maximum permissible power level (depending on the equipment state) on three loops from the “cold” state*

## Conclusion

The actual thermal-hydraulic characteristics of the BN-800 RP equipment are determined at the rated 100 % power and under partial loads. The actual margin for the IHX heat transfer surface close to the rated power level, determined based on the verification analysis using a 2D method, is estimated as 20 %. Based on the performed analysis, when designing a heat exchanger similar to the IHX of the BN-800 RP using 2D computer codes, the design margin for the heat transfer surface may be adopted at the level of 20-30 % (at the level of 40-50 % using 1D computer codes). The values of MCP-1, 2 rotation speeds ensuring the rated flow rate of primary and secondary sodium are lower than the design values by 5 and 8 % correspondingly. The analysis of thermal-hydraulic operation parameters for the IHX and MCP-1, 2 of the BN-800 RP has shown that the margins adopted in the design are sufficient.

The actual algorithms and operation parameters of the BN-800 RP (temperature, pressure, coolant flow rate) obtained during the commissioning of the Beloyarsk NPP Unit 4 at the stages of power startup and pilot-industrial operation are analyzed in the normal operation modes: startup, shutdown, operation at the rated 100 % power and under partial loads. The comparison of calculated and operation parameters of Unit 4 with the BN-800 RP at various power levels has shown a satisfactory coincidence with the algorithms applied in the design. The comparative analysis has shown that the TR-BN program determines the thermal-hydraulic parameters of the BN-800 RP with an acceptable accuracy and may be used to calculate the normal operation modes for the future BN reactor plants.

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