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Development and verification of the TR-BN software for substantiation of normal operation modes of BN reactors

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Abstract

Substantiation of design parameters of sodium-cooled fast reactor facilities (BN RF) in normal operation modes represent an important task solution of which is necessary for determining safe and optimal reactor operation conditions. Software tools existing for the purpose allow implementing calculation analysis of separate types of equipment (for example, steam generators) or of circulation loops (secondary and tertiary cooling loops). The TR-BN software developed for the purpose of complex analysis of thermal hydraulic parameters is intended for determination of the main design characteristics (temperature, pressure) for all heat removing loops (including the primary cooling circuit) and for optimization of algorithms of BN RF operation in normal operation modes on different power levels.

Brief description of the software and of the calculation methodology, as well as of possible calculation options depending on the steam generator design is given. Verification and cross-verification of the TR-BN software were implemented by way of comparison of calculated results with operational characteristics of BN-600 reactor facility and with results of calculation of BN-800 steam generator obtained using the Korsar/GP computer code. Analysis of the obtained results demonstrated satisfactory agreement with maximum discrepancy for temperature not exceeding 7.5% for sodium and 14.2% for steam. Standard uncertainties of parameters calculated using the TR-BN software and characterizing the accuracy of the performed calculations were determined. Possibility was demonstrated to use the software in the normal operation modes in the substantiation of safety of the BN RF.

Keywords: Verification; Sodium coolant; Steam generator; Uncertainty; Software; Reactor facility; Normal operation mode; Steady-state parameters; Temperature.

Introduction

Sodium-cooled fast reactor facilities have got extensive operational experience. The main operation mode for sodium-cooled fast reactor facilities (BN RF) is the stationary operation at 100% power level (base load operation mode). Besides that there exist a number of transitional normal operation modes, such as reactor start-up and shut-down, operation on reduced power levels with disconnected heat removing loop, etc.

Existing software programs, such as Korsar/GP (developed by the JSC "OKB Gidropress") and DYNMODVTI (JSC "VTI"), are intended for implementation of calculation analysis of the given operation modes in the third cooling loop jointly with the secondary cooling circuit within the volume of the steam generator, but, however, performing complex analysis of main parameters of BN RF for all cooling loops using this software is not possible [1].

In connection with the above development of engineering TR-BN software code [2] allowing determining steady-state parameters of the BN RF (temperatures and flow rates in cooling loops) for the primary, secondary and tertiary cooling loops on different power levels is an important problem

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solution of which is necessary in the substantiation of design parameters and implementation of multi-option optimization calculations of normal reactor operation modes.

The software can also be applied in the elaboration and analysis of ranges of possible discrepancies of rated parameters of the reactor facility associated with calculated uncertainties of determination of characteristics of equipment, in cases of disconnection of failed heat transferring surface in the steam generator, intermediate heat exchanger, in the situations of possible offsets in the control systems, etc. Since calculated parameters of the RF refer to the data used in the substantiation of safety of reactor facilities in normal operation modes the software must be appropriately verified and certified.

Results of verification of the TR-BN software code by the method of comparison of calculated results with operational data collected on the BN-600 RF and with calculations performed using Korsar/GP software for steam generator of the BN-800 reactor [3] are presented in the present paper.

Description of the software code

TR-BN software code is intended for calculation of steady-state parameters (temperatures and flow rates in heat transferring loops) of fast reactor facilities with three cooling loops (sodium–sodium–water (steam)) for heat transfer from reactor to turbine generator in normal operations modes on different power levels.

One cooling loop of the reactor facility is modeled in the assumption of symmetrical operation of cooling loops.

The software allows performing calculations for the following three options of circuit and design configurations of the once-through sodium–water (steam) steam generator:

– Vessel-type steam generator combining the functions of evaporator and main steam superheater;
– Section-modular steam generator each section of which consists of the evaporator module and the module of the main steam superheater;
– Section-modular steam generator each section of which consists of the evaporator module, main steam superheater module and intermediate steam superheater module with superheating by sodium. The main and intermediate steam superheaters are connected in parallel to each other.

Calculation layout with section-modular steam generator (consists of the evaporator module, main steam and intermediate steam superheaters) which corresponds to the most general case is represented in Fig. 1. Remaining steam generator options can be addressed from the viewpoint of the calculation model as particular cases.

Reactor core, intermediate heat exchanger, main steam superheater, intermediate steam superheater and evaporator are examined separately in the solution of the problem. Evaporator is divided into the following five sections: preheating, surface boiling, bubble boiling, degraded heat exchange and superheating. Reactor core and intermediate heat exchanger

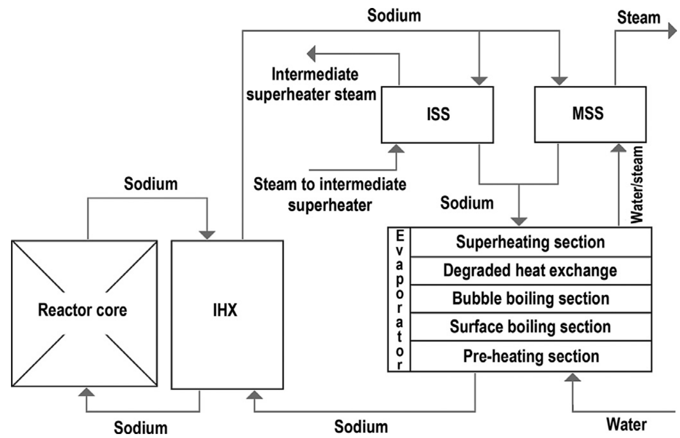

Fig. 1. Calculation layout of the RF: ПТО – intermediate heat exchanger (IHX); ПП – intermediate steam superheater (ISS); ОП – main steam superheater (MSS).

are calculated according to one-dimensional point calculation scheme and steam generator is calculated according to one-dimensional scheme with subdivision into sections along the length. Propagation of coolants in the steam generator and in the intermediate heat exchanger is arranged as a counter-flow.

Distribution of temperatures is described for cooling loops by the set of thermal balance and heat transfer equations solved by iteration method.

Thermal balance and heat transfer equations have the following form for the steam generator [4]:

$$dQ/dx = D \cdot di/dx,$$
$$dQ/dx = G_2 \cdot C_p \cdot dT_2/dx,$$
$$dQ/dx = K \cdot \Delta T_{2-3} \cdot dF_{SG}/dx. \quad (1)$$

Where Q is the reactor power, W; D is the feed water flow rate, kg/s; G_2 is the coolant flow rate in the secondary cooling loop, kg/s; C_p is the sodium specific heat, J/(kg·°C); i is the enthalpy of water (steam), J/kg; K is the surface heat transfer coefficient of the steam generator, W/(m^2·°C); ΔT_{2-3} is the temperature difference in the steam generator,°C; F_{SG} is the heat transfer surface area in the steam generator, m^2.

Formulas applied in verification calculations of counter-flow heat exchangers are used in the calculations of IHX as follows: two other temperatures values are calculated according to the known flow rates and two values of coolant temperatures (at the inlet and/or outlet) [4].

The input data for the calculation are the flow rates of coolants for the first and secondary cooling loops, sodium temperature at the steam generator (evaporator) outlet, feed water temperature and pressure, design characteristics of heat exchanging equipment. Sodium temperature in the primary cooling loop at the inlet (outlet) of the reactor core, sodium temperature in the secondary cooling loop at the outlet of the intermediate heat exchanger (inlet of the main and intermediate heat superheater), steam temperature at the outlet of the steam generator (main and intermediate superheater), distribution of temperatures along the length of heat exchanging