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Application of 3-D coupled code QUABOX/CUBBOX-ATHLET for RBMK-1000 vapor reactivity coefficient measurements

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ABSTRACT

The model implemented into coupled neutron-thermohydraulic code system ATHLET + QUABOX/CUBBOX for RBMK-1000 vapor reactivity coefficient measurements computer modeling is described.

The results of ATHLET + QUABOX/CUBBOX modeling of Kursk NPP unit 1 vapor reactivity coefficient measurements are presented.

Reasonable agreement between measurements and modeling results was shown.

1. Introduction

At the moment the regular method of the vapor reactivity coefficient of the RBMK-1000 measuring is based on measurement of reactivity changes upon feed water flow perturbations simultaneously in the right and left half of the reactor core. At the same time reactivity is determined indirectly by comparing efficiency of local automatic control rods (LACR) and results of the individual LACR groups "weighting". Changing the void fraction under feed water flow perturbation is calculated by the special code.

In this paper the results of direct numerical modeling of the vapor reactivity coefficient measuring procedure using a coupled codes system of QUABOX/CUBBOX (Langenbuch et al., 2005) and ATHLET 2.2a (Lerchl and Austergesilo, 2009) developed by GRS (Germany) for non-stationary processes in the reactor are presented.

Direct modeling of the measurement procedure is a very complex task that combines a detailed description of three-dimensional kinetics of the core along with detailed modeling of hydraulic processes in the external circuit. To solve this problem the computational model was developed. This model takes into account the specifics of the reactor systems and equipment of the RBMK-1000 and features occurring in the reactor processes.

For modeling of the vapor reactivity coefficient α_φ of RBMK-1000 measured data from Kursk NPP unit 1, held on 6 July 2010 were used.

2. Model of the Kursk NPP unit 1

2.1. The QUABOX/CUBBOX core model description

The QUABOX/CUBBOX is the neutronic code, which was developed for detailed 3-D reactor core modeling by solving the two-group diffusion equation with taking into account fuel temperature and coolant mass flow rate changing feedbacks.

The QUABOX/CUBBOX RBMK core model consists of 1654 fuel channels, 22 additional absorbers, 17 water columns, 191 control rods and 604 reflector channels. The axial channel nodalization scheme consists of 30 nodes.

In the static and dynamic state calculations QUABOX/CUBBOX uses the next parameters from NPP units:

Abbreviations: AA, additional absorber; CV, check valve; CPS, control and protection system; CR, control rod; DS, drum-separator; ECCS, emergency core cooling system; FA, fuel assembly; FC, fuel channel; FWP, feed water pump; GDH, group distribution header; GRS, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH; LACR, local automatic control rod; MCC, main coolant circuit; MCP, main circulation pump; PH, pressure heard; SECNRS, Scientific Engineering Centre for Nuclear and Radiation Safety; SH, suction header; TCV, throttle control valve; TSCV, turbine stop and control valve; TG, turbine generator; β_{ef}, effective delayed neutron fraction.

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– channels power distribution of the reactor;
– coolant flow rate distribution in the reactor;
– position of control rods;
– burnup distribution in the reactor;
– reactor loading map;
– inlet coolant temperature for two loops;
– pressure in the drum-separator (DS) for two reactor loops

The XS–library for RBMK-1000 core calculations was developed by Scientific Engineering Centre for Nuclear and Radiation Safety (SECNRS) specialists. This library uses special format for preparation of two group constants (D_1, D_2, $\sum_{a1}$, $\sum_{a2}$, $\sum_R$, $\nu\sum_{f1}$, $\nu\sum_{f2}$) and special procedure for interpolation between the reference points. This interpolation procedure treats the 5-D tables of two group constants depending on fuel and graphite temperature, coolant density (water), fuel burn-up and xenon concentration.

On Fig. 1 the core loading of unit 1 Kursk NPP is shown and the 12 LACR radial positions selected by black circles.

2.2. RBMK measurements modeling by ATHLET code

In this investigations vapor reactivity coefficient measurements modeling at nominal power by ATHLET code version 2.2A for RBMK-1000 has been used.

It is supposed that reactor is under normal stationary operation. The reactor power is maintained at nominal level. Pressure and DS level regulators are actuating. Automatic power control rods actuating by in-core detectors are in operation.

In calculation model used for RBMK-1000 vapor reactivity coefficient measurements modeling the feed water flow rate is disturbed stepwise with following time delay need for reactor core transient stabilization.

Criteria for correctness of the calculation model were the following:

– feed water flow rate stabilization after flow disturbance stopping;
– limiting feed water flow rate difference is not more than 500 t/h to each main;
– coolant circuit (MCC) half from the initial value;
– value of feed water flow rate after the "disturbances" is not less 85% of flow rate value in compliance with level of the reactor power;
– absence of control and protection system (CPS) warning or emergency signaling;
– reactor power difference is not more than 190 MW (thermal);
– value of induced reactivity is not more 0.05 β_{ef};
– the reactor power stabilization takes place after completion of the measurements.

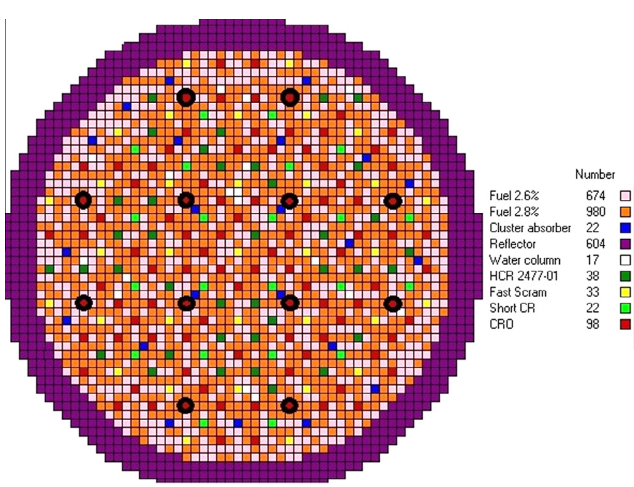

Fig. 1. Kursk NPP unit 1 core loading.

The main coolant circuit was simulated with the two-fluid model of the 6-equations system, which includes separate conservation equations for liquid and vapor mass, energy, and momentum. Steam lines, the feed water system, the emergency core cooling system and other auxiliary systems are described with the model of the 5-equations that consists of separate conservation equations for liquid and vapor mass and energy, and a mixture momentum equation, accounting for thermal and mechanical non-equilibrium.

2.3. Nodalization scheme of the reactor unit

The MCC nodalization scheme is simulated by two independent circuit loops and presented in Fig. 2.

The equivalent downward pipeline connects drum-separators to the suction header of main circulation pumps and through main circulation pump (MCP) binding pipelines to the pressure heard. The MCP binding pipelines have been modeled as two parts: a pipeline with MCP and a pipeline after MCP with throttle control valve and check valve. In the scheme it is modeled a bypass between the PH and the ECCS header. It has been simulated the coolant flow to the core from the PH through GDHs and the bypass and then through inlet feeder pipes with isolated control valves. The reserve fourth MCP is not modeled.

The core has been simulated by equivalent fuel channels, each of them consists of two parts: a channel part into the core and a top outlet part. The top part connects to a pipeline simulated steam-water communications. In Fig. 2 only one equivalent fuel channel for each part of the MCC is shown.

It has been assumed the reactor core consists of 1654 FCs of the total power 3142 MW (thermal). In the nodalization scheme in left half there are 5 types of fuel channels (FCs) with different power. The same situation is in right half. This 10-channels model was chosen as a compromise between running time and calculation accuracy. It is assumed that all channels in the frame of one group have the same thermohydraulic parameters and the division into groups was made according to channels' power.

To simulate MCP the dynamic ATHLET model of pump has been used that allows simulating MCP stopping if it is necessary.

In the calculation the heat exchange model was applied between fuel elements of fuel assemblies, cladding and main coolant, graphite blocks and channel tubes as well as their heat. Heat structures in water communications and steam water communications were also modeled. For graphite blocks heat exchange with FCs and the reactor space was applied.

The steam generation is calculated by taking into account the residual heat removal of reactor and phase transitions of saturated water under pressure.

The initial conditions have been accepted in compliance with nominal power level at the moment of vapor reactivity coefficient measurements:

– 3 MCPs are in operation for each MCC part;
– 4 feed water pumps (FWPs) are in operation;
– the water reserve in deaerators is 480 tons;
– the pressure in DSs is ~6.87 MPa;
– the pressure controller is in operation that is keeping up the DS pressures and acting the turbine generator (TG) turbine stop and control valve (TSCV);
– steam flow rate for the own needs is 200 t/h;
– feed water temperature is 160 °C;