Developing Supercomputer Twins Of Nuclear Power Plants For Various Applications With The Use Of Russian 3D Numerical Analysis Codes

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Abstract. The article describes the technology of the supercomputer twin of a nuclear power plant, which describes the main circulation circuit of the coolant. The technology is based on a joint one-dimensional and three-dimensional description of a reactor expanding the field of application of traditional one-dimensional system codes for describing fundamentally three-dimensional processes in reactor plenum. A description of the technology and verification data based on experimental studies is provided. The application of this technology to the analysis of the partial operating modes of the RITM-200 reactor plant was demonstrated, which made it possible to mitigate power limitations when disconnecting part of the heat exchange surface of the steam generator, reduce the costs of repair of the reactor plant associated with the replacement of steam generator cassettes, and avoid prolonged shutdown of a nuclear icebreaker.

1. Introduction

One of the priority lines of work for JSC “Afrikantov OKBM” is designing and complete deliveries of reactor plants for nuclear-powered icebreakers and ships, which ensure the progress and development of the Arctic region and Northern Sea Route. The specific features of the plants consist in heightened requirements for the mass- and size characteristics, for reliability and repairability of the entire plant and its elements, for simplicity of construction and maintenance. The RITM-200 integral reactor plant, which has been developed by JSC “Afrikantov OKBM”, completely satisfies the said requirements. RITM-200 is designed for double-draft multipurpose nuclear-powered icebreakers, which can combine the functions of open-sea icebreakers and limited-draft icebreakers. The RITM-200 reactor plant has a higher power than the currently operated KLT-40 reactor plant; it almost two times lighter and more compact and, accordingly, cheaper in terms of material consumption; and it takes smaller space in a ship. Along with the increased power and reduced material consumption, the reactor plant design validated an assigned lifetime extended more than two times for the main equipment as compared to the reactor plants on currently operated icebreakers. Considering the specificity of operating nuclear-powered icebreakers and ships under the Arctic conditions, an extremely important task is to ensure the survivability for the reactor plant in case any individual equipment fails. However, the integral layout of the RITM-200 reactor plant reduces the
plant repairability in case an individual steam generator cassette has to be replaced after it fails because of an inter-circuit leak. To restore the steam generator operability, to prevent a long-time and costly repair, to eliminate an icebreaker downtime, the reactor plant design implements a modular construction of a steam generator cassette and ensures an independent shutdown for leaking steam generator modules (SGM). However, shutting down the leaking steam generator modules results in thermal cyclic loads, which may have an effect on the lifetime of the heat exchange equipment; and in the case of incomplete mixing of non-isothermal flows in reactor plenums, it may result in degraded core thermal reliability characteristics. These negative factors require additional studies (R&D work) in order to validate a possibility of subsequent reliable plant operation, to determine the plant permissible power level and to analyse the effect to the lifetime characteristics of a steam generator cassette. While being based upon a meticulous experimental development with the use of full-size testing, the traditional approach to R&D work, in terms of the reactor plant, has considerable limitations caused by the substantial time and high cost. In a number of cases, full-size testing in the required scope is simply impossible due to technical reasons, that’s why the innovative supercomputer twin technology turns out to be especially vital for doing the studies into and validate technical characteristics of reactor plants. The supercomputer twin technology is based upon using state-of-the-art 3D thermal-hydraulic analysis codes and supercomputers.

2. The supercomputer twin technology

The technology enables a digital analog to be created for entire reactor plant equipment and the operating conditions of the said equipment to be analyzed in normal and emergency operation modes. For RITM-200 reactor plant, supercomputer twins are developed for the main closed coolant circulation circuit of the reactor plant and for a steam generator cassette. With the use of the supercomputer twin of the reactor plant main circulation circuit, a non-isothermal mixing process is modeled in the reactor plenum, when a part of the steam generator heat exchange surface is isolated. With the use of the steam generator cassette supercomputer twin, steam generator module operation is modeled under thermal cyclic loads.

Figure 1 illustrates the supercomputer twin of the reactor plant main circulation circuit element which consists of a 1D active thermal hydraulic part of the steam generator, fuel assemblies and pumps; and the 3D thermal hydraulic part of reactor mixing plenums [1]. The 1D and 3D parts are integrated together by a unique, one-of-its-kind 1D and 3D thermal-hydraulic analysis program binding, Figure 2.
A research based on supercomputer twin was carried out to analyze the possibility to mitigate limitation of RITM-200 power levels with different number of SG cassettes stopped. For that purpose non-isothermal mixing process in the core inlet in partial operation modes was analyzed, temperature field nonuniformity on different power levels was estimated, and finally core thermotechnical reliability was analyzed.

The analysis showed that time-averaged temperature nonuniformity in the core inlet was up to:
- 6 °C with 3 SG cassettes stopped for 68 % rated power level;
- 4 °C with 2 SG cassettes stopped for 72 % rated power level;
- 3 °C with 1 SG cassette stopped for 100 % rated power level.

By achieving the above mentioned power levels with one, two and three SG cassettes stopped and with four primary circuit coolant pumps in operation thermotechnical reliability is ensured in all operation modes and design basis accidents as well as the temperature nonuniformity in reactor cells does not impact the reactor control system functionality with appropriate optimization of thermocouple signals processing.

Therefore by using supercomputer twin technology opportunity of the following pattern of power level limitation mitigation is provided:
- with 1 SG cassette stopped (seven modules) power limitation is not required, operation at rated power is allowed;
- with 2 SG cassettes stopped (fourteen modules) by 30% - from 60% to 72% rated power;
- with 3 SG cassette stopped (twenty one modules) by 20% - from 60% to 68% rated power.

The supercomputer twin of the main circulation circuit is verified and its operability is confirmed on the basis of results from experimental studies. The established international approach consists in performing experiments with relatively small scale test models of reactor plants and in validating a possibility of scaling up (extrapolating) the obtained verification results to the reactor plant conditions. The test model developed for the verification is similar to test facilities widely cited in the literature, in particular, ROCOM (Rossendorf Coolant Mixing) and Fortum PTS, which are designed to study flow...
mixing processes in PWR plants [2]. The facilities are made to a 1:5 scale and a 1:2.56 scale, respectively. JSC “Afrikantov OKBM” solves the verification problem in two test facilities, in two stages.

At the first stage, tests are performed on a small-scale integral reactor plenum model. The model is in the fluid-dynamics laboratory at JSC “Afrikantov OKBM” [3]. The model is used to do the studies in a Reynolds number range of up to Re≈4×10^4.

The second stage is performed on a test model different in the layout of the coolant inlet nozzles, which are put horizontally the same as in the RITM-200 reactor plant. Photographs of the test models at JSC “Afrikantov OKBM” and at NNSTU n.a. Alekseev are shown in Figure 3 and Figure 4. In the tests, non-symmetric operation modes are studied that simulate isolation of a number of steam generator cassettes or modules. For this, a flow is injected into the test model via one of the nozzles. The flow differs from the main flow in its temperature or in an excess concentration of a diluted admixture. A thermal imager, thermocouples and conductance measuring rod sensors are used to study mixing processes in the model downcomer region and at the inlet to the reactor core channel simulators.

![Figure 3. Photograph of Test model of the reactor plenum at JSC “Afrikantov OKBM”](image1)

![Figure 4. Photograph of Test model of the reactor plenum at NNSTU n.a. Alekseev](image2)

As an example, Figure 5 and Figure 6 show calculated and experimental results for the temperature field in the downcomer region and at the inlet to the core channel simulators in the RITM-200 reactor plenum model. One can see from the Figures that, the flow is twisted in the calculation, which is explained by the geometry of the inlet nozzles, and the flow twisting is verified experimentally, which confirms that the calculations are correct.
The admixture concentration field in the downcomer region of the RITM-200 reactor plenum model in simulation in cross sections

**Figure 5**

The admixture concentration field in the downcomer region of the RITM-200 reactor plenum model in simulation in the central section

**Figure 6**

The supercomputer twin of the steam generator cassette is used to study the effect the thermal cyclic loads, resulting from coolant temperature pulsations, produce on the lifetime characteristics of the steam generator module cassette. The said supercomputer twin is based upon the use of the set of coupled “Fluid Dynamics-Temperature State-SSS-Damage” calculations. Figure 7 shows an instantaneous temperature field on the steam generator module model surface.

**Figure 7.** Instantaneous temperature field of the steam generator module metal at a random time moment

With the use of the temperature state results, a stress-strained state is modeled and steam generator cassette lifetime characteristics are evaluated using a multicycle fatigue mechanism. The evaluation results have shown that the maximum amplitude of the acting stresses is less than the allowable amplitude defined for the material of the steam generator module structural elements.

To verify and confirm the operability of the steam generator cassette supercomputer twin, experimental studies are performed for the fatigue strength of the structural materials in the reactor plant equipment under the effect of stochastic thermal cyclic loads produced by non-isothermal flow mixing. The experiments are performed on a specially designed model and in a test facility at NNSTU n.a. Alekseev (Figure 8).
Figure 8. A test facility section at NNSTU n.a. Alekseev with five test models

The accomplished numerical modeling of the test and the comparative analysis have shown a good match between the calculated and experimental data, which verifies the operability of the steam generator cassette supercomputer twin.

3. Conclusion

As a result of the accomplished R&D work based upon the innovative supercomputer twin technology and a supercomputer, a possibility has been validated of easing up the power level limitations for the case with a part of steam generator heat exchange surface isolated, and the possibility of extending the assigned lifetime of a steam generator cassette was analyzed. A unique result has been achieved that allows the reactor plant repair costs, associated with a steam generator cassette replacement, to be considerably reduced and a long downtime for a nuclear-powered icebreaker to be avoided.

References

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