Hydrodynamic analysis of a flow in a mixed core

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Abstract. This paper provides data on the performed analysis of hydrodynamics characteristics and calculation of crossflow distribution in a PWR mixed core. The analysis was realized using the subchannel thermal-hydraulic code VIPRE-01 and the CFD code STAR-CCM+. The paper sets out recommendations on choosing the computational model detailing and adjustment for the subchannel code. The analysis has shown that the mixed core model in VIPRE-01 takes into account the coolant flow redistribution correctly and provides the possibility of using this code for DNBR analysis in the mixed cores.

1. Introduction
Flow rate redistribution and lateral velocity of coolant in hydraulically non-identical assemblies have to be taken into account in the justification of operability and thermal performance of mixed cores consisting different types of fuel assemblies (FAs).

Coolant flow in a mixed core was analyzed by STAR-CCM+ CFD code and VIPRE-01 subchannel code.

The STAR-CCM+ CFD code is intended for numerical modeling of three-dimensional flows and heat and mass transfer.

The VIPRE-01 subchannel code is widely applied to analyze thermal performance of PWR cores.

In the process of justification of thermal-hydraulic characteristics of the PWR cores with Russian FAs design (TVS-K) verification of the STAR-CCM+ code was performed and the analysis of longitudinal-transverse coolant flow in a mixed core was conducted using the subchannel thermal-hydraulic VIPRE-01 code and the STAR-CCM+ code.

2. Verification of CFD Code
2.1. Description of Computational Models
CFD calculations were carried out with the use of segregated flow model and improved quadratic \( K - \varepsilon \) turbulence model with the coefficients recommended by the STAR-CCM+ developer to solve the fluid-dynamics problems under conditions when coolant flows through the rod bundles [1]. The viscous sublayer was described using the high \( y^+ \) wall treatment model. The detailed description of turbulence model and viscose sublayer model is given in [2]. One prismatic layer was built on the solid walls. The size of the prismatic layer was within \( 30 < y^+ < 100 \) range. The slip wall boundary condition was applied to the fluid walls.

The approach to numerical modeling developed in the process of CFD code verification was used to the mixed core fragment models with the TVS-K.
2.2. Verification Matrix
The following physical phenomena in PWR core were considered in the process of STAR-CCM+ verification: pressure loss, flow rate redistribution over the FA subchannels and longitudinal-transverse flow around non-identical spacer grids (SGs) under conditions of mixed cores.

In the process of verification the following characteristics were compared:
- The calculated values of a loss coefficient with empirical relations as a function on the Reynolds number for round pipes.
- The calculated and experimental data on pressure drops for the FA components.
- The calculated and experimental data for the velocity distribution in a mixed core fragments.

The verification matrix is given in table 1.

| Physical phenomena                  | Comparison with empirical relations | Experiments using small-scale fragments | Experiments using full-scale mockup |
|-------------------------------------|-------------------------------------|----------------------------------------|-------------------------------------|
| Pressure loss                       | +                                   | +                                      | +                                   |
| FA subchannels flow rate redistribution | +                                   | +                                      | -                                   |
| Flow around SGs in a mixed core     | -                                   | +                                      | -                                   |

Table 1. The verification matrix of the STAR-CCM+ code.

2.3. Verification Results
The results of STAR-CCM+ verification have shown the possibility of correct calculation of pressure loss, subchannels flow rate redistribution and flow around hydraulically non-identical grids of FAs.

The detailed description of tests and verification results is given in [3].

2.3.1. Loss coefficient. The dependence of loss coefficient on the Reynolds number for a smooth round pipe was analyzed. The calculation results were compared with empirical relations of Blasius (1) and McAdams (2) [4]:

\[
\lambda_T(Re) = 0.3164 \cdot Re^{-0.25} \quad (1)
\]

\[
\lambda_T(Re) = 0.184 \cdot Re^{-0.2} \quad (2)
\]

In the calculation, the Reynolds number changed due to variation of the coolant velocity from 0.52 to 5.2 m/s. The nominal parameters of PWR cores were used in calculations.

Comparison of the results is given in figure 1.

The difference between calculated loss coefficients and empirical values as per McAdams formula equaled 1%. The empirical values of loss coefficients as per Blasius formula are 6% lower than the calculated ones.

Figure 1. Comparison of calculated and empirical loss coefficients.
2.3.2. **Comparing pressure drops.** The pressure drops were obtained by using small-scale and full-scale models of different FA components.

The comparison of calculated and experimental data is given in table 2.

**Table 2.** The results of comparison of pressure drops of the FAs components.

| Model              | Number of modes | $M / P$ | $\sigma$, % |
|--------------------|-----------------|---------|-------------|
| FA bottom nozzle   | 24              | 0.98    | 3.0         |
| Fuel rod bundle    | 16              | 0.98    | 1.6         |
| Spacer grid        | 8               | 1.01    | 1.8         |

Here $M / P$ is the mean arithmetic deviation of experimental ($M$) and calculated ($P$) values of pressure drops, and $\sigma$ is the root-mean-square deviation of experimental and calculated values of pressure drops.

The maximum difference between calculated and experimental pressure drops across the height of fuel rod bundle and the FA components is ~6%, and the root-mean-square deviation does not exceed 3%.

2.3.3. **Data on flow redistribution around the hydraulically non-identical grids.** The experimental data on velocity distribution in a fragment of mixed cores obtained at the Mitsubishi Heavy Industries testing facility. The longitudinal-transverse flow around grids with different pressure loss was studied for various fragments of mixed cores (figure 2):

- Fragment 1 consisting of two 5x5 FAs with fuel rods of similar diameter.
- Fragment 2 consisting of 5x5 and 4x4 FAs with fuel rods of different diameter.

**Figure 2.** The scheme of mixed core fragments with measurement lines.

The calculated and experimental data on the crossflows, which occur in the flow around hydraulically non-identical SGs in a PWR mixed core are close.

**Figure 3.** Data comparison for fragment 1.  
**Figure 4.** Data comparison for fragment 2, line A.
3. Mixed Core Fluid Dynamics Analysis

3.1. Comparison of the calculation results obtained by using a mixed core test model in the subchannel code and the CFD code

To analyze the flow around hydraulically non-identical grids, the subchannel code and the CFD code data cross-verification was conducted with the use of the data on lateral velocity distribution and flow rates across the core fragment height (figure 7).

The mixed core fragment consists of two 3x3 FAs of full-scale height. The FA fragments of Type 1 and Type 2 differ in grid axial position and pressure losses of the grids. In CFD model, the grids patterns without mixing vanes and distance cells were used. The real pressure losses of grids in FA fragments were ensured by increasing the grid strap thickness.

In calculations of the subchannel code, the computational model detailing and parameters were varied. The detailed description of computational model formation method is given in [7]. The following computational model parameters in the VIPRE-01 code were chosen to analyze the coolant flow in a mixed core:

- The pressure loss coefficients of grids in subchannels are set in the input data, and the flow section reduction in the grids position is not modeled.
- The height of the axial node between grids equals ~10 mm.
- Convergence limit for crossflow calculation, energy and pressure is 0.00001, convergence limit of axial flow is 0.0001 and the number of iterations equals 1000.

Comparison of calculated results of flow redistribution across the core fragment height is given in figure 8.

The results on flow rate distribution and maximum lateral velocities obtained using the thermohydraulic subchannel and CFD codes are close. The analysis has shown the possibility of calculating the longitudinal-transverse flow of the coolant in mixed core using a subchannel thermal-hydraulic code.
3.2. Analysis of Fluid Dynamics in the Full-Scale Mixed Core

The mixed core with TVS-K surrounded by reference FAs was considered. It was calculated in the VIPRE-01 code.

The main differences between the TVS-K and reference FA are:

- different pressure losses of the spacer grids and mixing grids,
- anti-vibration grid installed in the TVS-K lower part.

Two models of 1/8 core symmetry is considered to analyze the effect of the computational model detailing in the cross section on the calculation results: 20-cell (figure 9) and 93-cell (figure 10). The 20-cell model contains lumped cells and is usually used in DNBR analysis. A more detailed calculation model consists of 93 cells, in which separate cells are used to model the hot FA and the peripheral cells of the adjacent FA.

Comparison of calculation results of lateral velocity distribution and flow rates across the TVS-K height in the mixed core is given in figure 11.
From the analysis it has been obtained that in the mixed core the maximum perturbation is realized in the lower part of the TVS-K and decreases in the height of the core. When using the calculated 20-cell model, the values of lateral velocities and the change in the FA height flow rate are less than when using the 93-cell model. The minimum flow rate through a FA is 1% lower in the 93-cell model than in the 20-cell model. For DNBR analysis in a mixed core it is recommended to use the model with complete splitting of the TVS-K into subchannels taking into account the recommendations on the level of detailing, height of axial node and accuracy of calculation obtained when comparing the calculation results of the subchannel code and the CFD code.

![Figure 11. Distribution of relative lateral velocities (a) and flow rates (b) across the height of TVS-K in a mixed core.](image)

**Conclusion**

This paper provides the results of verification of the STAR-CCM+ code and the VIPRE-01 code to analyze coolant hydrodynamics in a mixed core. Close values of pressure drops, lateral velocity distribution and flow rates across the height of the mixed core fragments have been obtained by comparison of calculated and experimental data.

The fluid dynamics of flow in a full-scale core with a TVS-K surrounded by reference fuel assemblies has been analyzed. As follows from the analysis, the maximum perturbation of coolant flow takes place in the lower part of FA.

The analysis has shown that the model of a mixed core in the VIPRE-01 code correctly considers the flow redistribution and allows applying this code for DNBR analysis in mixed PWR cores.

**References**

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