Simulation of 3D hydraulic effects in the IR-8 reactor's IRT-3M FA using ATHLET code

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Abstract. This article presents the results of the calculated determination of the 3D hydraulic effects in the gaps of the fuel assembly (FA) IRT-3M. Determination 3d hydraulic effects was carried out using the one-dimensional ATHLET code. Previous work has already been done to analyze the test results hydraulic eight- and six-tube FA IRT-3M reactor IR-8. However, it has not been paid attention to the partition of hydraulic structures in the FAs in the gaps between the fuel rods in the sector in accordance with the division of thermal structures. The new improved FA model was created according to model for neutron physics calculations to create coupling calculation further. The total consumption through the FAs of the improved model changed by less than 0.01% from the base model. The obtained differences in the velocities in the flat and angular sectors will make it possible to obtain a more accurate temperature field distribution for estimation of the margin before the onset of surface boiling. The results of this work can be used in determining the permissible power of the IRT type research reactors: IR-8 at NRC KI (Moscow), IRT-MEPhI at NRNU MEPhI (Moscow), IRT-T at TPU (Tomsk) and WWR-SM at INP (Tashkent).

1. Introduction

When performing deterministic safety analyzes of reactor facilities, computational programs built on a one-dimensional approximate description of hydrodynamics in the spatial coordinate (one-dimensional codes) are used. The reactor system is presented as a system of interconnected control volumes, each of which has a certain direction from the “inlet” to the “outlet”. There is only one projection of the velocity of each of the phases (liquid, vapor) on the selected direction in an explicit form of the initial equations of hydrodynamics. This approach is fully adequate to the hydrodynamics of flows in pipes or channels, where the transverse spatial structure of the velocity field is simple and relatively easy to take into account by complementary semi-empirical relations or correlations. The paper analyzes the results of modeling one of the types of FAs used in the reactor IR-8. IR-8 is a pool-type research reactor with a power of up to 8 MW with light water as a moderator, coolant and upper protection.
The hydrodynamic characteristics are used for thermal-hydraulic calculations of IR-8 (in particular, the velocity of the coolant in the gaps of fuel assemblies), obtained in the course of experiments on a hydraulic bench with a model of an eight-tube fuel assembly IRT-3M at the Kurchatov Institute [1].

Previous work has already been done to analyze the test results hydraulic eight- and six-tube FA IRT-3M reactor IR-8 [2]. However, it has not been paid attention to the partition of hydraulic structures in the fuel assemblies in the gaps between the fuel rods in the sector in accordance with the division of thermal structures used in the analysis of the spatial energy distribution with neutron physics program based on the Monte Carlo method. Figure 1 shows a cross-section of a six-tube fuel assembly with an azimuthal split.

The code of the improved estimation ATHLET was used to carry out the calculations [3], which is included in the AC2 software package, officially obtained by the National Research Nuclear University MEPhI on the basis of a license agreement with Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany [4]. The ATHLET code is certified in Russia for carrying out stationary and transient modes in reactors with a water coolant.

There are several possibilities in the ATHLET code to simulate cross-flow in a system of connected hydraulic parallel channels. Spatial modeling of fuel assembly hydrodynamics in combination with spatial modeling of thermal structures allows obtaining more detailed spatial distribution of both coolant velocities and other thermophysical parameters. The obtained values can be used in neutron-physical calculations.

2. Description of the hydraulic bench and FA

The measurement was carried out on a special hydraulic bench (figure 1). The main element of the bench is a column (figure 2), simulating a section of the core. In addition to a FA model that is different from a real FA by absence of fuel, plate packs to simulate neighboring fuel assemblies are installed in the column. Thanks to the latest, the movement of coolant at the boundaries of fuel assemblies does not differ from actual conditions. Water is circulated through the column using a centrifugal-type pump with a maximum flow rate of 58.2 m$^3$/h. The flow rate is measured using an orifice gage, a magnehelic gage and is controlled by a valve installed on the pressure line of the pump. The method of determining the velocity and processing of the results are described in detail in [5].

In brief, the essence of the method is as follows: in each gap, the dynamic pressure was determined, based of which the velocity of water was calculated. From the known velocity and cross section, the water flow through the gap was determined.

2.1. Bench parameters with eight-tube IRT-3M FA

IRT-3M FA consists of coaxial tubular fuel elements of square cross-section with rounded corners fixed in the upper and lower end parts. Each fuel element is three-layered, consists of a fuel and cladding. The length of the fuel is 600 mm, the fuel element is 630 mm. The thickness of the fuel element is 1.4 mm, the gap between the fuel elements is 2.05 mm. The transverse dimensions of the fuel elements, as well as the perimeters and the area of the transverse gaps for the eight-tube fuel assembly are shown in table 1.
**Figure 1.** Schematic diagram of the bench:
1 – drainage; 2 – model of FA; 3 – detectors; 4 – vessel; 5 – high-water overflow; 6 – top tank; 7 – orifice gage; 8 – pump; 9 – bottom tank.

**Figure 2.** Column cross-section:
1, 2 – model and imitators FA, respectively; 3 – shell; 4 – detectors; 5 – vessel.

**Table 1.** Parameters of the eight-tube IRT-3M FA.

| № gap | The radius of the outer part of the fuel element, mm | The radius of the inner part of the fuel element, mm | Gap cross section, cm² |
|-------|---------------------------------------------------|---------------------------------------------------|------------------------|
| 0     | 35.75                                             | 33.30                                             | 2.96                   |
| 1     | 34.70                                             | 29.85                                             | 5.29                   |
| 2     | 31.25                                             | 26.40                                             | 4.73                   |
| 3     | 27.80                                             | 22.95                                             | 4.16                   |
| 4     | 24.35                                             | 19.50                                             | 3.60                   |
| 5     | 20.90                                             | 16.05                                             | 3.03                   |
| 6     | 17.45                                             | 12.60                                             | 2.46                   |
| 7     | 14.00                                             | 9.15                                              | 2.64                   |
| 8     | 10.55                                             | 6.00                                              | 1.09                   |
| 9     | 7.00                                              | -                                                 | 1.13                   |

2.2. **Parameters of the six-tube IRT-3M FA**
The cross-section of a six-tube FA is shown in figure 3. The external 6 gaps of the six-tube FA are not different from the eight-column gaps.
3. Simulation of the bench using the ATHLET code

3.1. ATHLET code description
The thermal hydraulic (TH) system analysis code ATHLET (Analysis of Thermal-hydraulics of Leaks and Transients), based on the finite volume approach is continuously developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) for the analysis of the whole spectrum of operational transients, design-basis accidents and beyond design-basis accidents without core degradation, anticipated in nuclear or non-nuclear energy facilities [6]. The thermo-fluid-dynamic module is based on a two-fluid model with fully separated balance equations for liquid and vapor, while a five equation model with a mixture momentum equation and a full range drift-flux formulation for the calculation of the relative velocity between phases is also available [7]. ATHLET provides in the current code release version 3.1A a classical 1D flow model, a pseudo-multi-dimensional method, where the 1D model equations are applied separately to each coordinate direction of a multidimensional numerical grid, and an enhanced model with a genuine multidimensional set of TH conservation equations, for a better and a more realistic representation of the complex flow phenomena [8]. This approach comprises the 3-D momentum equations implemented in both Cartesian as well as cylindrical coordinates as an extension of the one-dimensional two-fluid model of ATHLET [9].

3.2. Simulation of the six-tube IRT-3M FA
Figure 4 shows the model of the hydraulic bench for ATHLET code. All elements are built using the “branch” and “tube” objects. The “pump” was also used. With the help of GCSM signals, the differential pressure was adjusted per column to obtain the necessary flow.

Figure 5 shows the model of an eight-tube FA. During the modelling of plate packs imitators, there was a problem with the inaccuracy in the drawings of hydraulic bench, which did not allow to simulate local hydraulic resistances with sufficient accuracy. Therefore, the method was developed allowed to determine the necessary pump head and local resistances at the input to the plate packs imitators. As an estimate the values that allows with flow rate through the column of 54.8 m³/h obtain the flow rate through plate packs imitators equals the experimental value were taken. The obtained values of pump head and local resistance of the valve in further calculations remained unchanged.
3.3. Modeling of mass transfer in the system of parallel connected channels of FAs IRT-3M

There is opportunity to simulate mass transfer in a system of parallel connected channels in the ATHLET code using the "CROSSCONNECTION" object [10-14]. This makes it possible to split each gap in the fuel assembly model according to the currently used model for calculating neutron fluxes and power distribution by the Monte Carlo method (Figures 6, 7) [15 - 17].

As mentioned above, the external 6 gaps of a six-tube FA are no different from those of an eight-tube FA. Instead of the 7 gap, there is a displacer (figure 6). The model of a six-tube FA in the ATHLET code is presented in figure 7.

Figure 4. Bench model.

Figure 5. Model of six-tube FA in ATHLET code; IN_FA, OUT_FA - top nozzle and bottom nozzle; 1-7 hydraulic clearance numbers.

Figure 6. Cross-section of a six-tube fuel assembly model in the MCU-PTR program.

Figure 7. Lengthwise-section of a six-tube fuel assembly model in the MCU-PTR program.
These models allow obtaining a more detailed spatial distribution of not only the coolant velocities, but also other thermophysical parameters for using in the physical calculation. Figures 8 and 9 show cross-sections of a six-tube fuel assembly with an azimuthal split. Each gap was named according to the principle "FA Name - Gap Number - Sector Number" in the improved model. There are 73 "TUBE" objects and 72 "crossconection" objects per FA in the improved model. In figures 10 and 11 show the models of the hydraulic gaps of the basic and improved models in the ATHLET code, respectively.

**Figure 8.** Cross-section of a six-tube fuel assembly with azimuthal split.

**Figure 9.** Part of cross-section of a six-tube fuel assembly with azimuthal split.

**Figure 10.** Hydraulic gap of a six-tube FA without azimuthal division in the ATHLET, ATHLET E12-T, E12-B code - FA head and shank.
Figure 1. Hydraulic gap of a six-tube FA with azimuthal division in the ATHLET code, E12T, E12-B - FA head and shank; 1-12 numbers of hydraulic gaps.

4. Results of calculations

The values of the velocities in various gaps of a six-tube fuel assembly were obtained in the course of calculations. Figures 12 and 13 show the flow characteristics of the improved model.

Table 2 shows the velocities obtained in calculation of the hydraulic bench with a six-tube fuel assembly with and without azimuth splitting. It should be noted that the total consumption through the FAs of the improved model changed by less than 0.01% from the base model.

The obtained differences in the velocities in the flat and angular sectors will make it possible to obtain a more accurate temperature field distribution for further estimation of the margin before the onset of surface boiling. An increase in the permissible power of the reactor is expected when using the improved model of the IRT-3M FA.
Figure 12. Flow rates of the sectors of the external hydraulic gaps of a six-tube fuel assembly with an azimuthal split in the ATHLET code.

Figure 13. Flow rates of flat and angular sectors of various hydraulic gaps of a six-tube fuel assembly with an azimuthal division in the ATHLET code.
Table 2. Water velocities in the gaps of the IRT-3M FA.

| Gap number | Without azimuthal splitting | six-tube FA | azimuthal splitting |
|------------|----------------------------|-------------|--------------------|
|            |                            | flat        | angular            |
| 1          | 2.58                       | 2.57        | 2.56               |
| 2          | 2.84                       | 2.84        | 2.83               |
| 3          | 2.82                       | 2.82        | 2.81               |
| 4          | 2.81                       | 2.81        | 2.80               |
| 5          | 2.80                       | 2.80        | 2.80               |
| 6          | 2.80                       | 2.80        | 2.79               |
| 7          | 2.78                       |             | 2.78               |

5. Conclusions

There is opportunity to simulate mass transfer in a system of parallel connected channels in the ATHLET code. The difference in flow rate between the old and new models through fuel assemblies was 0.01%. This makes it possible to split each gap in the fuel assembly model according to the currently used model for calculating neutron fluxes by the Monte Carlo method. The movement of the coolant in the radial direction of a six-tube IRT-3M FAs was simulated using the one-dimensional ATHLET code. The values of water velocities into flat and angular sectors were determined.

The results of this work can be used in determining the permissible power of IRT type research reactors: IR-8 at NRC KI (Moscow), IRT-MEPHI at NRNU MEPHI (Moscow), IRT-T at TPU (Tomsk) and WWR-SM at INP (Tashkent).

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