Hydrodynamics of coolant in VVER reactor core with fuel assemblies of various designs

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Abstract. The article presents the results from experimental investigations into local coolant flow fluid dynamics that were carried out on the fragmental model of a VVER-type pressurized water reactor’s mixed core consisting of two types of fuel assemblies (FAs): TVSA-T (one segment) and TVSA-T.mod.2 (two segments). The coolant flow processes in the fuel rod bundle were simulated on an aerodynamic test bench. The pressure field in the flow was measured using a five-channel pneumometric probe. The obtained pressure field in the flow was recalculated for the coolant velocity vector according to the dependences derived during calibration. For drawing up a detailed flow motion pattern, a characteristic model cross section area was separated, which included the space between the assemblies and four fuel rod rows in each TVSA-type fuel assembly. The spatial distribution of coolant flow velocity projections was analyzed, as a result of which it became possible to reveal the regularities associated with the streamlining of spacer, mixing-, and combined-spacer grids in TVSA assemblies by coolant; to determine coolant cross flows resulting from streamlining of hydraulically nonidentical grids and to determine their localization in the experimental model longitudinal and cross sections; and to reveal the effect of accumulating flow hydrodynamic disturbances in the model longitudinal and cross sections resulting from the staggered arrangement of hydraulically nonidentical grids. The results obtained from investigations of interassembly interaction of coolant between the neighboring TVSA-T and TVSA-T.mod.2 assemblies have been adopted for practical use at JSC “Afrikantov OKBM” in estimating the thermal reliability of VVER-type reactor cores and have been included in the database for verification of computation fluid dynamics computer programs (CFD codes) and detailed cell-wise numerical analysis of VVER reactors’ core.

1. Introduction

By the present time, the Temelin NPP Unit 2 VVER reactor’s core has been partially refueled, and during this process newly designed TVSA-T.mod.2 fuel assemblies [1] were installed instead of the standard TVSA-T assemblies.

For improving the operational capacities of fuel in TVSA-T.mod.2 assemblies in comparison with the serially produced TVSA-T assemblies, certain design modifications have been made, one of which is the replacement of combined spacer grids (CSGs) performing dual-purpose functions (spacing of the fuel rod bundle and enhancement of heat transfer processes) by spacer grids (SGs) and mixing grids (MGs) separately positioned over the assembly height. In the design of TVSA intensifying grids, trapezoid-shaped deflectors are used, which produce directed flow streams in the assembly cross...
section. The deflectors used in the TVSA-T CSGs are installed according to the “swirl” arrangement, with which the streams swirl around the fuel rods, whereas the deflectors used in the TVSA-T.mod.2 MGs are installed according to the “ducting” arrangement, a solution that makes it possible to produce directed “in-line” turbulent flows.

If hydraulically nonidentical TVSAs are jointly used in the core, the distribution of coolant velocities in the cross section (referred to hereinafter as transverse velocities) and flow rates should be known. Since FAs of both types are jacketless ones, the flow is mixed not only within the boundaries of one assembly but also between the neighboring assemblies. This phenomenon must be taken into account in substantiating the operability of mixed cores [2] consisting of FAs of different types, a circumstance that generates the need of carrying out comprehensive numerical and experimental investigations of interassembly interaction of coolant between neighboring TVSAs of different designs.

2. Experimental test bench

The coolant flow in the core was simulated on the aerodynamic test bench installed in the Reactor Fluid Dynamics Laboratory of Nizhny Novgorod State Technical University n.a. R.E. Alekseev [3].

For carrying out the investigations, experimental models (EMs) geometrically similar to the design of different high level areas of the VVER reactor core fuel rod bundle were fabricated. All EM components were proportionally increased by the geometric similarity coefficient $K_g$ is equal to 4.4. The models included segments of the TVSA-T.mod.2 and TVSA-T assemblies and the space between the assemblies. The schematic arrangements of grids in the studied parts of the core fuel rod bundle are shown in Fig. 1.

![Figure 1](image)

**Figure 1.** Layout of grids in the fuel rod’s (a) lower, (b) middle, and (c) upper fragments. Grid: 1—spacer; 2—combined spacer; 3—spacer.

The coolant flow pressure field was measured by means of a pneumometric probe. The sensor consisted of five steel capillaries arranged in two mutually perpendicular diametric planes. The obtained field of flow pressures was recalculated, using the dependences derived in the course of calibration, for the coolant velocity vector in accordance with the article [4]. The error of flow pressure measurements carried out by the probe did not exceed 7%.

3. Research procedure

The inter-assembly coolant interaction processes were studied on three core fuel rod bundle fragments shown in Fig. 1.

The characteristic features of the EM model representing the fuel rod bundle lower fragment is the symmetry of the flow motion inlet conditions and that SGs of the same design are installed at its inlet.
(see Fig. 1a). The experimental model of the middle fragment features asymmetry of the inlet flow motion conditions due to the fact that SGs and CSGs are installed at the EM inlet (see Fig. 1b). The EM representing the fuel rod bundle’s upper fragment features not only asymmetry of inlet flow motion conditions but also the availability of MGs (see Fig. 1c).

The research procedure involved the following (see Fig. 2):

1. The characteristic areas in the EM cross section were selected.
2. The characteristic areas were subdivided into measurement zones, after which the flow pressure fields were measured in each of them in the characteristic sections over the EM length using the pneumometric probe, and then the obtained distribution of pressures was recalculated for the velocity projections on the coordinate axes x, y, and z, which were averaged over the gaps between the fuel rods and over the interassembly space.
3. Based on the obtained data, the distributions of velocity vector components were plotted in graphic form, and the coolant flow motion pattern in these areas was analyzed.

The coolant fluid dynamics was investigated on the models of VVER core fragments in the flow motion self-similarity zone. Thus, the obtained experimental results can be extended to the real coolant flow motion conditions in the VVER reactor core. The substantiating of representativeness of the experimental investigation of coolant flow motion conditions behind the intensifying grids carried out on the experimental test bench is given in the publications [4, 5].

![Figure 2. Layout of characteristic gaps in the EM cross section](image)

4. Substantiating of representativeness of experimental investigations

Confirmation that the experimental investigation is representative in nature is an important stage of its procedure. With the standard coolant parameters in the VVER reactor core, the Reynolds number \( Re = 500000 \), which is difficult to reach under laboratory conditions. However, since the flow of water coolant is simulated by air flow, it can be stated based on the hydrodynamic similarity theory that the profile of relative velocity \( \frac{w_{loc}}{w_{bulk}} \) remains unchanged in the self-similarity region, where \( w_{loc} \) is the velocity vector component value at the five-channel probe positioning point (local) and \( w_{bulk} \) is the axial (bulk) velocity value at the experimental model inlet. Therefore, the results obtained from studying the coolant flow fluid dynamics on the EM in the self-similarity region can be transferred to the standard coolant flow motion conditions. Thus, for substantiating of representativeness of investigations on the test bench, experiments for determining the self-similarity motion zone lower boundary were carried out.

For determining the self-similarity zone lower boundary, investigations were carried out on the test bench in the range \( Re = 20000–80000 \), which were aimed at constructing the empirical dependence of the studied part flow friction coefficient on the Reynolds number. The obtained array of points was approximated by two linear dependences: one in the turbulent flow transition region and the other in the self-similarity flow region. According to the obtained experimental results, the flow motion self-
similarity region in the EMs begins from Re = 55000, and all investigations were carried out at Re = 80000 in the section of stabilized self-similar coolant flow. The local flow friction coefficients of the spacer and combined spacer grids corresponding to the flow friction coefficients of the full-scale SGs and CSGs of standard fuel assemblies were also determined.

5. Investigation results of interassembly coolant flow interaction
Based on an analysis of the experimental investigation results, general regularities relating to the flow motion were revealed, and the following conclusions were drawn:

As the coolant flows over hydraulically non-identical spacer-, combined-, and mixing grids located at different levels (see Fig. 1), cross flows arise in adjacent TVSAs, which have a significant influence on the coolant flow in the neighboring fuel assemblies.

The following features are characteristic for the motion of coolant in the studied parts: when the flow streamlines the CSG installed in the TVSA-T, the cross flow moves to the TVSA -T.mod.2, and the cross flow upstream of the SGs and MGs installed in the TVSA -T.mod.2 is directed toward the TVSA-T.

The transverse flow velocity in the interassembly space region is approximately a factor of two lower than it is in the fuel rod bundle. This is because a coolant flow with high axial velocities exists in the gap between the assemblies, which has a damping effect on the cross flow of coolant by entraining part of the transverse mass flow in a longitudinal direction. The transverse velocity values that take place when the flow streamlines the CSGs and SGs in the studied fuel rod bundle fragments \( w_y/w_{bulk} \) make 0.30 for the middle fragment, 0.25 for the lower fragment, and 0.20 for the upper fragment, where \( w_y \) is the velocity vector projection on the y axis, and \( w_{bulk} \) is the bulk velocity at the EM inlet (Fig. 3a).

When the coolant flows over the MG located in the fuel rod bundle upper fragment, a cross flow directed to the TVCS-A is generated in the interassembly space, and the transverse velocity value is 0.25 (see Fig. 3a). This phenomenon is characteristic only for the interassembly space region and is not observed in the assembly fuel rod bundle.

The flow pattern in the fuel rods row adjacent to the interassembly space is characterized by the following features:

When the flow streamlines the CSGs and SGs located in the fuel rod bundle lower fragment, the transverse velocity values are the same and equal to \( w_y/w_{bulk} = 0.4 \) (see Fig. 3b).

The highest cross coolant flow intensity is observed when the flow streamlines the CSGs and SGs located in the fuel rod bundle’s middle fragment. When the coolant flow streamlines the CSG, the transverse velocity is \( w_y/w_{bulk} = 0.50 \), and this velocity has a close value, namely, \( w_y/w_{bulk} = 0.45 \), when it streamlines the SG (see Fig. 3b).

When the flow streamlines the CSGs and SGs in the upper fragment, the transfer velocity values are \( w_y/w_{bulk} = 0.47 \) and \( w_y/w_{bulk} = 0.40 \), respectively (see Fig. 3b). These values are close to the results obtained in the middle fragment, which may be due to the availability of the MG.

When the coolant moves through the fuel rod bundle lower and middle fragments, its transverse velocity increases. Namely, when the flow streamlines the CSGs and SGs in the middle fragment, the transverse velocity values become, respectively, by 20 and 10% higher than they are when the flow streamlines the grids of the same designs in the lower fragment (see Fig. 3b).

An analysis of the coolant hydrodynamic disturbance propagation pattern in the fuel assembly transverse section has shown the following:

Starting from the second row of fuel rods, the transverse velocity that takes place when the flow streamlines the grids of different designs decreases by a factor of two for all of the studied fuel rod bundle fragments (Fig. 3c).

The flow hydrodynamic disturbance distribution pattern in the cross section of fuel assemblies changes depending on the studied fuel rod bundle fragment. Namely, the propagation of flow disturbances is limited to the third, fourth, and fifth rows in the lower, middle, and upper fragments, respectively.
Starting from the sixth row of fuel rods, a turbulent coolant flow is observed in all studied parts of the fuel rod bundle; the transverse velocity has a value equal to approximately 0.05.

**Figure 3.** Transverse velocity distribution (a) in the space between assemblies, (b) in the fuel rod row adjacent to the space between assemblies, and (c) in the second row of fuel rods from the space between assemblies ($= 27.5 \text{ m/s, } \text{Re} = 78\,000$). Grids: 1—spacer, 2—combined spacer, and 3—mixing. Fuel rod bundle fragment: 4—lower; 5—middle; 6—upper.
6. Conclusion

Cross flows generated in streamlining of hydraulically nonidentical grids have a significant influence on the motion of coolant in the fuel rod bundle in the mixed core of a VVER reactor.

The transverse flow velocity in the space between fuel assemblies is approximately a factor of two lower than it is in the fuel rod bundle. This is because coolant flow with high axial velocities exists in the gap between fuel assemblies.

The highest transverse velocity is observed when the flow streamlines the combined spacer grid located in the fuel rod bundle’s middle fragment.

When coolant moves through the fuel rod bundle’s middle fragment, the flow transverse velocity increases: in streamlining the CSGs and SGs, it is by 20 and 10% higher, respectively, than in streamlining the grids of the same designs in the lower fragment.

The flow disturbance propagation pattern in the fuel assembly cross section varies depending on the studied fuel rod bundle fragment: the propagation of flow disturbances in the lower, middle, and upper fragments is limited to the third, fourth, and fifth row of fuel rods, respectively.

Reference

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