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# Experimental studies into the fluid dynamic performance of the coolant flow in the mixed core of the Temelin NPP VVER-1000 reactor

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**Abstract**

The paper presents the results of studies into the interassembly coolant interaction in the Temelin nuclear power plant (NPP) VVER-1000 reactor core. An aerodynamic test bench was used to study the coolant flow processes in a TVSA-type fuel assembly bundle. To obtain more detailed information on the coolant flow dynamics, a VVER-1000 reactor core fragment was selected as the test model, which comprised two segments of a TVSA-12 PLUS fuel assembly and one segment of a TVSA-T assembly with stiffening angles and an interassembly gap. The studies into the coolant fluid dynamics consisted in measuring the velocity vector both in representative TVSA regions and inside the interassembly gap using a five-channel pneumometric probe. An analysis into the spatial distribution of the absolute flow velocity projections made it possible to detail the TVSA spacer, mixing and combined spacer grid flow pattern, identify the regions with the maximum transverse coolant flow, and determine the depth of the coolant flow disturbance propagation and redistribution in adjacent TVSA assemblies. The results of the studies into the interassembly coolant interaction among the adjacent TVSA assemblies are used at OKBM Afrikantov to update the VVER-1000 core thermal-hydraulic analysis procedures and have been added to the database for verification of computational fluid dynamics (CFD) codes and for detailed cellwise analyses of the VVER-100 reactor cores.



*Keywords:* Reactor core; Fuel assembly; Spacer and mixing grids; Interassembly interaction; Coolant fluid dynamics.

## Introduction

Rosatom State Corporation is facing a challenging task of expanding the presence of Russian companies in the international market. Market positions cannot be strengthened without improving the supplied equipment, including through optimizing the fuel assembly (FA) design.

OKBM Afrikantov carries out the development and design of fuel assemblies for the VVER-type reactors based both within and beyond Russia. One of OKBM's partners is the Temelin nuclear power plant (NPP) in the Czech Republic in which unit 1 has a core fully loaded with TVSA-T fuel assemblies.

Specific to the TVSA-T design is the use of combined spacer grids (CSG) consisting of a cellular spacer grid (SG) and a plate-type mixing grid (MG) with deflectors arranged so that to create a vortex-type flow of the coolant about the fuel elements [1].

At the present time, the TVSA-T assemblies have been partially replaced for improved TVSA-12 PLUS assemblies featuring an optimized SG arrangement with the MG deflectors arranged so that to generate a horizontal coolant flow between the rows of fuel elements.

Since both FA types have a shroudless design, the coolant mixing takes place not only within one assembly but also among the adjacent assemblies. This phenomenon shall be allowed for when estimating and justifying the thermal-hydraulic reliability of the VVER reactor core, and this has dictated the need for investigating the interassembly interaction of the coolant flow [2].

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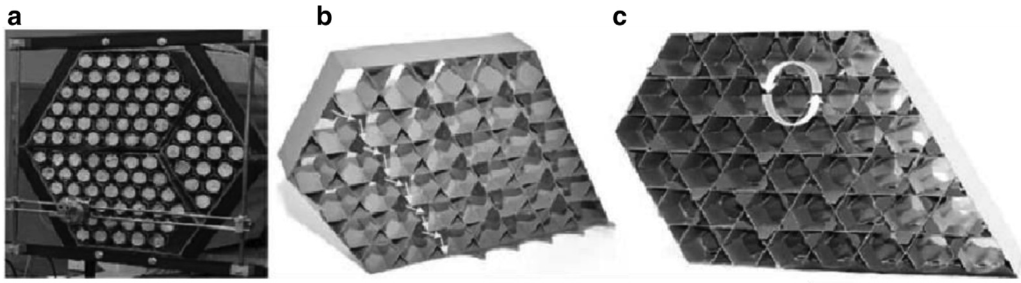


Fig. 1. Test model and investigated TVSA grid belts: (a) – test model; (b) – TVSA-12 PLUS MG belt; (c) – TVSA-T CSG belt.

## Test bench

An aerodynamic test bench in the form of an open circuit with air pumped through it was built at NNSTU to study the interassembly coolant interaction in the VVER reactor core. The test bench comprises a high-pressure fan, a receiver tank, a test model (TM), a flow meter, and a measuring system [3,4]. For the bench operation, air is injected into the receiver tank using the HP fan, passes further through the damping section and the TM, and is then discharged into the atmosphere.

The test model is a fragment of the VVER reactor core, comprising two segments of a TVSA-12 PLUS assembly and one segment of a TVSA-T assembly with an interassembly gap (Fig. 1a), and has exactly the same geometry as the prototype.

The TVSA-12 PLUS mixing grid belt (Fig. 1b) has eddying deflectors arranged so that to create the coolant flow between the rows of fuel elements [5]. The deflectors in the TVSA-T CSG belt (Fig. 1c) are arranged so that to generate a vortex-type coolant flow.

## Measuring system

The measuring system comprises a five-channel pneumometric probe, a block of analog pressure transducers and a computer with respective software.

The coolant flow velocity vector was measured using the five-channel pneumometric probe. The threshold deviations of the absolute velocity projections on the $X$, $Y$ and $Z$ axes did not exceed 7% of the absolute velocity.

The probe readings were taken by the block of analog pressure transducers. The threshold value of the transducer basic permissible error was $\pm 0.25\%$.

## Representative status of the studies

An important stage in an experimental study is to confirm its representative status. Since the water coolant flow is modelled by air, then one can state, based on similarity theory, that the relative velocity profile remains practically invariable in the self-similarity region. Therefore, a TM-based study into the interassembly coolant interaction in the self-similarity region will make it possible to extend the experimental results to the full-scale conditions of the coolant flow in standard reactor cores. A series of studies was conducted to identify the coolant flow conditions in the TM and find the self-similar coolant flow area boundaries. According to test results, the self-similar flow region inside the TM originates from a Reynolds number of 55,000, and all interassembly coolant interaction studies were conducted with the Reynolds number being 80,000 in the coolant stabilized self-similar flow area. The SG, MG and CSG flow resistance coefficient (FRC) was experimentally found on the aerodynamic test bench. The need for conducting the studies was dictated by the fact that demonstration of the representative status of an experimental research requires the equality of the FRC for standard grids and for the TM grids to be observed. An analysis into the FRC investigation results shows that the selected design and geometry of SGs, MGs and CSGs in the self-similar flow region provide for the desired hydraulic resistance, while the values obtained are consistent with the standard grid FRC and are equal to $\xi_{SG}=0.55$, $\xi_{MG}=0.55$, and $\xi_{CSG}=1.05$.

## Investigation procedures

The experimental studies into the interassembly coolant interaction in the adjacent TVSA-12 PLUS and TVSA-12 assemblies consisted in measuring the local velocity fields by a five-channel pneumometric probe. The velocity vector was measured in a representative region of the TM interassembly gap with the SG, MG and CSG arrangement matching the VVER core fuel bundle's upper and lower fragments (Fig. 2). A detailed coolant flow pattern was constructed based on the test data.

## Test data on the interassembly coolant interaction in the lower fragment of the TVSA-T and TVSA-12 plus fuel bundle

An analysis of the experimental research results has allowed the following conclusions to be made.

1. The transverse flow moves into the TVSA-12 PLUS in the region of the TM interassembly gap upstream of the TVSA-T CSG, and in the opposite direction upstream of the TVSA-12 PLUS SG. The value of the transverse velocity ($Wy/W^{aver}$) is the same upstream of the CSG and the SG and is equal to 30% of the flow-average velocity (Fig. 3).

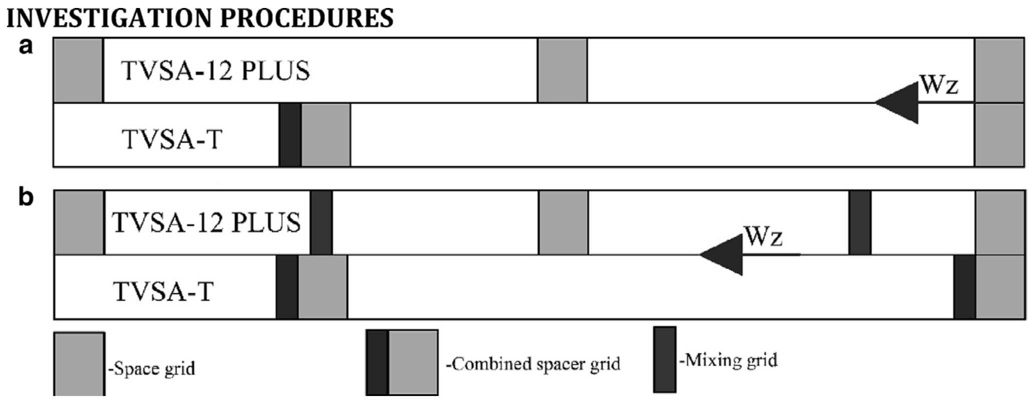


Fig. 2. SG, MG and CSG arrangements across the TM: (a) – upper fragment of the TVSA fuel bundle; (b) – lower fragment of the TVSA fuel bundle.

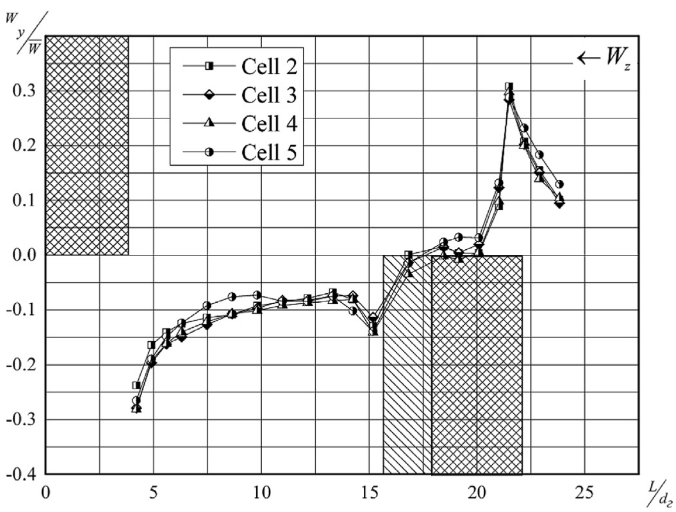


Fig. 3. Distribution of the relative transverse velocity in the interassembly gap.

2. The spaces between the fuel elements adjoining the interassembly gap have the maximum transverse coolant flow for the given fragment of the TVSA fuel bundle. The transverse velocity ($Wy/W^{aver}$) upstream of the CSG and the SG is equal to 40% of the flow-average velocity (Fig. 4a, b).
3. The distribution depth of the coolant flow disturbance in the TVSA-T and TVSA-12 PLUS assemblies caused by the coolant flow about the SGs and CSGs is limited to the fuel elements in row 4. This makes it clear that the intense redistribution of the flow among the adjacent assembly segments starts as early as at the model's fuel bundle inlet.

## Test data on the interassembly coolant interaction in the upper fragment of the TVSA-T and TVSA-12 plus fuel bundle

The major difference between the TVSA bundle upper and lower fragments is that the TVSA-12 PLUS assemblies use mixing grids designed such that the deflectors may be optionally arranged as shown in Fig. 5.

An analysis into the experimental data has made it possible to identify the effect the MG has on the interassembly coolant interaction. The following has been found.

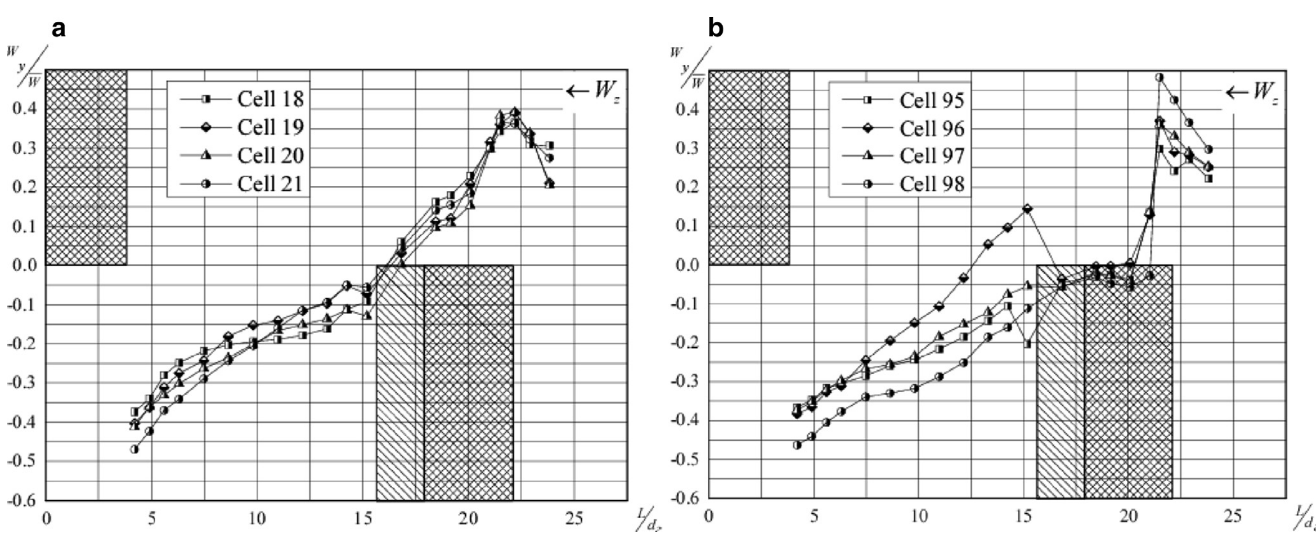


Fig. 4. Distribution of the relative transverse velocity in the fuel element row adjoining the interassembly gap: (a) – TVSA-12 PLUS; (б) – TVSA-T.

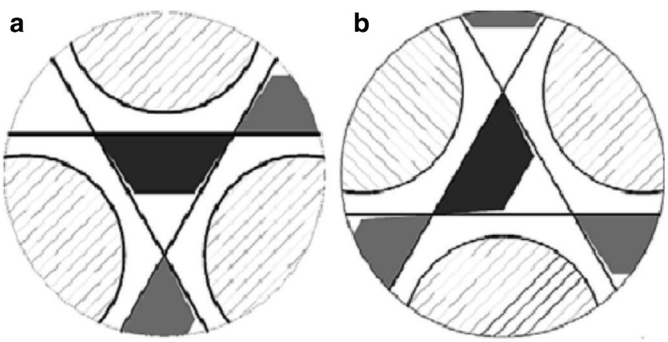


Fig. 5. MG deflector arrangement in a TVSA-12 PLUS cell: (a) – downward directed deflector; (b) – laterally directed deflector.

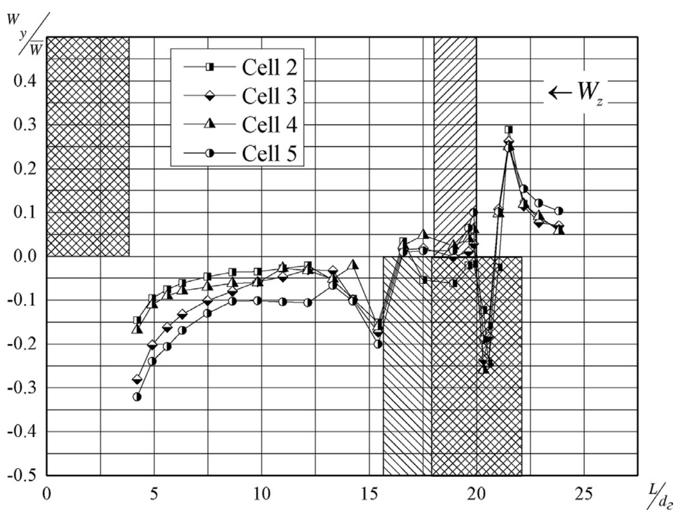


Fig. 6. Distribution of the relative transverse velocity in the interassembly space.

1. The transverse flow moves into the TVSA-12 PLUS upstream of the TVSA-T CSG, and oppositely, that is, into the TVSA-T, upstream of the TVSA-12 PLUS MGs and SGs. The transverse velocity value ($Wy/W^{aver}$) in the interassembly gap upstream of the CSG and the MG is equal to 30% of the flow-average velocity (Fig. 6).
2. The value of the relative transverse velocity ($Wy/W^{aver}$) reaches 30% of the flow-average velocity in the interassembly gap regions bordering the TVSA-12 PLUS cells with the deflector directed towards the interassembly gap, and 15% of the flow-average velocity in the regions adjoining the cells with the deflector directed towards the TVSA-12 PLUS assembly (Fig. 6).
3. The gaps between the TVSA-12 PLUS fuel elements adjoining the interassembly space have a transverse coolant flow created by the coolant flow about the TVSA-T CSGs. The value of the transverse velocity ($Wy/W^{aver}$) upstream of the CSG is 50% of the flow-average velocity (Fig. 7).
4. Apart from the transverse flow created by the flow about the SG, the formation of the coolant flow downstream of the TVSA-12 PLUS MG depends on the MG deflector arrangement. The transverse velocity ($Wy/W^{aver}$) accounts for 50% of the flow-average velocity in the gaps between the TVSA-12 PLUS fuel elements adjoining the interassembly space where the deflector is directed towards the interassembly gap, and is 30% of the flow-average velocity in the gaps between the fuel elements where the deflector is directed towards the TVSA-12 PLUS assembly (see Fig. 7).
5. The gaps between the TVSA-T fuel elements adjoining the interassembly space have a transverse coolant flow moving into the TVSA-12 PLUS assembly immediately upstream of the CSG, and oppositely, that is, into the TVSA-T assembly, upstream of the TVSA-12 PLUS SG. The transverse velocity ($Wy/W^{aver}$) is 20% of the flow-average velocity upstream of the CSG and 30% of the flow-average velocity upstream of the SG (Fig. 8).

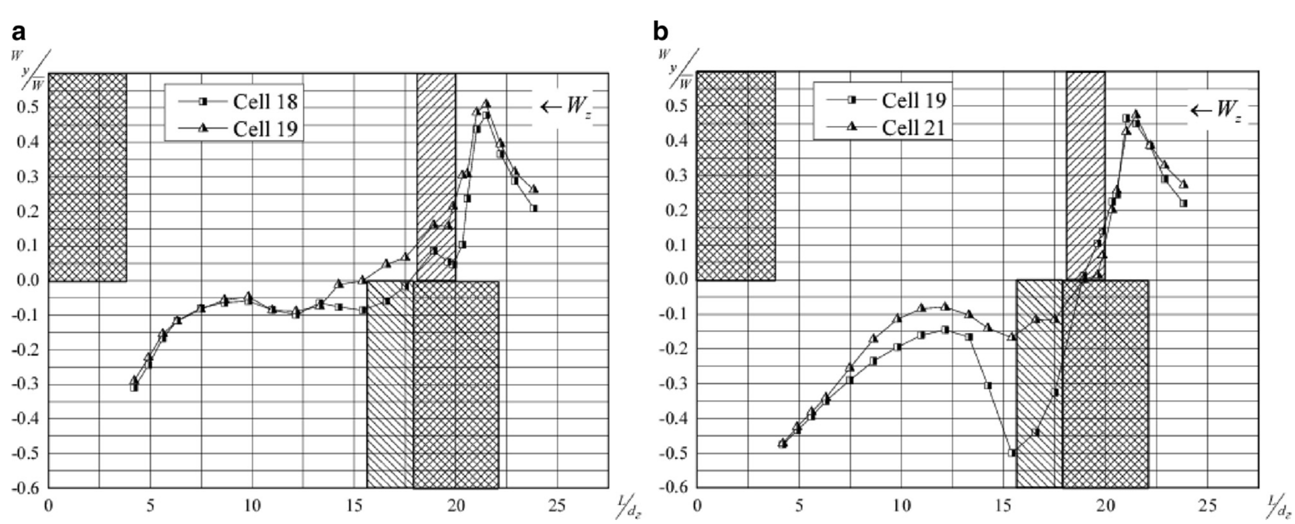


Fig. 7. Distribution of the relative transverse velocity in the gaps between the TVSA-12 PLUS fuel elements adjoining the interassembly space: (a) – the gap with the deflector directed towards the interassembly space; (b) – the gap with the deflector directed towards the TVSA-12 PLUS assembly.

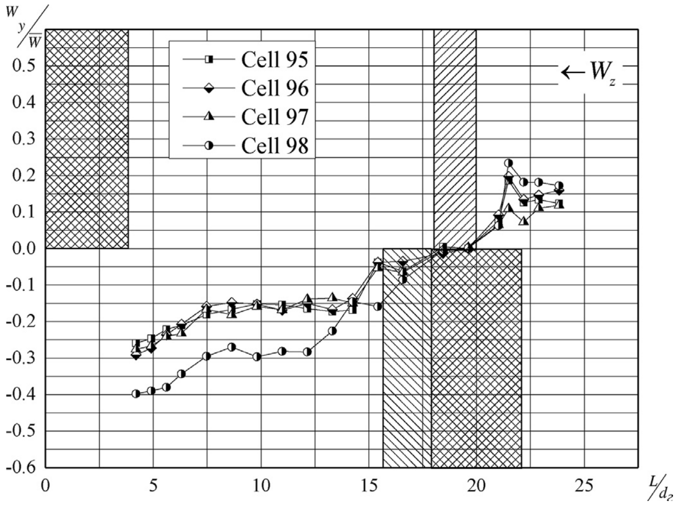


Fig. 8. Distribution of the relative transverse velocity in the TVSA-T fuel element row adjacent to the interassembly gap.

6. The distribution depth of the TVSA-12 PLUS and TVSA-T coolant flow disturbances is limited to the four extreme fuel element rows with the flow being about the CSG, and to the third fuel element row in each of the assemblies with the flow being about the SG. This proves that there is an intense interassembly interaction among the adjacent TVSA assemblies.
7. The TVSA-12 PLUS MG design suggests two options for the deflector and MG rim shaped edge mutual arrangement forming the coolant flow: the opposite positions of the deflector and the MG rim shaped edge and a codirectional arrangement of the deflector and the MG rim shaped edge.

It may be concluded based on results of a coolant flow distribution analysis that the TVSA-12 PLUS assembly regions with the deflector and the MG rim shaped edge being positioned oppositely have a 10% decreased coolant flow, and the regions with a codirectional arrangement of the deflector and the MG rim shaped edge have a 10% increased coolant flow.

## Conclusion

The obtained test data have allowed the pattern of the coolant flow about the TVSA spacer and mixing grids to be detailed, and the following conclusions to be made.

1. The maximum value of the velocity vector transverse component (about 40–50% of the flow-average velocity) occurs in the gaps between the TVSA-T and TVSA-12 PLUS fuel elements adjoining the interassembly gap.
2. The value of the transverse velocity vector component does not exceed 30% of the average-flow velocity in the TVSA-T and TVSA-12 PLUS interassembly space region.
3. The distribution of the TVSA-T and TVSA-12 PLUS coolant flow disturbances is limited to the four peripheral fuel element rows, which evidences of a highly intense redistribution of the coolant flow among the adjacent assemblies.
4. A 10% decrease in the coolant flow is observed in the TVSA-12 PLUS assembly regions with the deflector and the MG rim shaped edge positioned oppositely, and a 10% coolant flow increase is observed in the regions with the deflector and the MG rim shaped edge arranged codirectionally.

The obtained results may be used as the database for the verification of CFD codes and programs for detailed cell-wise analyses of water-cooled water-moderated nuclear reactor cores to reduce the conservatism in justifying the thermal reliability of cores.

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