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Investigation of Coolant Mixing in Reactor VVER-1000

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Abstract –*We present an experimental investigation of coolant mixing in downcomer and lower plenum of VVER-1000 here. The arrangement of the problem, the methodology and results are discussed. Three groups of experiments simulating coolant mixing were executed: in conditions of RCP start-up, during natural circulation recovery in the course of SB LOCA and in conditions of stable operation of different amount of RCPs. Results of experiments are used for validation of numerical codes.*

I. INTRODUCTION

The issue of coolant mixing in downcomer and lower plenum of PWR- and VVER-type reactors is very important for the basis of reactor unit safety. Currently, 1-D thermal hydraulic codes are widely applied for the performance of DBA analyses. In Russia those are KORSAR, TRAP, RELAP, CATHARE, ATHLET etc.

The spectrum of the analyzed accidents and transients includes the initiating events resulting in asymmetric spatial perturbation of either the coolant temperature or boron concentration at the core inlet. This leads accordingly to a local reactor power change and affects the reactor safety. However, it is impossible to simulate asymmetric 3-D transient processes in the reactor hydraulic system with 1-D codes. The response of the core to the transients with non-homogeneous conditions at core inlet strongly depends on degree of mixing in downcomer and lower plenum before coolant reaches the core itself. It is necessary to highlight that one of most complicated 3-D hydrodynamic processes is the process of boron transport and dilution.

The assumptions of "ideal mixing" and "absence of mixing" could give a wide variety of predicted consequences in the core during a computational assessment. The first assumption leads to highly optimistic results, while the second one leads to excessively top-heavy penalizing results. A precise method is required for simulation of the mixing process enabling to allow a sound reduction in the conservatism of calculations for DBA analysis.

At present, a series of simplified 3-D thermo-hydraulic codes, such as TRAP-KS, DKM, KORSAR/GP, etc, are used in OKB "GIDROPRESS" for performing the design calculations. Commercial CFD codes, such as CFX and STAR-CD are used to support the thermo-hydraulic codes. However, nowadays the mentioned codes are validated insufficiently and creditability of calculations performed could be subjected to a doubt.

The investigation of coolant mixing, as well as obtaining the data for validation of computer codes was the main objective of the international project TACIS R2.02/02 "Development of safety analysis capabilities for VVER-1000 transients involving spatial variations of coolant properties (temperature or boron concentration) at core inlet”. The collaborators from AREVA (France), Forschungszentrum Dresden (Germany) and University of Pisa (Italy) took part in the project together with the specialists of OKB “GIDROPRESS”. Actually, a series of standard problems was implemented and alongside with the experiments the pre-test and post-test calculations were performed.

II. INVESTIGATED PROCESSES

In the framework of the project, 10 experiments were performed. The experiments have been classified into 3 groups.

The first group of the experiments replicated the mixing process of flows with different boron concentration during RCP start-up. In these experiments the insertion of a condensate slug into the core model was simulated, where the formation of such a slug is possible in the loop seal. Two experiments were performed with different slug volumes.

The second group of the experiments reproduced the mixing processes of flows with different boron concentration undergoing natural circulation recovery during the course of SB LOCA. In these experiments condensate slugs with different densities were inserted into the core model. Three experiments were performed.

The third group covered experiments that replicated the effect of a steam line break or an asymmetric boron (or condensate) injection into one of the loops. Five experiments within the third group were examined with different combinations of operating RCPs.

It should be noted that for the three groups of experiments described above, the distribution of the coolant is ruled by three different forces:

- for the RCP start-up conditions, it is the inertia, characterized by the Strouhal number of Eq. (1):

$$\mathrm{Sr} = \frac{\mathrm{W} \cdot \tau}{\mathrm{L}} \qquad (1);$$

- during natural circulation it is gravitational force, characterized by the Froude number of Eq. (2):

$$Fr = \frac{W^2}{g \cdot L \cdot \frac{\Delta\rho}{\rho}} \qquad (2);$$

- for the conditions with stable reactor coolant flowrate it is the friction force, characterized by the Reynolds number of Eq. (3):

$$\mathrm{Re} = \frac{W \cdot d}{\nu} \qquad (3).$$

III. EXPERIMENTAL FACILITY AND METHODOLOGY OF INVESTIGATION

The experiments were run at OKB “GIDROPRESS” 4-loop test facility representing the 1:5 scale model of VVER-1000 reactor. Schematic diagram of the test facility is presented in Figure 1. An overhead view of the test facility and the model is provided in Figure 2.

The test facility includes the main coolant pipeline (MCP) with four loops, pressurizer and auxiliary systems for the make-up and blow-down of the MCP. The diameter of MCP pipes was chosen in accordance with reactor model scale. The length of coolant pipelines was chosen in such a way as to ensure that coolant transport time in the loop was consistent with the full-scale reactor.

The investigation of the mixing processes was achieved through the use of conductivity measurements, where a sodium chloride solution used as a tracer. Thus, the facility is equipped with the systems for the preparation and injection of salt solutions.

The pressurizer is connected to loop 2. Other loops are similar to loop 2 except for loop 4, which is equipped with two additional valves for the simulation of the loop seal, where the accumulated condensate can be replicated by means of the tracer slug injection. The core is not simulated completely. The core imitator is installed in reactor model instead of fuel assemblies and the protective tube unit. The core imitator presents a bundle of 91 tubes, held by three spacer grids used for simulation of pressure loss of the core and the protective tube unit. Conductivity probes are located at core inlet and they are installed into tubes through the reactor model cover.

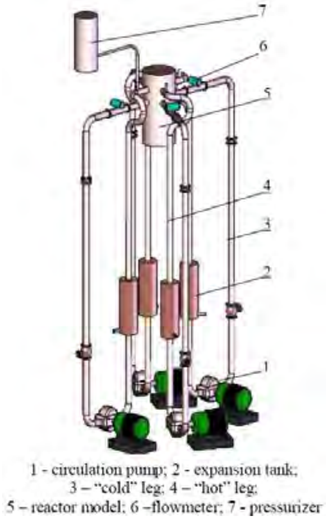

Fig. 1. Scheme of the 4-loop test facility.

Fig. 2. Overhead view of the test facility and reactor model.

The main technological and experimental parameters to be registered at the facility are listed below:

- coolant flowrate in loops and flowrate of the salt solution in injection lines;
- pressure drop across the reactor model;
- pressurizer pressure;
- liquid levels in salt solution tank and pressurizer;
- temperatures of coolant and salt solution.

For measurement of salt concentration during the experiments conductivity probes were used. They sensors were installed at:

- the core imitator inlet – 91 sensors;
- the inlet and outlet nozzles of the reactor model.

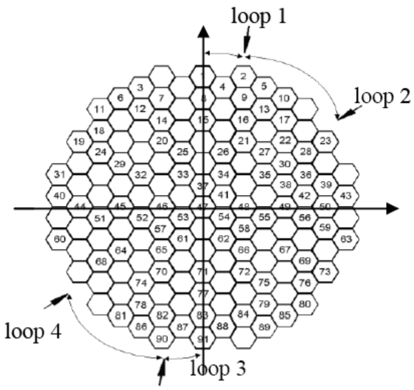

Fig. 3. Arrangement of the conductivity probes at the core inlet (model viewed from the top).

Figure 3 shows the layout of the conductivity probes at the core inlet. The probes measure the conductivity of coolant at the point of sensors location. The conversion of conductivities into solution concentrations is based on pre-test calibrations performed with a standard conductometer. As a result, the actual values of the concentrations were determined at each point, where conductivity sensors had been installed.

Experimental data presentation and their analysis were performed using a dimensionless (relative) concentration, defined from Eq. (4):

$$\theta(x,y,z,\tau)=\frac{C_i(x,y,z,\tau)-C_0}{C_1-C_0} \qquad (4);$$

where, $C_i(x,y,z,\tau)$ – is local value of concentration at the point of measurement, g/kg;

C_0 – is initial concentration in the circulation circuit, g/kg;

C_1 – is the concentration of tracer injected into the circulation circuit, g/kg.

Each experiment was performed five times for statistical reliability.

IV. RESULTS OF INVESTIGATION

In the first group of experiments the volume of condensate slug, supplied to the reactor as a result of RCP start-up in the loop 4, was varied. In experiment E1, volume of slug was 0,072 m^3, that corresponds to 9 m^3 at the full-scale reactor. In experiment E2, the volume of slug was 0,12 m^3. Before the experiment, the section of pipeline in loop 4 between the quick-operation valves was filled with salt solution. Both quick-operation valves were opened at the same time with the RCP startup. As a result, the forced circulation was formed in loop 4 with the flowrate of about 220 m^3/h, and reverse flow was set up in other loops. Figures 4 and 5 provide the contour plots of the variation of relative concentration at the core inlet in experiments E1 and E2.

The character of the flow at the core inlet is defined by the operation of the RCP in the loop containing the slug. In the beginning, the concentration of tracer started to increase in the peripheral part of the core located opposite to loop 4, then the concentration of tracer began increasing in the area of loop 4 and only after that the relatively uniform filling up of the core inlet section with the tracer took place. The flow of "pure" coolant through the cross-

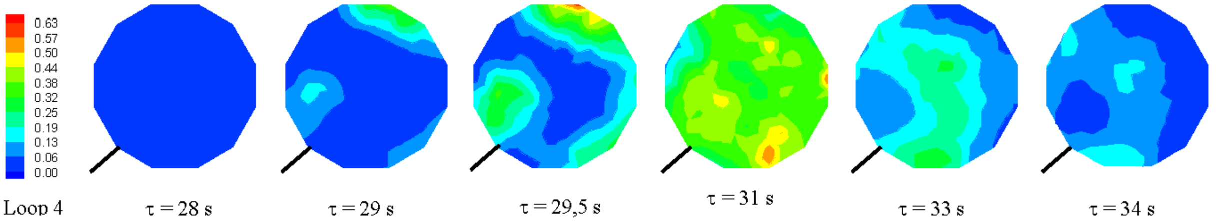

Fig. 4. Variation of relative concentration at the core inlet. E1.

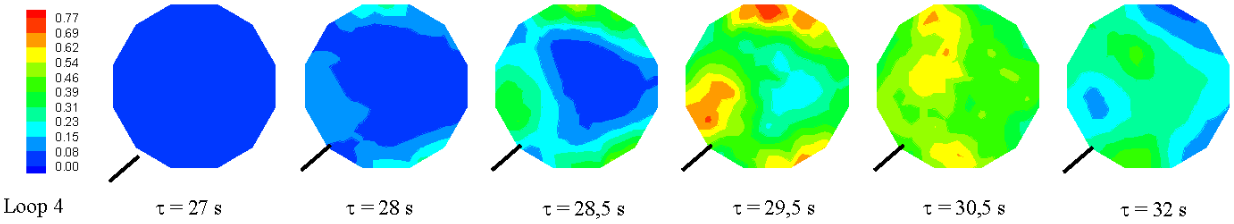

Fig. 5. Variation of relative concentration at the core inlet. E2.

section at the core inlet occurred in a similar way later in the experiment. The maximum value of local tracer concentration in the core did not reach 100 % in the experiments of the first group.

In general and when applying the results of the first group of experiments to the full-scale reactor, one might conclude that during the RCP start-up, coolant flow moves in the annulus downcomer surrounding the core barrel. At the same time, the increase in volume of condensate slug formed in the loop seal has no influence on the character of coolant flow, but it does lead to higher perturbation at the core inlet. Accordingly, it is possible to conclude that the increase in the volume of the condensate slug transported to the reactor during the RCP start-up leads to an increase in the degree of boron dilution in the core. Thus, there is an increasing potential danger of fuel rods damage. However, there are no flow regions occupied by pure condensate in the core due to good coolant mixing in the downcomer and lower plenum.

Results of ANSYS CFX-10.0 calculations [Ref. 1] (see Figure 6) are in agreement with the conclusions on the character of flow in the downcomer annulus made on the basis of the results of experiments E1 and E2.

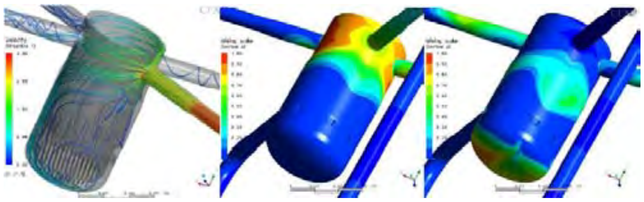

Fig. 6. Variation of parameters in the downcomer of the reactor model. E1.

Figure 7 presents the evolution of relative concentration at the core inlet for the separate sensors in experiment E2. It is clear that results of the calculation and experiment have a good coincidence in time as well as in the amplitude of the perturbation.

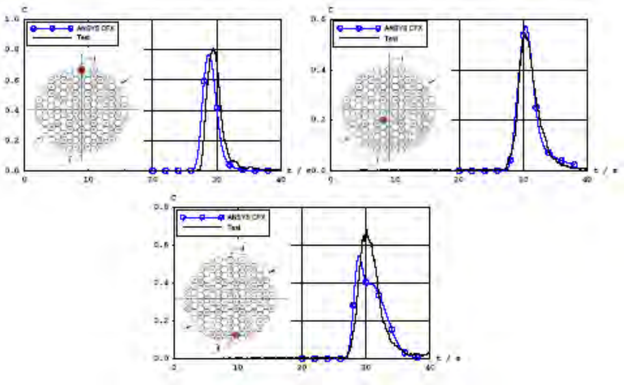

Fig. 7. Variation of relative concentration at the core inlet. Comparison of the results of from the calculation and measurements of experiment E2.

In the second group of experiments the density ratio between coolant in the slug and coolant in the circulation circuit was varied. Conditions of natural circulation recovery in the course of SB LOCA caused the transport of the condensate slug to the reactor. In experiment E3 a "heavy" slug was simulated (the density ratio was 1,05), in experiment E4 a neutrally buoyant slug in the circulation circuit was simulated, and in experiment E5 a "light" slug was simulated (the density ratio was 0,98). Supply of the reactor with the slug was performed in the same way as in the first group of experiments. However, a coolant flowrate of 20 m^3/h was formed in loop 4, while in the other loops the coolant flowrate was absent.

In experiment E3 (see Figure 8), the concentration of tracer began to increase in the core periphery, to the left of and to the right of loop 4. Subsequently, the concentration of tracer increased in the central part of the core. And the cross-section at the core inlet became relatively uniformly filled up with the tracer. The central part of the slug slowly passed through the core, and its flowing finished by 280-300 s approximately. It testifies to the effect that the "heavy" slug had accumulated in the centre of the lower part of the reactor vessel bottom, and due to the small lifting velocity of coolant it was slowly lifted up into the core.

In experiment E4 (see Figure 9), the concentration of tracer started to increase in the peripheral part of the core located opposite to loop 4. Then the concentration of tracer began to increase in the area of loop 4, and only after that a relatively uniform filling up of the section at the core inlet with the tracer took place. The slug passed through the core significantly faster in experiment E4 than in experiment E3. The maximum value of local tracer

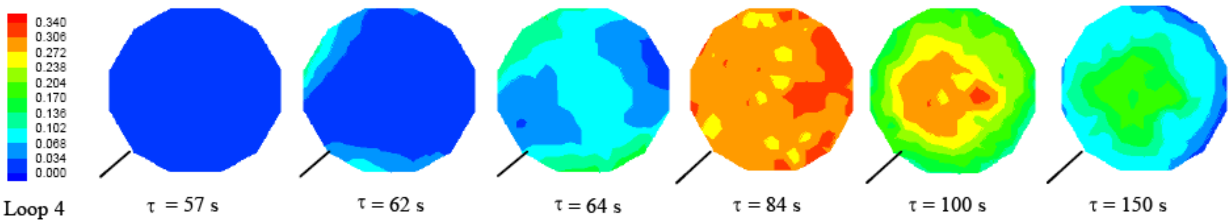

Fig. 8. Variation of relative concentration at the core inlet. E3.

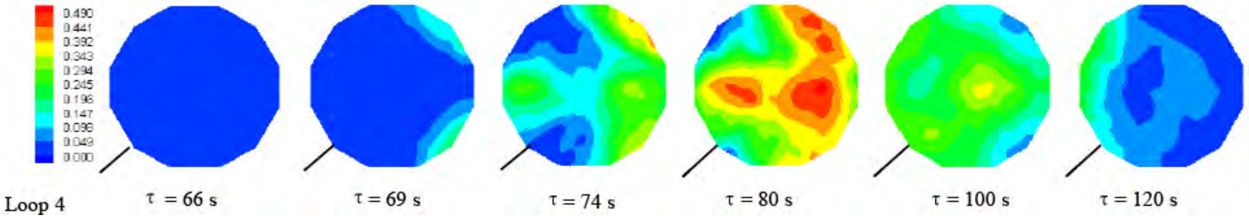

Fig. 9. Variation of relative concentration at the core inlet. E4.

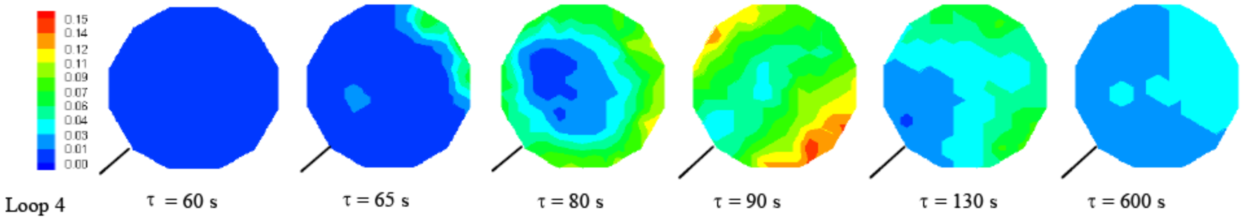

Fig. 10. Variation of relative concentration at the core inlet. E5.

concentration in the core in experiment E4 was essentially greater, than in experiment E3, however in both cases it did not reach 100 %.

In experiment E5 (see Figure 10), the concentration of tracer started to increase in the peripheral part of the core and then in the central part of the given section. The time required for slug to pass through the core was significantly greater in experiment E5 than in experiments E3 and E4. The maximum value of local tracer concentration in the core in experiment E5 was two times less than in experiment E3 and three times less than in experiment E4.

The following conclusions can be drawn by the results of the second group of experiments and applied to full-scale reactors. In the conditions of natural circulation, the transport of the condensate slug strongly depends on density difference between the condensate slug and the main coolant. For the neutrally buoyant case, the slug moves together with the coolant, and maximum concentration changes are observed at the core inlet. In the case of a "heavy" slug transportation the condensate slug lingers at the bottom of the reactor lower plenum and gradually washes away during a long time starting from the periphery. The value of the concentration perturbation at the core inlet is less than the neutrally buoyant case. A similar result takes place during "light" slug transportation. However, in this case, the condensate slug accumulates in the upper part of the downcomer under the separating shoulder and also gradually washes away from there. The analogous result was obtained by ANSYS CFX-10.0 calculations [Ref. 2]. Figures 11 and 12 present the tracer distribution in the downcomer of the reactor model in experiments E3 and E5.

Figure 13 presents evolution of relative concentration at the core inlet for separate sensors in experiment E4. It is clear that the results of calculation and experiment have a good coincidence in time as well as in the amplitude of the perturbation.

<u>In the third group of experiments</u> the number of initially operating RCPs was varied. In experiment E6, the

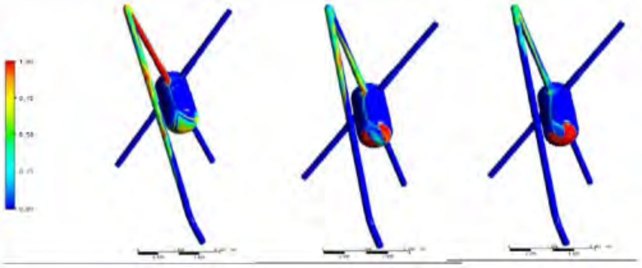

Fig. 11. Tracer distribution in the reactor model in different moments of time. Results of the calculation of experiment E3.

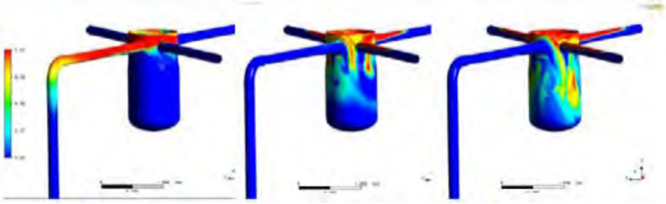

Fig. 12. Tracer distribution in the reactor model in different moments of time. Results of the calculation of experiment E5.

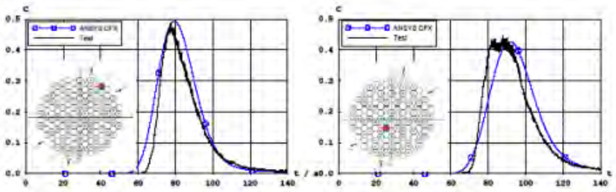

Fig. 13. Variation of relative concentration at the core inlet. Comparison of the results of the calculation and measurement of experiment E4.

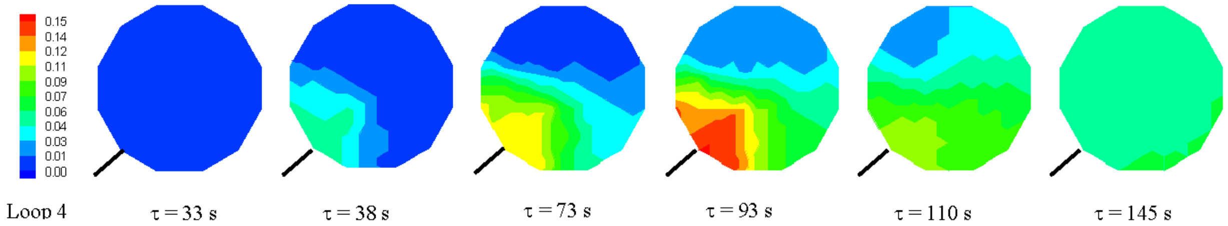

Fig. 14. Variation of relative concentration at the core inlet. E6.

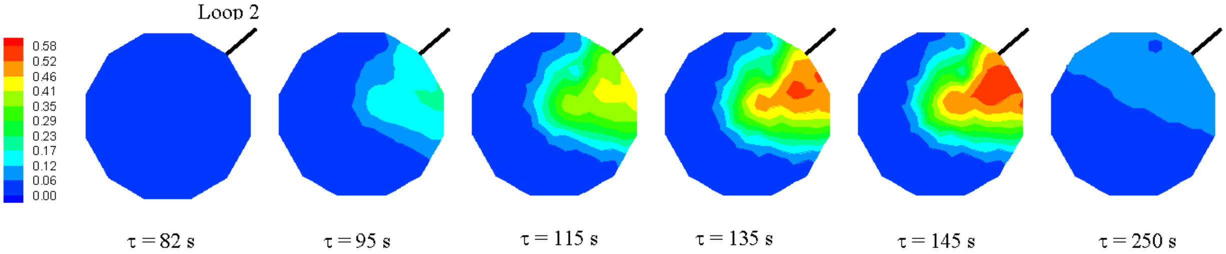

Fig. 15. Variation of relative concentration at the core inlet. E7.

operation of all RCPs was simulated, natural circulation was simulated in experiment E7, the operation of three RCPs was simulated in experiment E8, the operation of two RCPs was simulated in experiment E9, operation of one RCP was simulated in experiment E10. In the loops with operating RCPs the forced circulation was applied with a flowrate of about 172 m^3/h, and reverse flow was set up in the idle loops. Tracer injection was realized in one of the loops with operating RCP. The flowrate of the of the tracer injection was equal to 14 m^3/h, the duration of the injection was 60 seconds. Figures 14-18 provide the contour plots of variation of relative concentration at the core inlet in experiments E6-E10.

The following conclusion can be made by the results of the third group of the experiments as applied to the full-scale reactor. During condensate injection into the circulation loop of primary side under the conditions of four, three and two RCPs operation, and also under the conditions of natural circulation, a sector with reduced concentration of boron forms at the core inlet.

From the viewpoint of the sector formation, experiment E10 simulating operation of one RCP (see Figure 18) differs from other experiments of the third group. In experiment E10 was no formation of the sector with increased concentration of the tracer (Figures 14 to 17). Nevertheless, sufficient uniform filling of the whole cross-section at the core inlet with the tracer took place.

In Figure 19, the examples of tracer distribution at the core inlet observed in experiments E7 and E8 and obtained from calculations using ANSYS CFX-10.0 [Ref. 3] are presented at different time moments of investigated processes. It is clear that results of calculation and experiment are in good agreement.

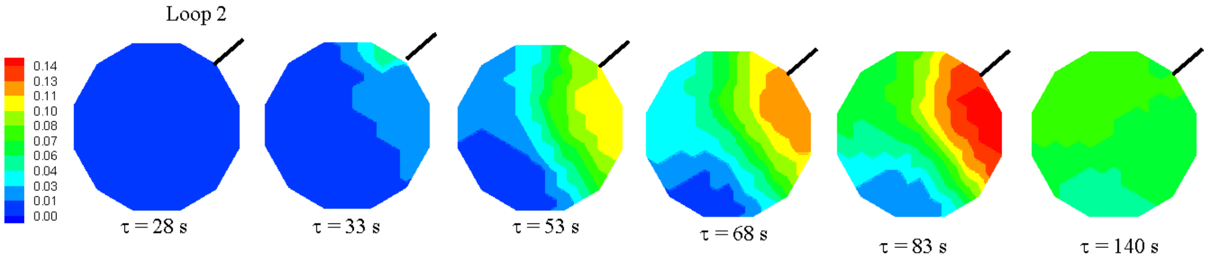

Fig. 16. Variation of relative concentration at the core inlet. E8.

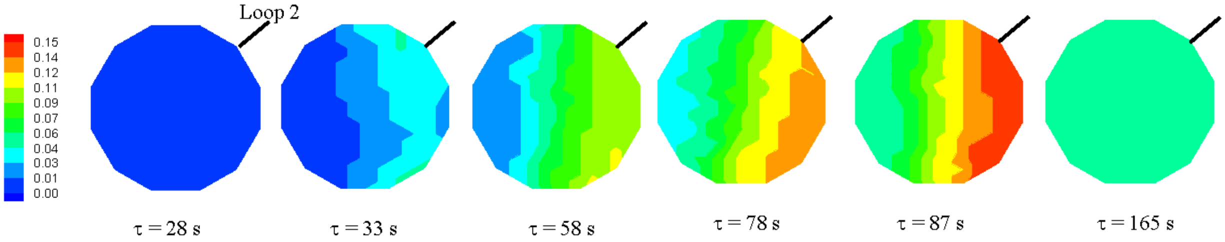

Fig. 17. Variation of relative concentration at the core inlet. E9.

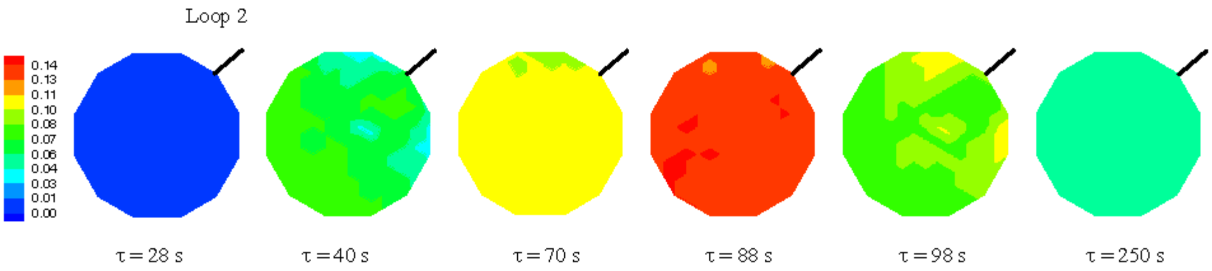

Fig. 18. Variation of relative concentration at the core inlet. E10.

To summarize, one could say that results of the experiments have highlighted spatial nature of tracer distribution in the reactor model. The creditability of experiments is proved by multiple repetitions of the same phenomena.

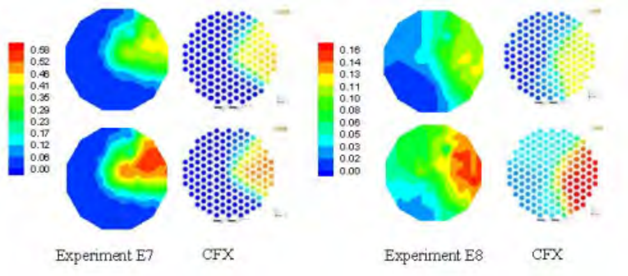

Fig. 19. Comparison of results of experiments E7 and E8 and ANSYS CFX calculations.

V. COMPARISON OF INVESTIGATION RESULTS WITH FOREIGN ANALOGUES

In this section we try to compare the results of the experiments performed by OKB "GIDROPRESS" with the results of the investigations executed at ROCOM facility (Germany) and at Vattenfall (Sweden) [Ref. 4]. Quantitative comparison is limited due to differences in the geometry of the considered facilities and an inaccessibility of the full scope of experimental data set. Therefore, only a qualitative comparison has been performed.

The contour plots of relative concentration at the core inlet for different test facilities, simulating both VVER, and PWR reactors, are presented in Figure 20. The contour plots illustrate the beginning of the process of tracer slug passing through the section at the reactor core inlet. For reasons of convenience, some of plots are rotated so that to provide the same orientation of the loop, containing a slug, in all of the cases considered. Distribution of relative concentration is rather similar in all cases and makes the evidence that in all the experiments coolant flow moves surrounding the core barrel in the annulus downcomer as a result of the RCP start-up.

In spite of the conformity of the results, there are some differences in the distributions. The differences arise due to the location that the tracer penetrates the core periphery. For VVER, the tracer penetrates the periphery of the side being opposite and adjacent to the loop with the RCP started, while for PWR, the tracer penetrates the core only on the periphery of the side being opposite to the loop with the RCP started. Nevertheless, it could be said that the coolant mixing processes in the downcomer and lower plenum of PWR- and VVER-type reactors are of similar nature.

A more detailed description of the experiments performed by OKB "GIDROPRESS" and Forschungszentrum Dresden (Germany) was reported in [Ref. 5]. Besides the experiments with RCP start-up, the experiments with tracer injection into the circulation loop under the conditions of constant reactor coolant flowrate had also been considered. In spite of some differences in experimental results, formation of the sector with increased tracer concentration at the core inlet was similar in both cases. This fact also provides further evidence of the similarity of the coolant mixing processes in PWR- and VVER-type reactors.

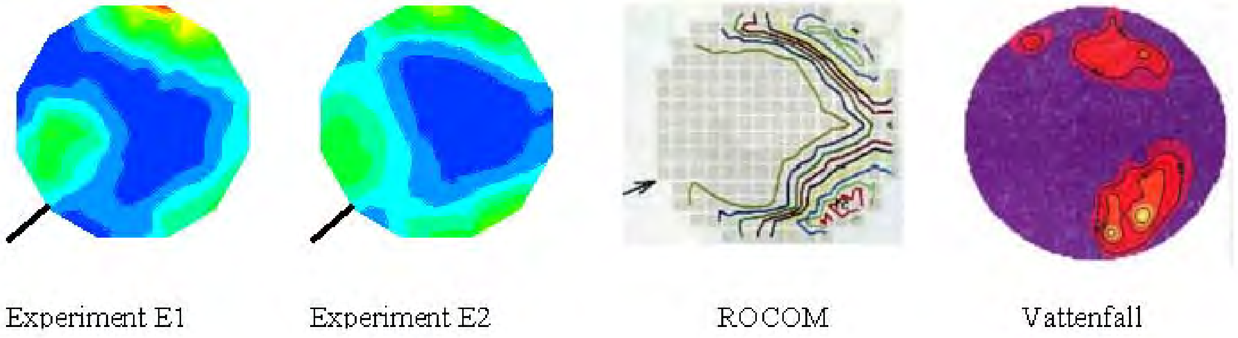

Fig. 20. Variation of relative concentration at the core inlet of different facilities. Beginning of the process

VI. CONCLUSIONS

1. Experimental investigations of coolant mixing in the downcomer and lower plenum of VVER-1000 reactor have been performed. Ten experiments were implemented and the obtained experimental results are used for validation of thermohydraulic codes.

2. It is determined that mixing of the flows with different boron concentration at the reactor core inlet reduces the risk of a reactivity-initiated accident under the conditions with first RCP start-up. The degree of boron dilution at the core inlet for the investigated conditions with RCP start-up does not exceed 37 % on the average, and 63 % at local minimum with reference to the full-scale reactor.

3. In the case of the condensate slug penetration into reactor under the conditions of natural circulation recovery during the course of SB LOCA, the density difference in the slug and main coolant has a strong influence on the nature of the coolant mixing in the downcomer and lower plenum. "Light" or "heavy" slugs linger in either the downcomer, or the lower plenum, and the process of condensate penetration into the core is stretched in time. This effect also significantly reduces the risk of a reactivity-initiated accident. The degree of boron dilution at the core inlet for the investigated conditions with natural circulation recovery during SB LOCA does not exceed 37 % on the average, and 49 % at local minimum with reference to the full-scale reactor.

4. The experimental investigations, presented here indicate a direct improvement in the knowledge of mass transfer and hydrodynamics in LWRs. Such investigations provide for essential improvement of Russian and Western users of thermohydraulic and CFD codes that is supported, in particular, by good agreement of the results of calculation and experimental results. The given fact creates the pre-conditions for the computational simulation of the processes with the mixing of flows for either different boron concentrations, or coolant temperatures.

ACKNOWLEDGMENTS

The work reported about in this paper was supported by the EC TACIS Project R2.02/02 "Development of safety analysis capabilities for VVER-1000 transients involving spatial variations of coolant properties (temperature or boron concentration) at core inlet".

ABBREVIATIONS

CFD – computational fluid dynamics;
DBA – design basis accident;
MCP – main coolant pipeline;
RCP – reactor coolant pump;
SB LOCA – small break loss of coolant accident.

NOMENCLATURE

d = hydraulic diameter (m)
g = gravity acceleration (m/s^2)
Fr = Froude number
L = linear dimension (m)
Re = Reynolds number
Sr = Strouhal number
W = velocity (m/s)
$\Delta\rho$ = density difference (kg/m^3)
ν = viscosity coefficient (m^2/s)
θ = relative concentration
ρ = density (kg/m^3)
τ = time (s)

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